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Report on the Komárno - Štúrovo pilot area model

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GeoZS
ŠTÁTNY GEOLOGICKÝ ÚSTAV DIONÝZA ŠTÚRA
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1 INTRODUCTION

The report presents the results of the steady state modelling in the Komárno – Štúrovo pilot area of the Transenergy project. The modelling was focused on the karst aquifer of the Triassic limestones and dolomites in the NE part of the Transdanubian regional karst flow system.

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

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

2 AIM OF THE MODEL

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

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

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

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

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

3 DESCRIPTION OF THE MODEL AREA

3.1 Geographic settings

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

The borders of the pilot area fit the presence of the Triassic carbonate basement and the watershed of the carbonate aquifer. The south-eastern and eastern borders are the same as the south-eastern and eastern border of the Supra-regional model pilot area, then towards west, the northern border set along geological structure between the Mesozoic and metamorphic formations of the Veporic unit in Slovakia. In north-west the border is the boundary of the Triassic formations. Only the south-western part of the model boundary – between settlements of Ugod and Eplény – is artificial (Figure 1).

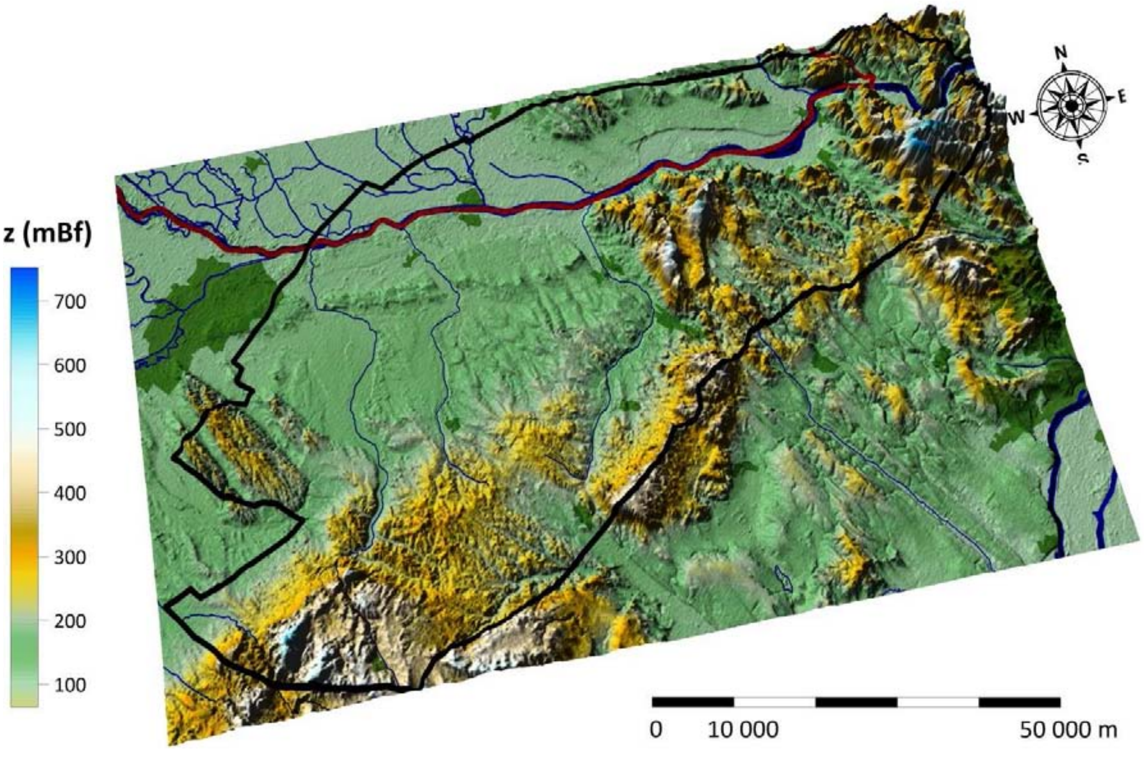

Figure 1. The area of the pilot model

3.2 Geological and hydrogeological setting

3.2.1 *Geological settings of the Pilot Area*

The Pre-Tertiary basement in the modelled area is build up shallow-water Middle to Upper Triassic platform carbonates (Main, or "Haupt" dolomite, Dachstein Limestone) focused by the hydrogeological modelling deposited on the passive margin of the Tethys ocean. This sequence has tectonic limit towards the Veporic crystalline unit and the Danube Lowland. The overlying rocks of the Triassic carbonates are pelagic Jurassic limestones, marls and cherty limestones with Lower Cretaceous clastic sequence in the Transdanubian Range and in the middle of the Slovakian part of the model area. In the western foreland of the Gerecse and Vértes Hills, the succession continued during the Middle and Late Albian with terrestrial clastics, shallow-water limestones and finally turned to open-marine marl. Figure 2 represents the basement formations of the pilot area.

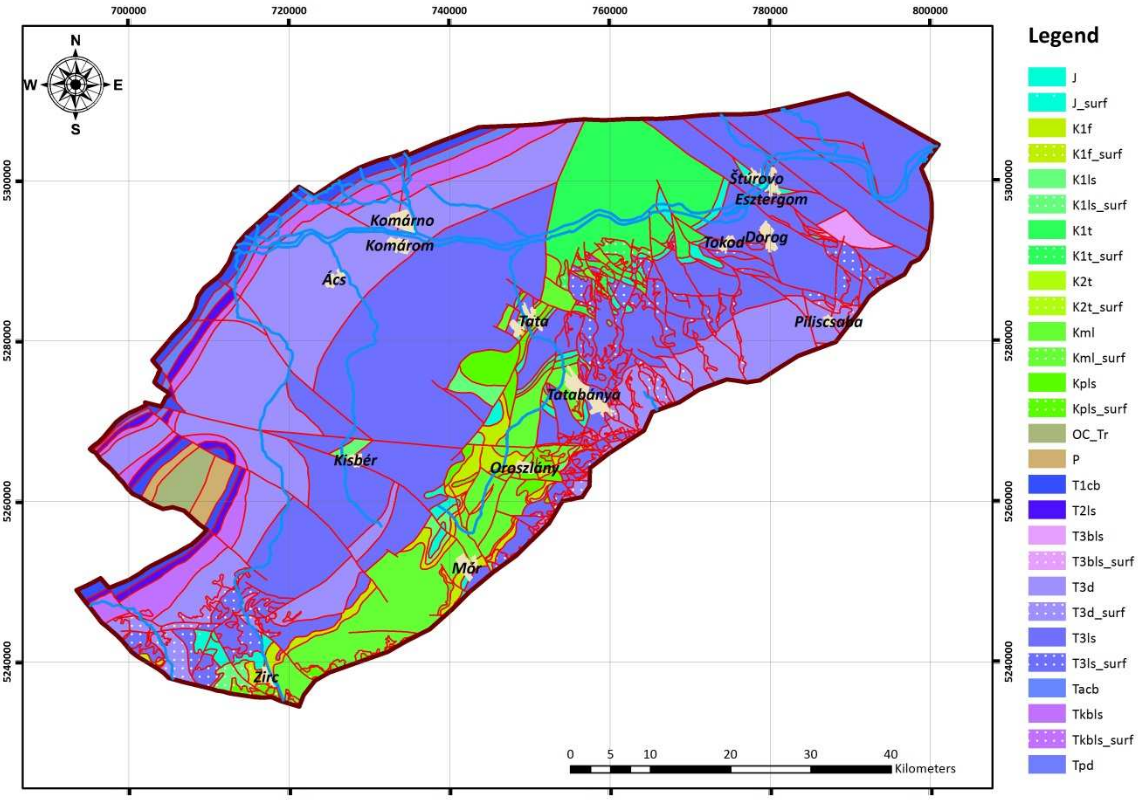

Figure 2. The geology of the Mesozoic basement of the pilot model

The Mesozoic succession was deformed by Cretaceous (mainly Berriasian and Albian) deformation phases resulted in the nappe emplacement of the whole Transdanubian Range over other units. These processes followed by an extensive denudation period ended in the Middle Eocene which resulted in denudation surfaces and strong karstification in carbonates. In the Middle Eocene some karst-bauxite deposits were formed.

In the Middle Eocene a new basin formed named Hungarian Palaeogene Basin. Here the Eocene sequence started with continental deposits followed by neritic nummulitic limestones and bathyal (locally turbiditic) marls. The transgressive Eocene sequence has been extensively, the regressive sequence has been completely eroded in the area during an early Oligocene denudation event. In the western part of the area the Eocene covered by Oligocene fluvial formations. The basin was filled up by sandstones and siltstones during the late Oligocene.

The Neogene sedimentation started in the late Early Miocene in the western part of the Gerecse Hills resulted in fluvial-limnic successions with thin coal layers, while the subsidence of the Danube Basin started at the end of the Early and the beginning of Middle Miocene.

Karpatian and Badenian sediments exists in the eastern margin of the Danube basin, in the western foreland of the Gerecse consist of transgressive conglomerates, sandstones and volcanoclastics overlain by neritic calcareous clays, siltstones and subordinately sandstones. Terrestrial Miocene sediments occur only in the southern part of the pilot area.

The Sarmatian sediments deposited in shoreline shallow-marine environment: biogenic calcareous sediments and in the basin fine-siliciclastic sediments were deposited.

The Late Miocene lacustric and delta and fluvial sediments have small thickness along the Mesozoic outcrops of the Transdanubian Range, but towards the Danube Lowland in the Hungarian part and in the Slovakian part of the studied area are thicker.

In the northeastern part of the pilot area: in the Pilis, Visegrád Hills and Börzsöny Mountains the Neogene volcanic–volcanosedimentary rocks exist.

Quaternary is mostly represented by fluvial sediments, loess, and slope deposites.

3.2.2 Hydrogeological and geothermal settings

The main and the most important aquifers in the pilot area are the Upper Triassic platform limestones and dolomites (Dachstein Limestone and Main Dolomite). The Middle Eocene denudation caused strong karstification in the more than 1500 meters thickness carbonate sequence. These well karstified conduits and fractures along the tectonic elements determine the groundwater (karst-water) flow system: due to the karstification the upper part of the system has higher permeability so the groundwater flow take place in this zone.

The topography of the karst aquifer also determines the natural groundwater flow: on the area of outcrops of the Upper Triassic rocks in the studied area (North-Bakony, Vértes, Gerecse, Pilis mountains) the precipitation infiltrate and along the karstified conduits the water flows towards the deeper regions. One part of the infiltrated cold water comes up near the recharge area as cold karst water but the rest of the recharge reaches greater depths, warmed up and enters the surface in lukewarm (~20 °C) karst springs along the margins of the mountains (Tata, Dunaalmás, Patince, Esztergom). A third part of the water warmed up more than 30 °C which also part of the flow system ended at natural discharge points, but smaller amount: these thermal karst water also produced by deep wells in the north-western part of the pilot area (near Bábolna, Ács, Komárom, Komárno the wells produce thermal water with 40-60 °C temperature).

The Upper Triassic carbonate aquifer uplift to shallow (app. 100 m) depth in Komárno high block. From a hydrogeothermal point of view, the area is divided into a high and marginal block (Remšik - Franko, et al. 1979; Franko, et. al. 1984; Remšik, et al. 1992). The Komárno high block has a fast water circulation and is considerably cooled (temperature is 20 – 22°C at a depth of 600 – 800 m, 24,5-26,5°C at 1100-1300 m, and around 40 °C at 3000m). The Komárno high block is encircled by the marginal block in the west, north and east and contains groundwater with a temperature exceeding 40°C.

The Transdanubian Range is affected by intensive groundwater abstraction connected to the coal and bauxite mines. These abstractions effected regional depressions and changes in the flow system in the whole region. Although the bauxite mining started in the early 1900's, the most intense mining and the coupled dewatering started in the 1950's and 1960's. In the early period of the mining the cold springs were disappeared. From the 1950's and 1960's the lukewarm springs along the Transdanubian Range started to destroy. The spring yields reduced and after some years most of them were disappeared (Esztergom, Sárisáp, Dunaalmás, Tata, Patince). After the mine closures the karst flow system started to regenerate and the beginning of the 2000's the hydraulic heads continuously rising (e.g. Tata, Tatabánya, Patince, etc.) and some of the springs reactivated (e.g. Dunaalmás, Tata, etc.) (Figure 3).

Figure 3. The regenerated (app. 2010) Lilla spring in Almásneszmély

The temperature and chemical composition of the lukewarm springs around the pilot area (Esztergom, Tata, Dunaalmás) serves good evidences of the uniformity and continuity of the whole karst system are. The regional depression caused by the mining also indicate an unified flow system.

4 HYDRAULIC MODEL

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

4.1 Model geometry

4.1.1 Horizontal extent

The model area is outlined in accordance with the TE project pilot area (Figure 1).

4.1.2 Vertical extent

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

4.1.3 Horizontal resolution

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

The finite element mesh needed to be refined around the main rivers, wells and springs because of the character of the modeled problem. Thus the generated mesh is consisting of triangular prisms, counting up to 155 517 nodes per slice (in total 2 021 721), forming 308 862 elements per layer (total 3 706 344).

4.1.4 Vertical resolution

The geometry of the lithostratigraphic units, location of the covered and uncovered karst and the hydrogeological units of the area were taken into consideration. The model layers follow the geological settings: the pinched out layers exists towards E, SE. This pinching out were built in the model by parameter change in the same layer. Six main hydrostratigraphic units were defined this way in twelve numerical layers (Table 1 and Figure 4-5):

Table 1. The main hydrostratigraphic units of the model.

Model layer	Hydrostratigraphic unit
1	Quaternary
2-5	Upper Pannonian
6-7	Lower Pannonian
8	Miocene
9	Paleogene
10-12	Triassic basement

The Upper Pannonian and the Triassic units were divided into four and three, the Lower Pannonian was divided into two numerical layers. In this phase the fifth layer was represent the Upper Pannonian thermal water aquifer, the tenth layer is the uppermost 100 meters of the cavernous Triassic carbonate unit (Figure 3-4).

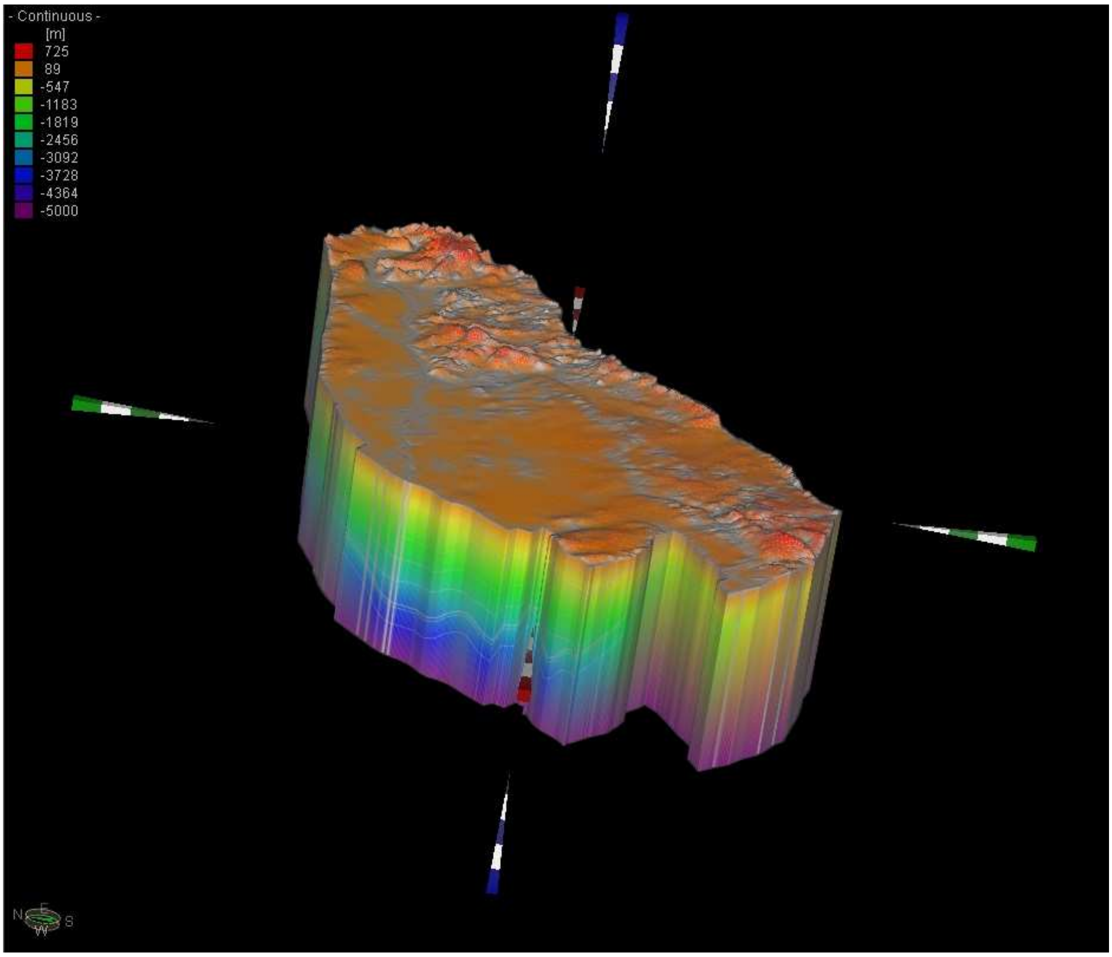

Figure 4. Geometry of the pilot area model

The main (Triassic) karst aquifer is outcropped in the southern and the south-western part of the model area. The bottommost part of the aquifer was settled down in the north-western and northern part of the pilot model area. At these locations the top of the Triassic aquifer is lower than 2500 m mASL (Figure 5).

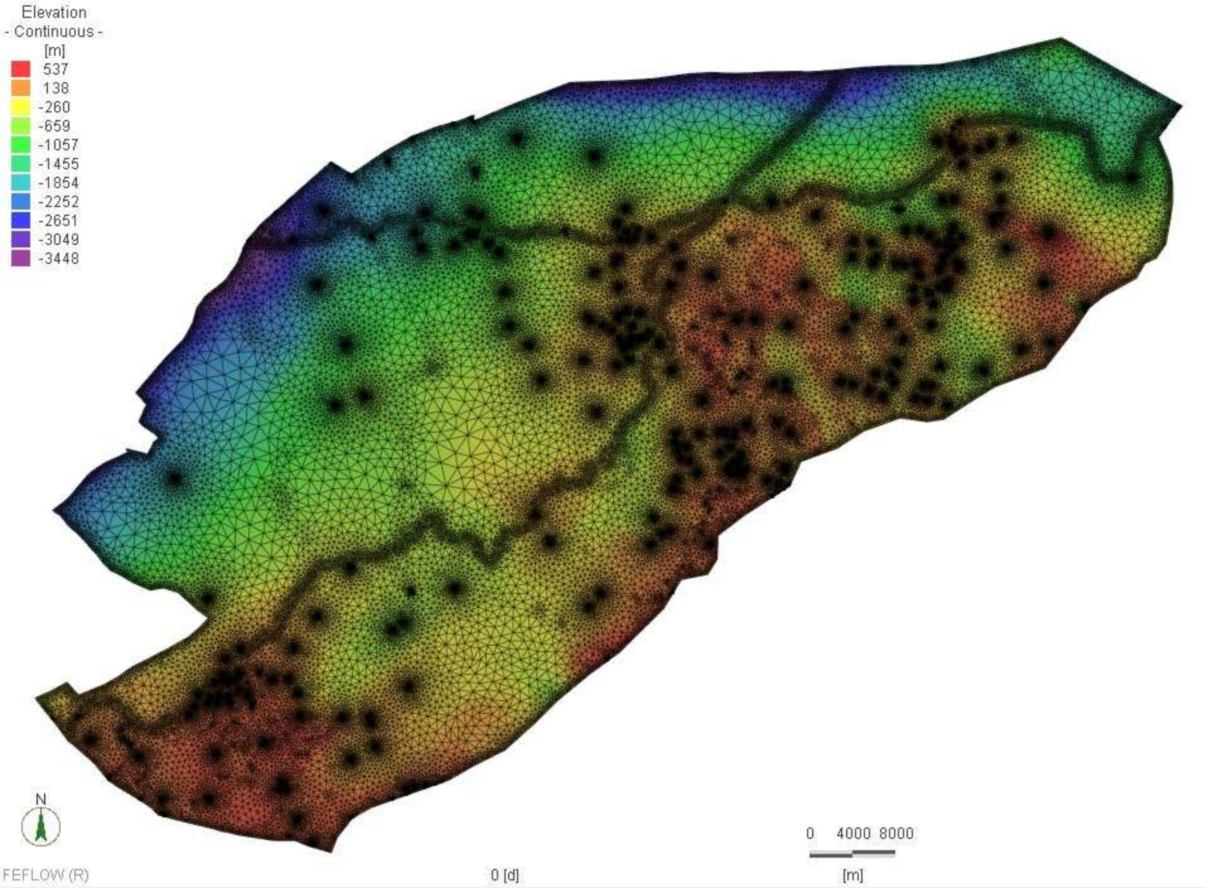

Figure 5. Elevation on the top of layer 10 (top of the Triassic karst aquifer)

4.2 Recharge

The hydrodynamic system of the karst aquifer complex is recharged from the precipitation. Although the infiltration is derived from the precipitation (minus the runoff and the evapotranspiration), the runoff and the evapotranspiration depends on several factors (land coverage, spatial distribution of the precipitation, sunshine hours, vegetation, climate etc.) we calculated the infiltration in a simply way derived from the monthly average of the precipitation. We collected monthly average precipitation data of 24 meteorological gauging stations (eg.: Zirc, Tata, Fenyőfő, Dorog etc.) in and out (close) of the pilot area from 01. 01. 1950 to 31. 12. 2011. (Figure 6).

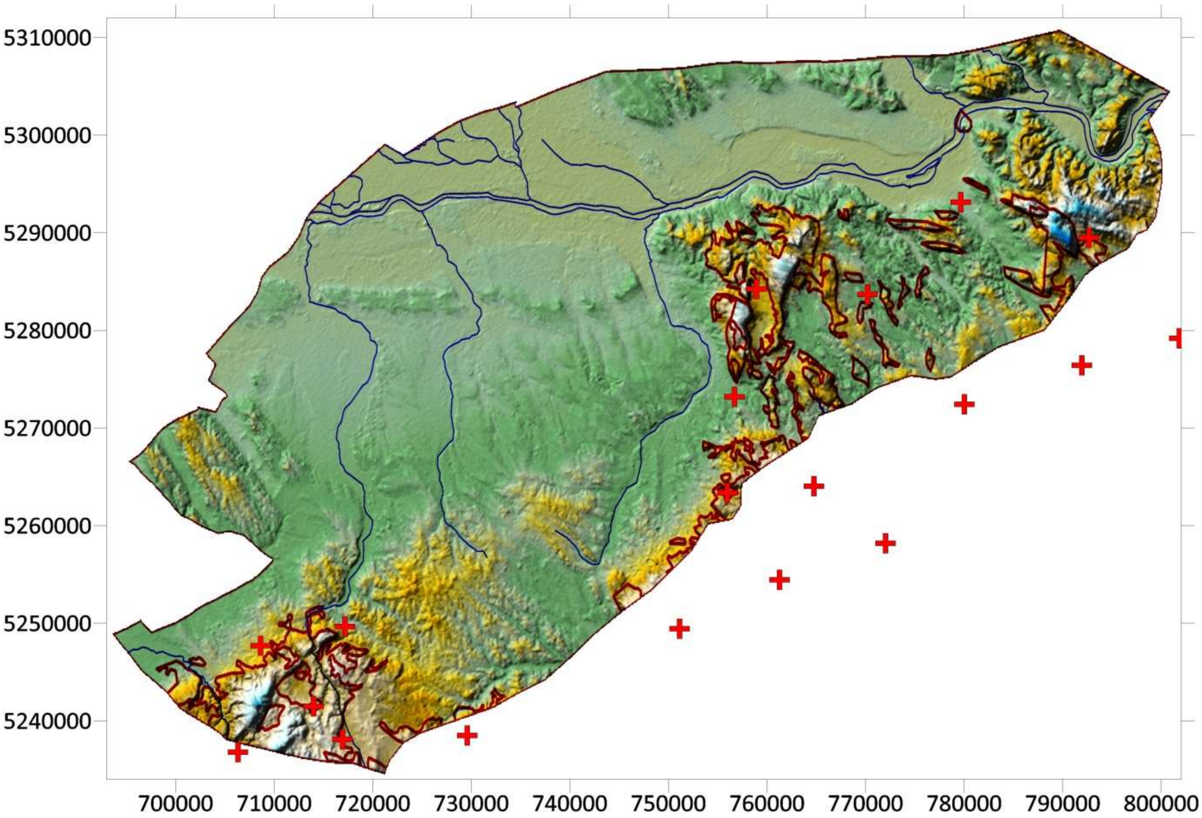

Figure 6. Meteorological gauging stations on and close to the pilot area (Ruby red line: Triassic outcrops)

The main recharge areas are represented by the higher elevated regions in the SW, SE and E part of the model area: here the Triassic limestones and dolomites are outcropping on the surface (with ruby red on the map) (Figure 6). These recharge areas situated at the margin of the modelled area, but there are some smaller areas inside the model region (between Tata and Dorog, etc.) where recharge also can take place.

In the model we use the 30 % of the precipitation data as infiltration on the area of Triassic outcrops. The minimum monthly average infiltration is 0 mm, the maximum is 119.1 mm, while the average 16.6 mm. The yearly average infiltration in the pilot area is between 83.1 mm and 447.6 mm, with an average of 199 mm/year.

Some subsurface recharge in the NE and SSW border of the model area can probable.

4.3 Discharge

There are several natural and artificial discharges of the karst system on the area. In the shallow region of the porous system the rivers are the main natural discharge zones. The most important natural discharge points of the karst system are the springs, here mainly cold and lukewarm springs (Tata, Esztergom, Patince) (Figure 7-9).

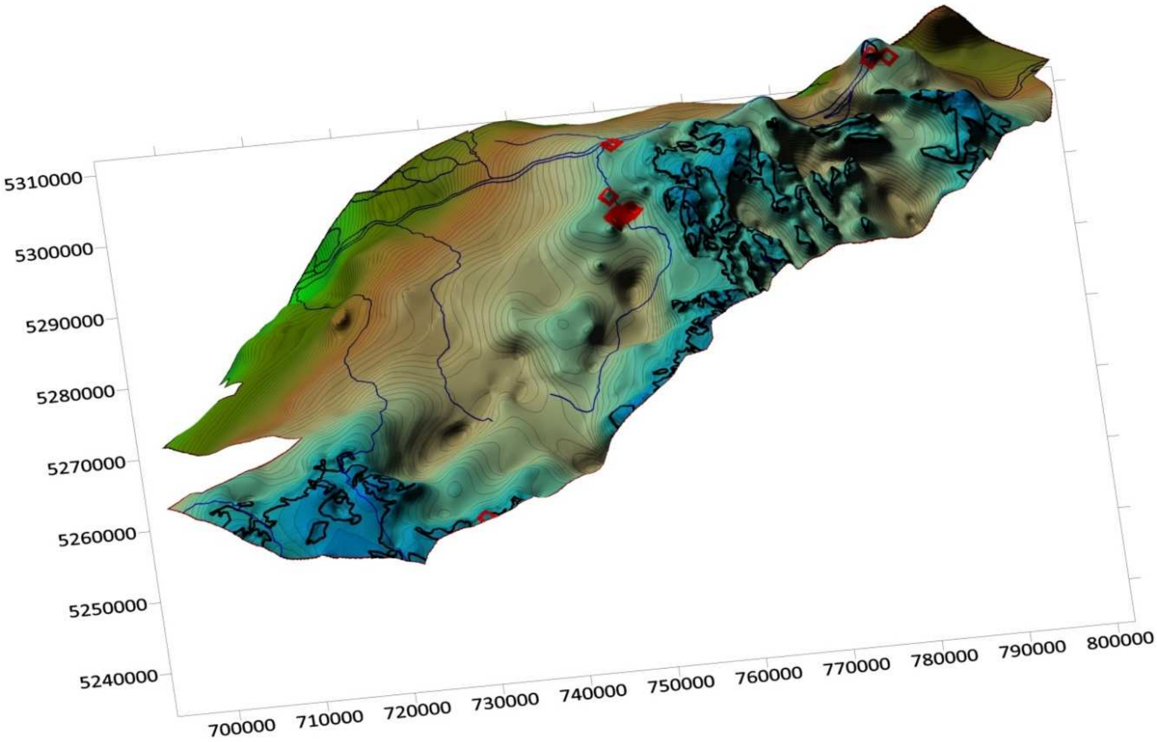

Figure 7. Lukewarm springs on the model area (red dots) (black line: Triassic outcrops, map: top of the Mesozoic basement)

Figure 8. Lukewarm (20 °C) springs in Tata

Figure 9. Csokonai spring in Almáésneszmély (regenerated around 2005)

The artificial discharge on the model area is represented by the mining water abstraction and the cold and thermal wells on the karst and porous system.

4.4 Abstractions

More than 150 discharge points take place in the area (including the main lukewarm springs also) (Figure 10). The time series of the collected data of the water abstractions started from 1951 and ended in 2011. We have 1-57 year-long time series, 18 year-long average. Although the mining water abstraction of the bauxite and coal mines gradually finished from the 1990's, we will have to build in the transient model to simulate of the refilling of the karst system. In the first step, the steady state model built for the modelling of the original flow system before the mining water abstraction, so the abstraction was no taken into consideration in this model.

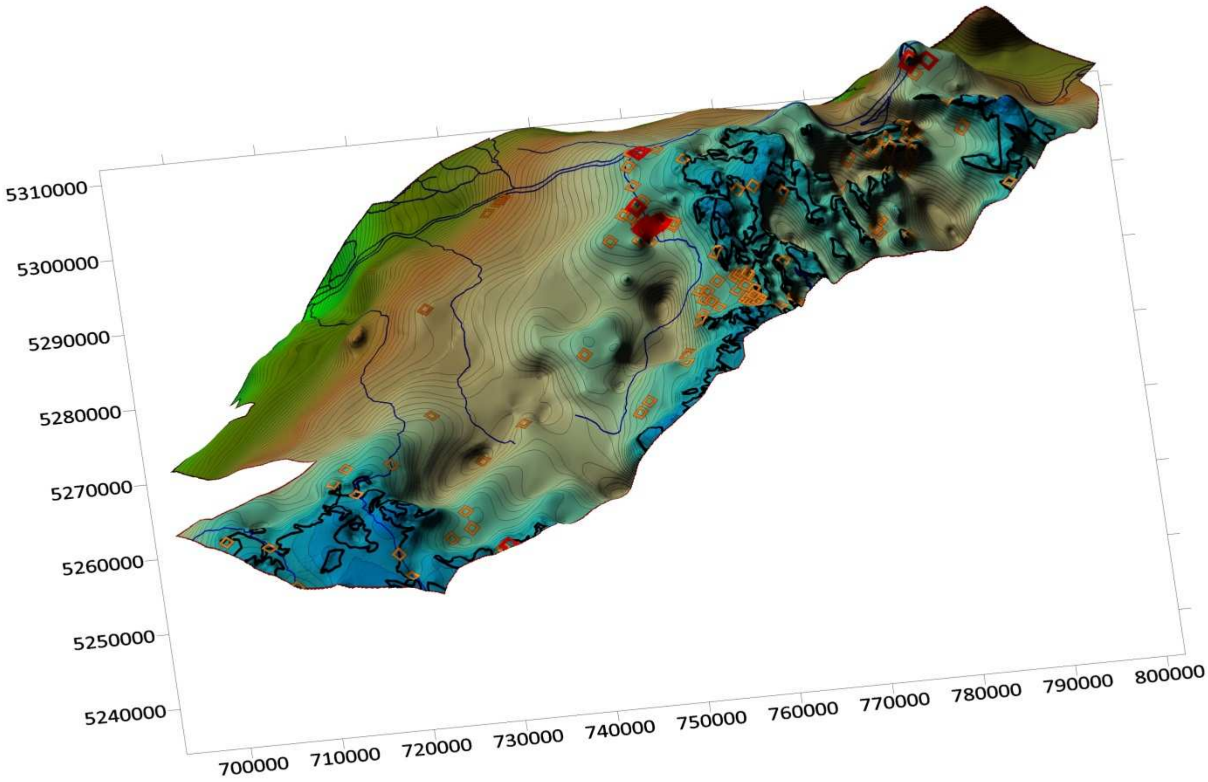

Figure 10. Discharge places on the model area (red dots: springs, orange dots: wells and mining abstraction places) (black line: Triassic outcrops, map: top of the Mesozoic basement)

4.5 Boundary conditions

We try to follow the rule to choose borders along “no-flow” boundaries.

The model boundaries are equal the supra-model boundaries along the SE boundary of the pilot area, so this border delineates the watershed of the karst system. The northern boundary is tectonical between the Vepor unit and the Transdanubian Unit and supposed as low permeable “wall”. The NW border of the model follows the geology, the boundary of the Triassic and rocks and the deeper non-karstic system. These borders have no flow boundary conditions. The SW and the NE boundary of the model is artificial, on the model layer 10 we used fixed hydraulic head boundary conditions derived from the available hydraulic head maps of the Transdanubian karst system (Alföldi 2007).

On the top of the model we use a diffuse type of the infiltration calculated from the precipitation, which control the recharge of the karst system. The Danube represented as a fixed head boundary condition in this model phase on the model top.

The bottom of the model also represented with no flow boundary condition.

4.6 Material properties

4.6.1 Conductivity and permeability

The hydraulic conductivity is one of the most important hydrogeological parameters. The conductivity determine the natural flow systems and also has an effect through water movement to the heat (and mass) transport in a certain area. In the nature and in the models the rocks and geological formations are represented by their K values and the vertical and/or horizontal anisotropy. In regional scale we cannot use K values derived from the hydraulic test of the wells directly because of their local nature, so we have to simplify the K-field: the local diversity of hydraulic conductivity is handled by average values.

The knowledge of the thickness of K-fields is very important in the karst system. Unfortunately we have some measured data from the depth of wells and springs only, not in the deeper region of the karstified system. Therefore we use an average thickness, 200 meters of the karstified aquifer, where we use uniform conductivity values. From this depth, the carbonate system is assumed to be unweathered, non-karstified and possess with lower hydraulic conductivity.

The applied K values are based on well hydraulic tests, well measurements, literature data and previous observations and modelling experience.

The conductivity zones of the model layers are based on and determined, or assumed according to the hydrogeological characterization of the geological formations. In one layer to represent the different formations parameters change was used (Figure 11-12).

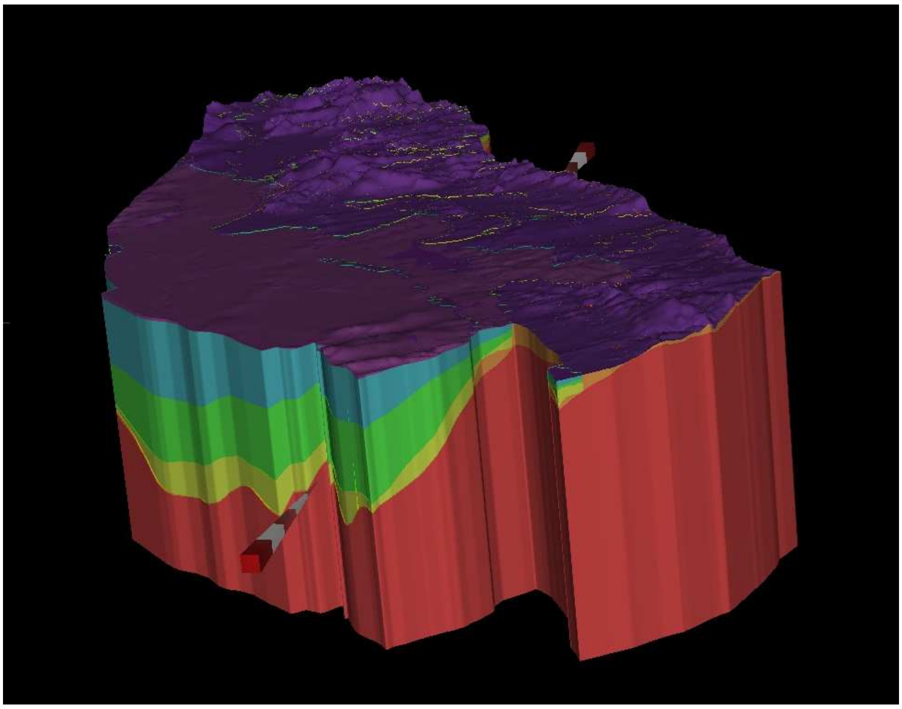

Figure 11. The main hydrostratigraphic units of the model

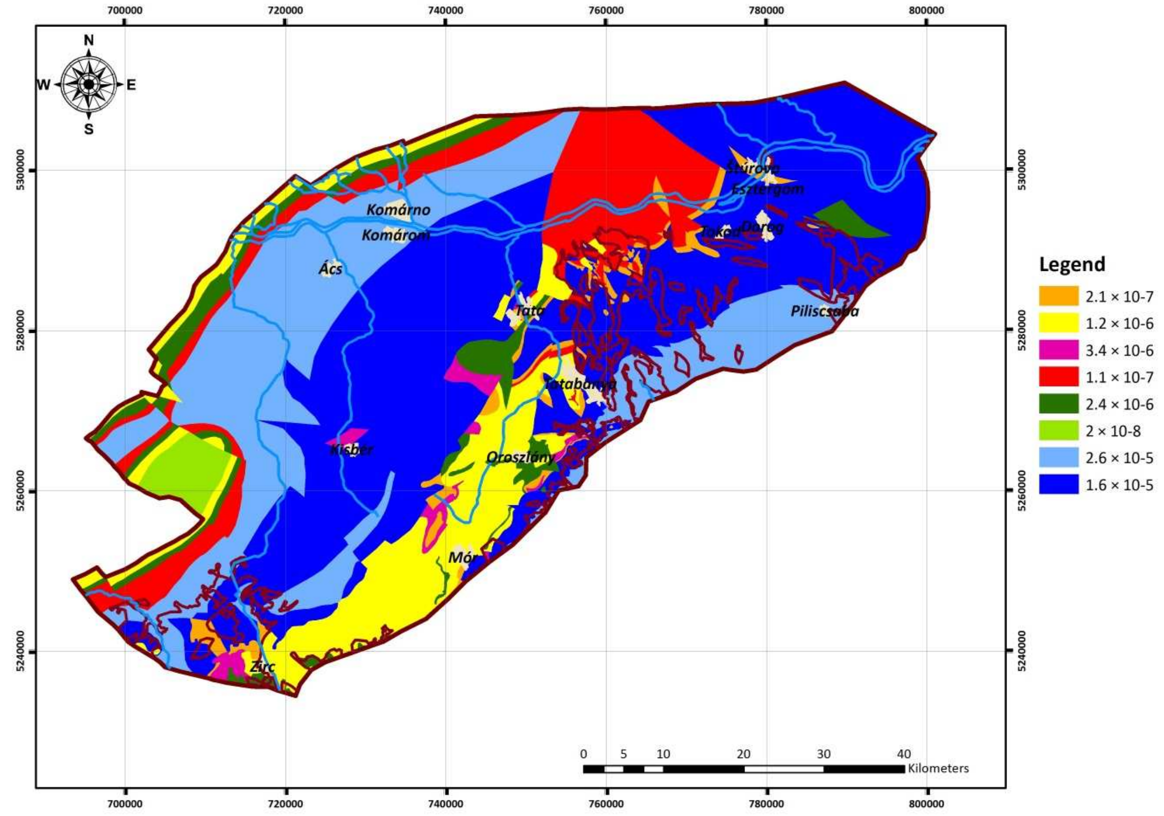

Figure 12. Hydraulic conductivity of the model layer '10', represented the Mezozoic basement

4.6.2 Porosity

Porosities can derive from laboratory measurements, geophysical logs, analogies and experiences from previous models, giving a possible range of values for regional hydrogeological modelling. In the first step a general effective porosity value (0.15) was determined but during the calibration phase the value changed and the finally used porosity values are shown in Table 2.

4.7 Calibration and validation of the model

Initial values of parameters were derived from the supra regional TE model, literature and measured data and previous experience which were adjusted during the calibration process. Due to the long term mining water abstractions, the natural flow field had changed, thus we had to calibrate to calculated hydraulic heads (Alföldi, 2007).

The applied and calibrated hydraulic conductivity values of the model are the following (Table 2):

Table 2. Hydraulic conductivities of the model

Hydrostratigraphic unit	**Kxx = Kyy (m/s)**	**Vertical anisotropy (Kh/Kv)**
Quarternary	8×10^{-6} - 2.5×10^{-4}	10
Upper Pannonian	4×10^{-6}	100
Lower Pannonian	1×10^{-9}	1000
Miocene (Sarmatian and Badenian)	1×10^{-8} - 1×10^{-6}	10 - 1000
Paleogene (Eocene – Oligocene), and low permeable createceous	1×10^{-7} – 1.5×10^{-5}	10 - 100
Triassic basement weathered zone	2.6×10^{-5} - 2×10^{-8}	10 - 100
Triassic basement non-weathered, fresh zone	2.6×10^{-6} - 2×10^{-9}	10 - 100
Lower non-weathered zone of older Mesozoic layer	1×10^{-8}	10

5 GEOTHERMAL MODEL

5.1 Boundary conditions

The estimation of boundary conditions for the heat transport contains more uncertainties then of the flow systems. The only certain data is the temperature of the surface: the mean air temperature. At the top of the model a Dirichlet boundary condition with uniform temperature, 11 °C was set. A uniform temperature exists on this model boundaries with fixed head. The heat boundary condition of the model bottom is taken from the supra geothermal model. To simplification we use a uniform data, 80 mW/m^2 heat flux on the bottom of the pilot model.

5.2 Material properties

The main heat transport parameters are evaluated by measured and literature data. Default data of the FeFLOW® software were accepted for the thermal conductivity of fluid, the volumetric heat capacity of fluid and solid. The heat conductivity of the model layers is used from literature and the supra geothermal model data (Table 3). The longitudinal and transversal dispersivity are an-two orders of magnitude larger than the default data.

Due to the high specific heat capacity of the water and the low heat capacity of the rocks and the intensive groundwater movement, the infiltrated water keeps its temperature for a long time. In the pilot area the main heat source of the subsurface rocks is the convective heat flow of the water flow.

5.3 Calibration and validation of the model

Calibration of geothermal parameters was based on temperature measurements in lukewarm springs (Tata, Almásneszmély, Esztergom) and thermal wells abstracted from the Triassic carbonate aquifer (Ács, Bábolna, Komárom, Komárno, Patince, Štúrovo, Esztergom).

The thermal conductivity values in the model are derived from supra regional TE geothermal model, literature and measured data.

The applied and calibrated geothermal parameter values of the model are the following (Table 3). (Parameters are not included in Table 3 used with default values of FeFLOW®.)

Table 3. Geothermal parameters of the pilot model

Hydrostratigraphic unit	**Heat conductivity of solid [W/mK]**	**Porosity**
Quarternary	1.5	0.25
Upper Pannonian	1.8	0.1 - 0.15
Lower Pannonian	2	0.05
Miocene (Sarmatian and Badenian)	1.5 - 2	0.01 - 0.1
Paleogene (Eocene – Oligocene), and low permeable Createceous	1.5 - 2.1	0.1 - 0.5
Triassic basement weathered zone	2.2 - 3.8	0.01 - 0.1
Triassic basement non-weathered, fresh zone	2.2 - 3.8	0.01
Lower non-weathered zone of older Mesozoic layer	3.5	0.01

6 RESULTS

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

6.1.1 Hydraulic head distribution

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

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

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

The Figure 13 presents the simulated hydraulic head distribution of the karst aquifer.

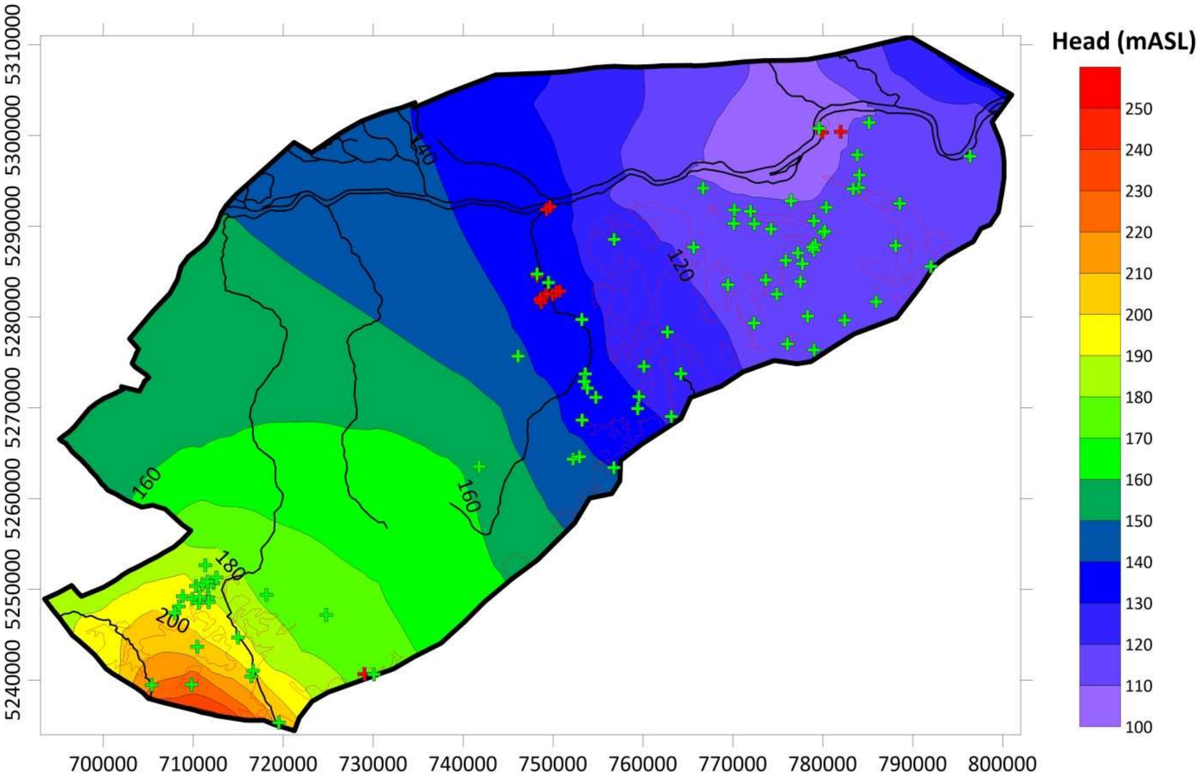

Figure 13. Modelled hydraulic head on the model layer '10', represented the Mezozoic karst aquifer

6.1.2 Temperature distribution

The temperature distribution of the Transdanubian karst flow system is mainly affected by forced heat convection. In the karstified dolomite and limestones the water can flow deep down the surface without any barrier: the recharged precipitation water cool down the system even at high depths. Due to the intensive flow system, this cooling effect can observed also far from the recharge areas (Figure 14).

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

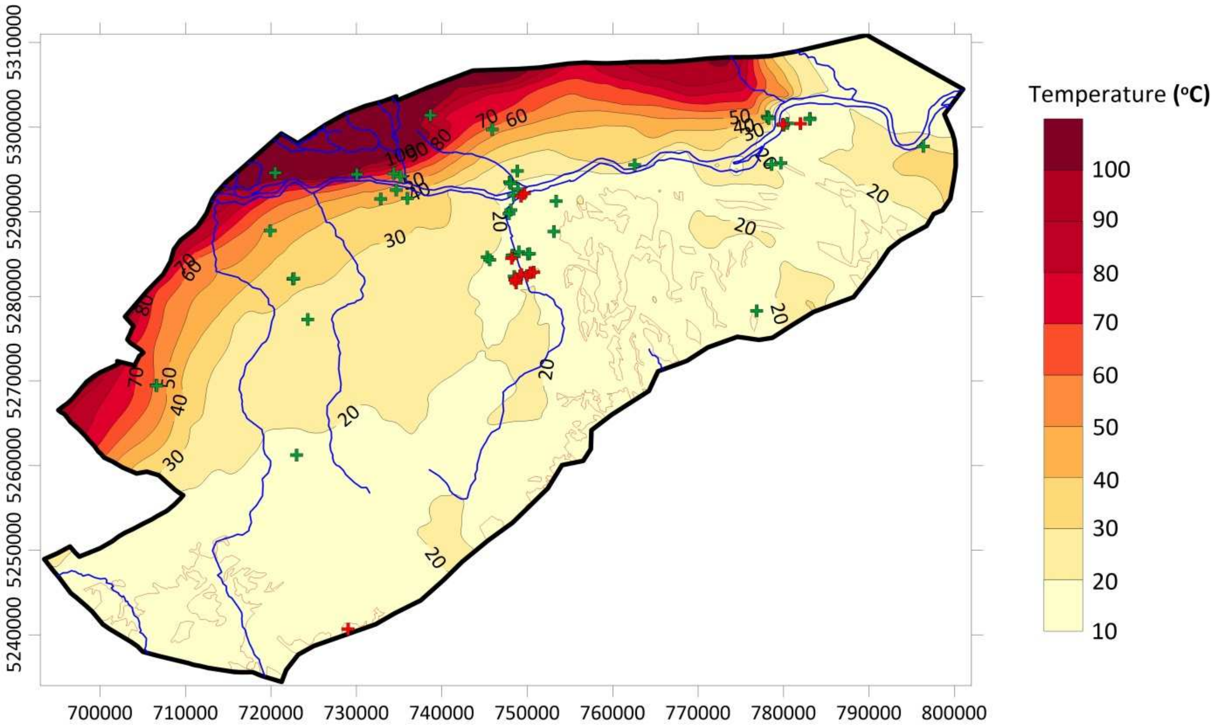

Figure 14. Modelled temperature distribution in layer '10' (top of Mesozoic basement)

7 CONCLUSIONS AND PROPOSALS

The modelling of the Komárno – Štúrovo pilot area was focused on the karst aquifer of the Triassic limestones and dolomites in the NE part of the Transdanubian regional karst flow system. Due to the specific characteristics of the karst aquifer a finite element method was applied for the modelling: FEFLOW was used for the modelling of the karst system flow and coupled heat transport. Steady flow and steady heat flow were taken into account during the model simulations.

The constructed 12-layered numerical model simplified the complex geological and hydrogeological system and capable to simulate the steady state natural flow and heat transport processes before the intense mine water abstraction in the transboundary area.

The model presented the close connection between the water and heat flow: in the karst system the recharged precipitation from the area of the outcropping carbonates flows fast and to large depth in the karstified carbonate aquifer. This flow basically affects the heat transport in the area: a convective heat transport takes place in the karst system, thus the recharged water cooled down the system even at long range from the recharge area.

Although — based on this preliminary relatively good results, — the model would be able to prescribe properly the natural system, detailed hydrogeological data are needed from the period before the intense mine water abstractions to get better matching simulated values. However poor data of the “natural” system are available from this period, the further (transient) model period can serve reliable results for the flow system.

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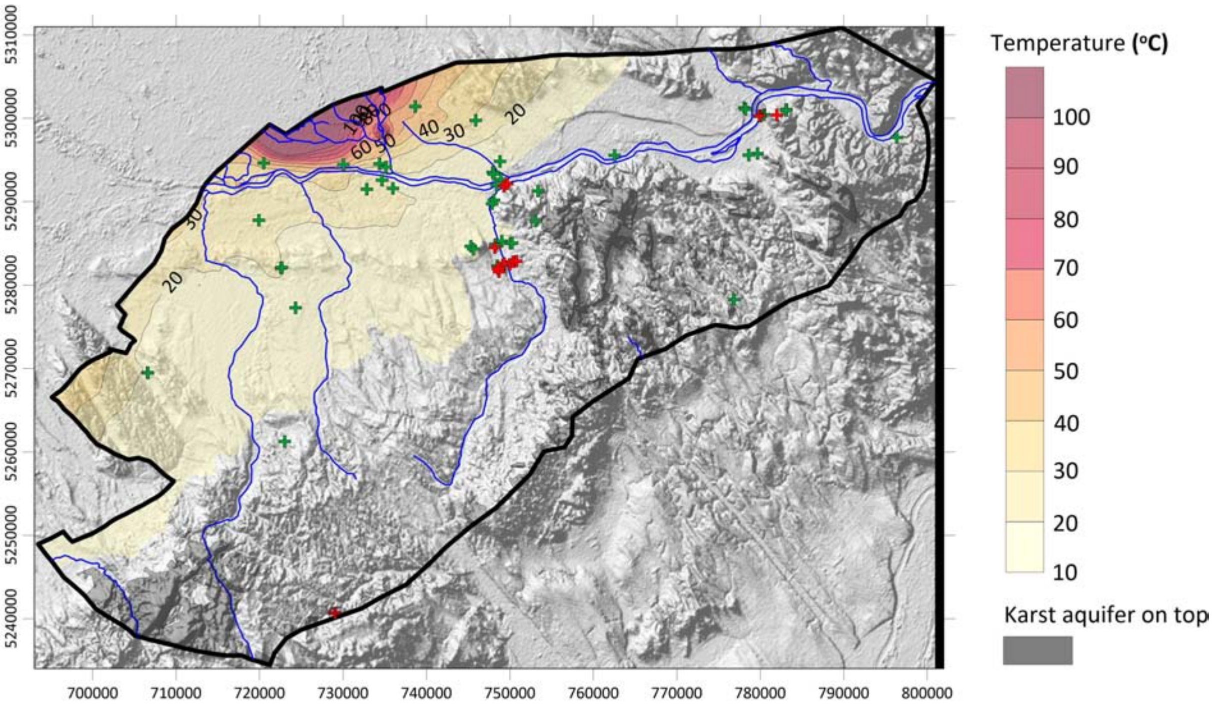
Annex I

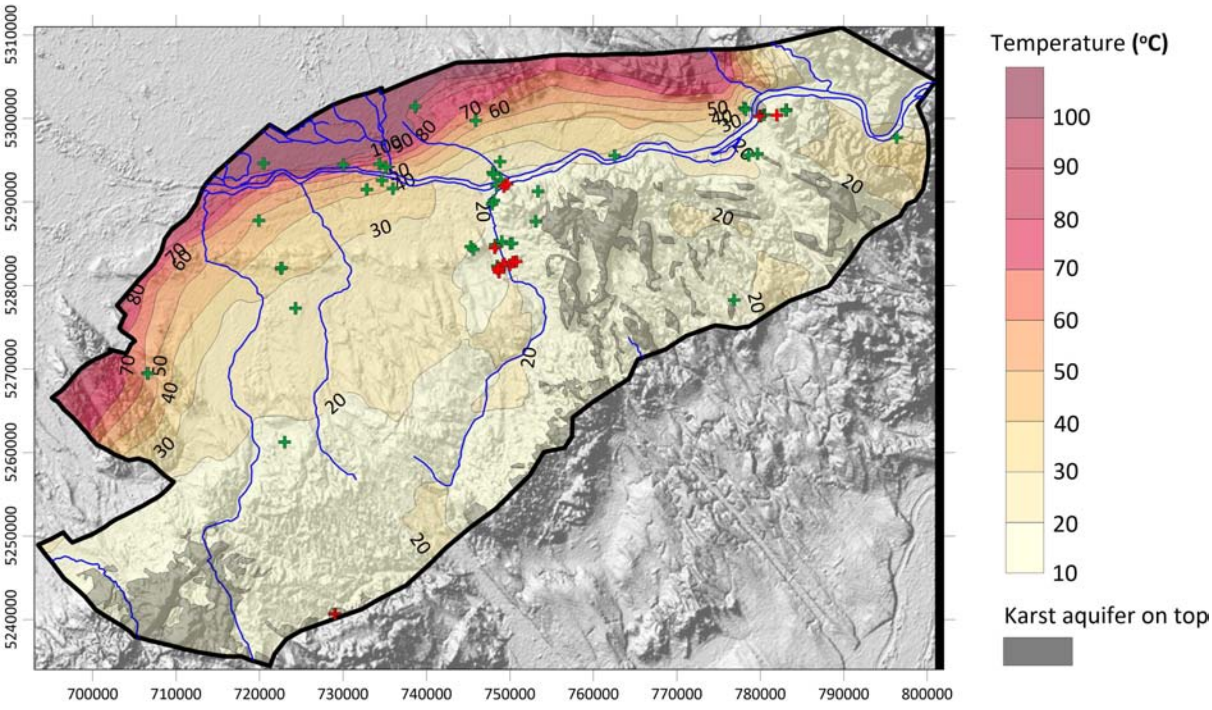
Simulated water budget (natural system before mining)		
Boundary type	**In (m3/d)**	**Out (m3/d)**
Dirichlet BC	1.99e+6	2.18e+6
Infiltration	1.9e+5	-

Annex II

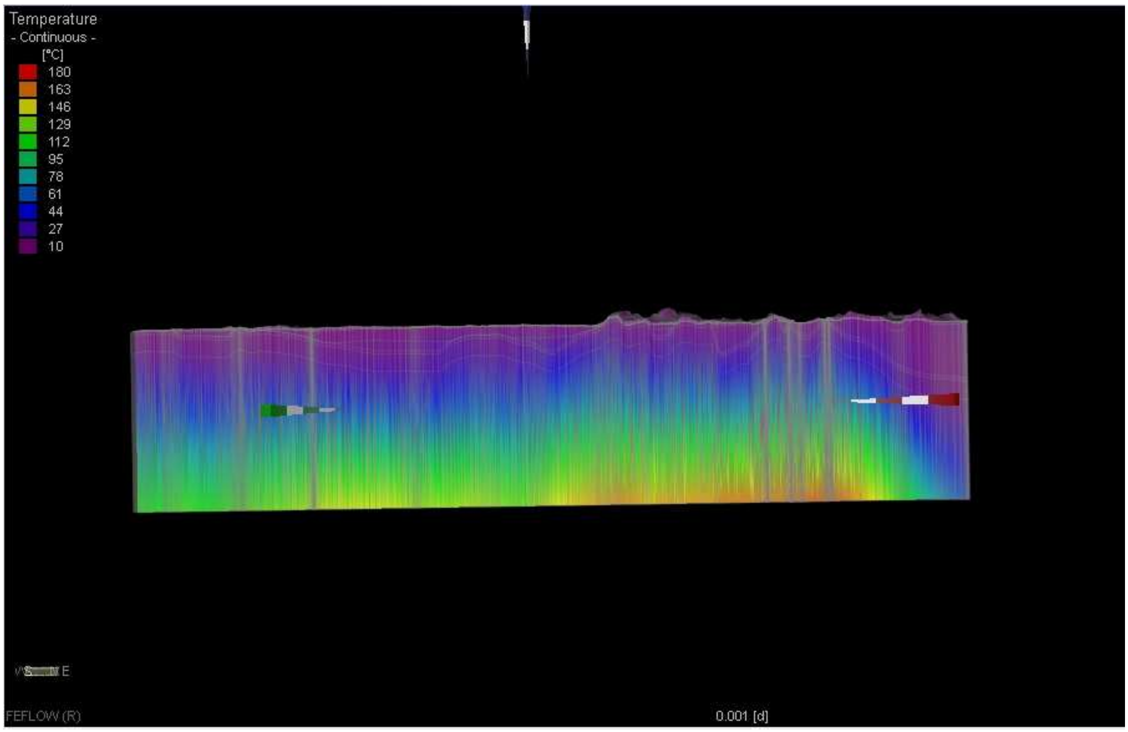
Temperature distribution at the lower part of Upper-Pannonian Formation



Temperature distribution at the top of the Basement Formation



Temperature distribution in the SW-NE cross-section



Temperature distribution in the N-S cross-section