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MODEL REVIEW AND SENSITIVITY ANALYSIS OF THE SÁROSPATAK RESERVOIR MODEL, NE-HUNGARY

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ABSTRACT

Hungary's favourable natural conditions for geothermal energy production and utilization are well known. The anomalously high thermal gradient and the significant expanse of deep aquifers make Hungary one of the most notable European countries regarding low-temperature geothermal resources. Among other cities, Sárospatak in northeast Hungary has utilized its deep carbonate geothermal reservoir for bathing purposes since the 1960s. In recent years, a 7-layer, three-dimensional numerical model with two proposed wells for district heating was constructed by the Icelandic company Vatnaskil Consulting Engineers. The main objective was to predict the impact of the planned well duplet on the geothermal reservoir at Sárospatak with a special focus on the existing geothermal wells associated with the thermal spa of the city. In this study, after a model and literature review, a detailed sensitivity analysis with 11 different scenarios was performed. Results of the analysis show that 1) the model is not sensitive to input parameters in its lower layers, 2) the model is not sensitive to the porosity and 3) the model is very sensitive to the hydraulic conductivity in the top model layers, especially the producing layer. It has also been shown that the proposed wells are not likely to have any negative impact on the existing thermal wells. On the other hand, the study shows that the existing thermal wells could have a significant impact on the reservoir pressure at the proposed well duplet. Lack of data related to the existing thermal wells (their actual production and the exact thickness and extent of the tuff layer from which they are producing) are crucial factors preventing their actual impacts from being known. These impacts could be the key in determining the success of the Sárospatak geothermal project.

1. INTRODUCTION

Hungary's favourable natural conditions for geothermal energy production and utilization are well known. The heat flow density within the Pannonian basin is high compared to the rest of central Europe (Figure 1). The anomalously high thermal gradient and the significant expanse of deep aquifers make Hungary one of the most notable European countries regarding low-temperature geothermal resources. According to REN21 (2016) data, Hungary is third in geothermal heat capacity per capita in the world (not including heat pumps) and sixth in direct heat capacity utilization. Although geothermal energy has been used mainly for bathing purposes in the country since historical times (e.g. the famous spas of

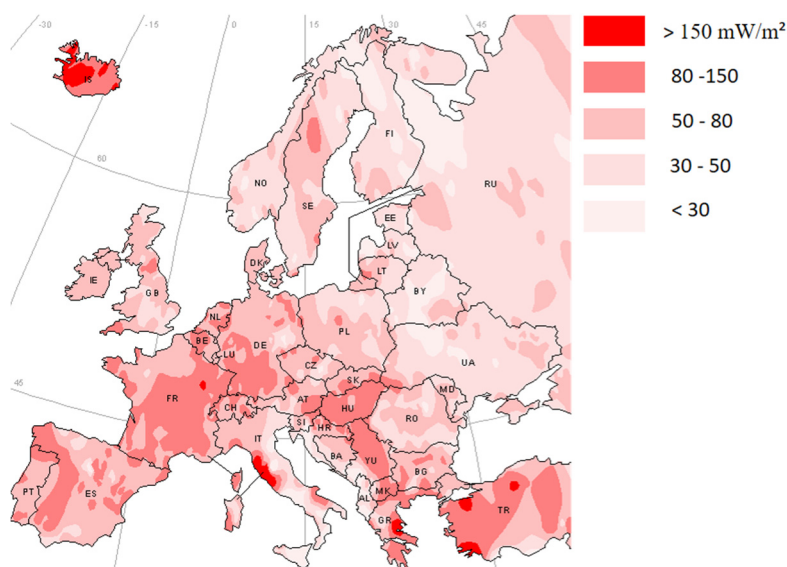


FIGURE 1: Geothermal heat flow density of Europe (Rollin et al., 1995)

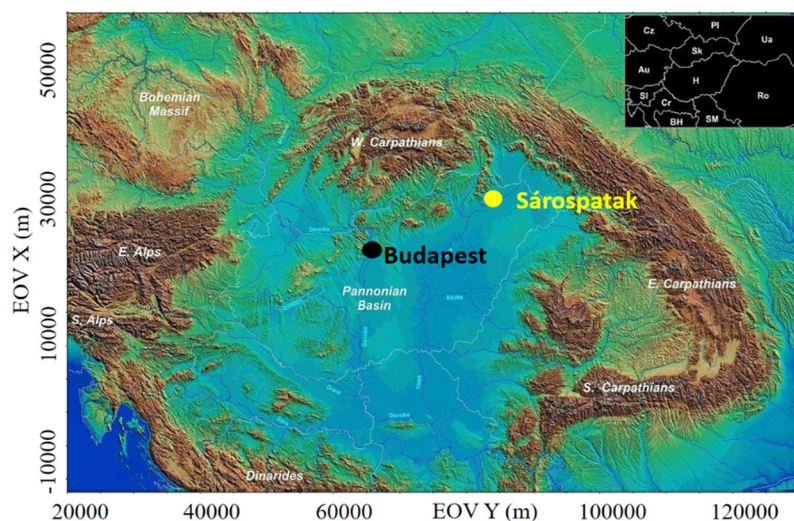


FIGURE 2: Location of the Sárospatak model in the Pannonian basin (modified after Horváth et al., 2006)

Budapest), other types of utilization have been increasing in the last decade. More and more municipalities are investigating and implementing geothermal production for alternate energy supply and for space heating in residential, public and industrial buildings. In addition, the first geothermal power plant is also about to be built near the town of Tura.

Using numerical reservoir models in order to simulate field capacity/performance under a variety of conditions is not just helpful, but is also a crucial part of successful geothermal exploration and development. With the help of numerical modelling, it is possible to predict worst- and best-case exploitation scenarios in a geothermal project, and therefore manage the development of the project in an efficient manner. Perhaps the most important and challenging part of the modelling process is the collection and integration of information compiled by all the geoscientific disciplines, leading to the development of the conceptual model.

The geothermal potential of Sárospatak in northeast Hungary (Figure 2) was first discovered in the late 1950s when geothermal wells began supplying water for a thermal spa in the city. The thermal wells have been producing from a relatively thin layer of a fractured rhyolite tuff formation. The lateral extent of this tuff formation is unknown, but it is believed to be hydraulically connected to the deeper Triassic carbonate reservoir in the basement, which is believed to have a much larger lateral extent (Erhardt, 1962). Overall, the area is lacking in detailed data from the carbonate reservoir and its exact hydraulic parameters. In 2013, an Icelandic company, Vatnaskil Consulting Engineers, constructed a numerical model of the geothermal reservoir at Sárospatak as part of a preliminary feasibility study. The model was used to simulate the effects of a proposed well duplet for use in district heating. The main objective was to predict the impact of the planned production and injection wells with a special focus on the existing geothermal wells associated with the thermal spa of the city of Sárospatak.

The goals of this study were twofold. First, the original model developed by Vatnaskil in 2013 was reviewed and analysed in an effort to determine the input parameters with the most amount of uncertainty. A literature review was performed in order to find new data which could improve the understanding of the most important model parameters. The second part of the study entailed performing a sensitivity analysis on the model in order to determine model parameters which have the most

influence on the simulated results. It is hoped that this evaluation of the model of Sárospatak helps give a better understanding of the geothermal potential of the reservoir, and therefore contribute to the energy development plan of the city of Sárospatak.

2. MODEL REVIEW

2.1 Geological setting

On a large scale, the study area is located on the northeast edge of the Pannonian Basin (Figure 2). The basin is surrounded by a mountain range, namely the Carpathians. It was formed during the Middle Miocene due to extension and thinning of the lithosphere. This thinning is the main reason for the relatively high heat flow and thermal gradient of the area (Lenkey et al., 2002).

On a smaller scale, the model area lies on the southeast margin of the Tokaj Mountains and the northeast edge of the Great Hungarian Plain, along the river Bodrog at an elevation of around 100-200 m above sea level. The surface geology consists mainly of alluvial and fluvial sediments from the Pleistocene, such as gravel, loess and clay (Lengyel, 1957). Underneath these units and on the hills of the Tokaj Mountains, Miocene-aged volcanics are common, and consist of mainly tuffs and breccias with a composition ranging from andesitic to rhyolitic. These formations are often extensively altered due to volcanic hydrothermal processes, creating silicified successions often composed of kaolinite or bentonite. These volcanic units can exceed 300 m thickness (Lengyel, 1957).

The Miocene formations directly overlie the basement units with an unconformity indicating a long chronological gap. These basement rocks consist of Triassic carbonates which are in an uplifted, horst position and are thus capable of forming a productive geothermal reservoir (Pentelényi et al, 2003, Haas et al., 2010). Figure 3 shows the elevation of the basement along with the known extent of the Triassic carbonates in the area. Besides indirect investigations of the basement formations, such as basement rock inclusions or hydrothermal veining in the younger volcanics, the only direct information available is from well Sp-5, which is the only well that penetrates into the Triassic carbonates (Figure 3). Despite that fact that Sp-5 was drilled to a depth of close to 400 m, it did not penetrate the entire sequence of

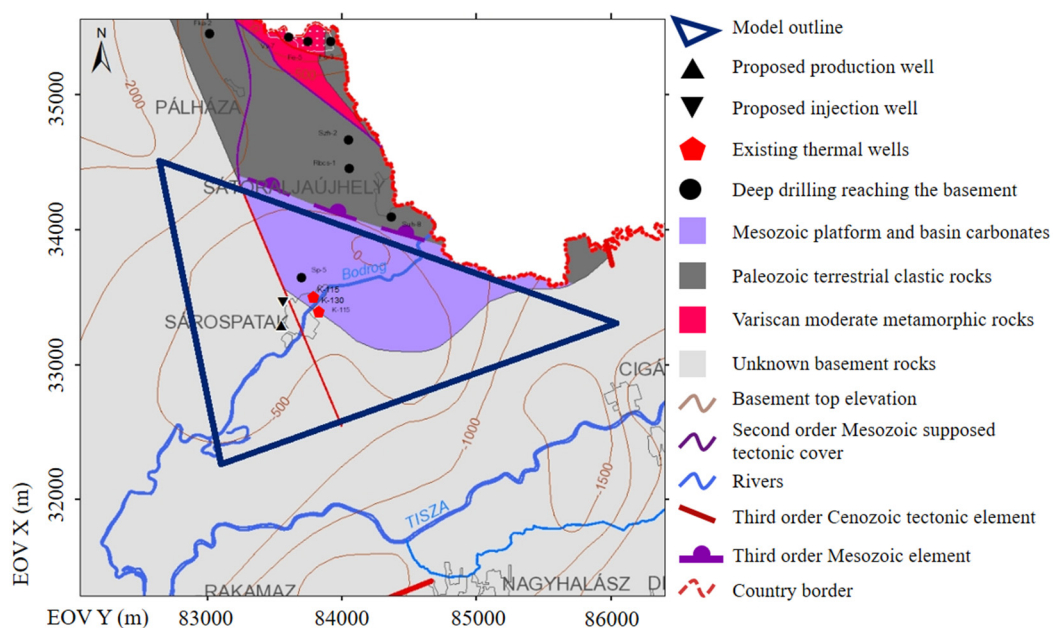


FIGURE 3: Model boundaries and the basement geology of the study area (modified after Haas et al., 2010)

Triassic carbonate rock (Csoma and Molnár, 1999; Pentelényi et al., 2003). The well has confirmed, however, that the Triassic sequence is mainly composed of the Dachstein-type platform carbonate (“Dachstein Limestone Formation”), which is known and well-studied in other parts of the Pannonian basin (Wein, 1977; Császár, 1997). Based on these studies, it is assumed that the Dachstein Formation overlies a Triassic dolomite succession, called the “Hauptdolomite” Formation. Altogether, the estimated thickness of the entire carbonate sequences exceeds 1700 m (Császár, 1997).

The geothermal potential of these types of deep carbonate reservoirs is recognized around the world. Besides the faults and fractures, the most important process that contributes to the creation of a productive reservoir is karstification (Goldscheider et al., 2010). Two different processes can be distinguished, the well-known “epigene” and the less known “hypogene” karstification. Many deep carbonate rocks were exposed to epigene karstification in earlier geologic times and then buried by younger sequences, preserving their karstic features. Thus, they create “paleokarsts” which contribute to the reservoir porosity (Smosna et al., 2005). However, several processes can enlarge fractures and conduits after burial, and these processes are called “hypogenic” karstification or speleogenesis. These processes can considerably enhance both the porosity and the hydraulic conductivity in the reservoir, thereby creating significant geothermal reservoirs. This type of reservoir has been observed all over the world (Klimchouk, 2007). In fact, one of Europe’s largest thermal systems, the “Buda Thermal Karst” in Hungary, which is partly composed of the same Triassic carbonates as occur in Sárospatak, has been mainly formed by these processes (Goldscheider et al., 2010). This also supports the assumption that the geothermal potential of Sárospatak is indeed considerable.

2.2 Model description

The original numerical model of the Sárospatak reservoir was constructed by Vatnaskil in 2013, and the following description of the reservoir dimensions and parameters is based on the Vatnaskil memo (Myer, 2013) describing the modelling work.

The modelled reservoir consists of fractured and karstified carbonate rocks of Triassic age which extend uninterrupted within the model area.

2.2.1 Dimensions and boundaries

The lateral boundaries of the model (Figures 2 and 3) were defined by using regional tectonic and structural features and were determined as no-flow model boundaries. However, because of the sparse availability of the data in the area, assumptions were made in many cases. The northeast boundary is an interpreted nappe structure described by Haas et al. (2010). The southeast boundary follows a large fault which is parallel to the mid-Hungarian tectonic line. The western boundary lies along a hydrothermal calcite vein near the village of Komlóska (Figure 2), which has been mapped by Csoma and Molnár (1999). They assumed that the origin of the vein-forming hydrothermal fluids was the Triassic carbonate and this was therefore interpreted as the last indirect proof of the basement rocks to the west.

The vertical dimensions of the reservoir model were determined using lithological boundaries. The upper part consist of the Dachstein Limestone Formation while the lower part is made of the Hauptdolomite Formation. The vertical discretization consists of 7 layers according to the distinctive hydrostratigraphic units (Table 1). The upper 4 layers belong to the Dachstein Limestone Formation. The efficiency of surface karstification decreases with depth, and therefore, the hydraulic conductivity of the limestone also decreases with depth. The lower 3 layers are built up by the Hauptdolomite Formation. The hydraulic parameters were defined according to the abundance of the fractures in the formation. The proposed production/injection well duplet targets the uppermost limestone layer.

TABLE 1: The main hydraulic parameters of the original Sárospatak model

Model layer	Rock type	Alteration	Thickness [m]	Hydraulic conductivity [m^2/s]	Porosity (%)	Rock compressibility [m^2/N]
1	Dachstein Limestone	Heavily karstified	100	1×10^{-4}	1.00	1×10^{-9}
2		Karstified	100	1×10^{-5}	0.50	1×10^{-9}
3		Poorly	100	1×10^{-6}	0.50	1×10^{-9}
4		Limestone	100	1×10^{-7}	0.10	1×10^{-10}
5	Hauptdolomite	Fractured	30	1×10^{-4}	1.00	1×10^{-9}
6		Dolomite	24	1×10^{-6}	0.25	1×10^{-10}
7		Fractured	30	1×10^{-4}	1.00	1×10^{-9}

The elevation of the top layer was made using available data on the pre-Tertiary basement map by Haas et al. (2010) (Figure 3) and the thickness of the layers were assumed constant (Figure 4). The total thickness of the 7 layers is 700 m which is a rough average between theoretical thicknesses of the Triassic carbonate formations and the measured thickness by well Sp-5 (Pentelényi et al., 1993). Two cross-sections of the modelled reservoir are shown in Figure 4. Their locations are shown in Figure 5.

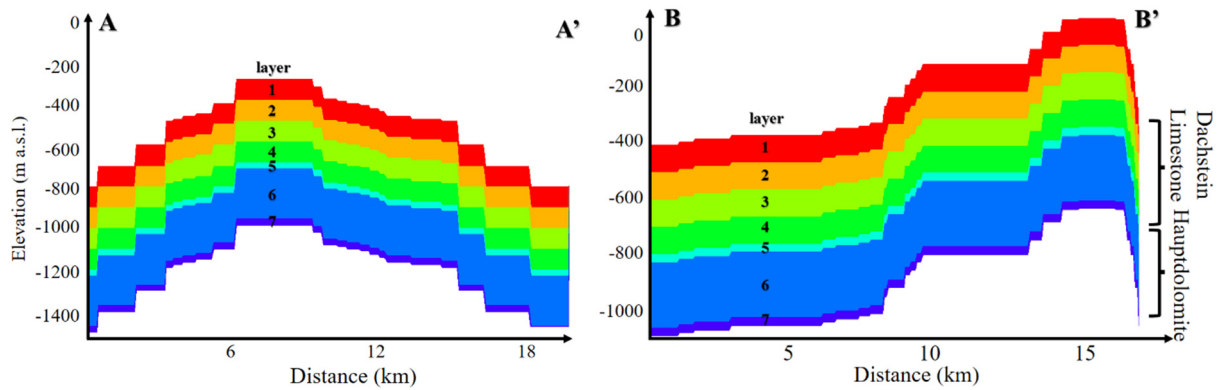


FIGURE 4: Cross-sections A-A' and B-B' showing vertical discretization of the model

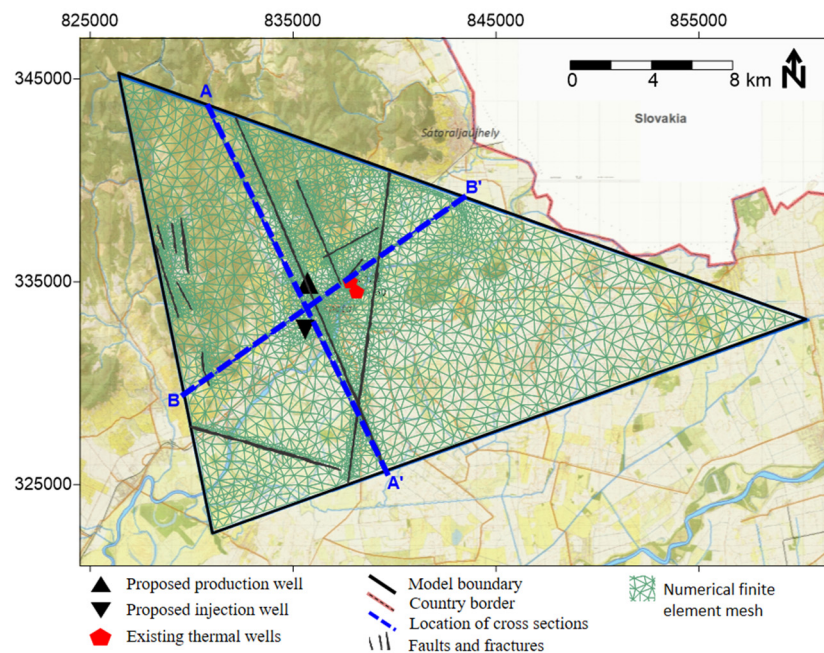


FIGURE 5: Fractures and faults, the locations of the cross sections (Figure 4) and the finite element mesh

The upper no-flow boundary of the reservoir model is the overlying Miocene tuff caprock. Most of the formation contains clay layers, which provide a barrier to vertical groundwater flow. On the other hand, the existing thermal wells in Sárospatak are producing from the lower 0-50 m of this tuff which is silicified and fractured and therefore hydraulically connected to the Triassic carbonates. However, there is no evidence that the zone exists elsewhere in the model area outside of Sárospatak so the zone was not included in the original reservoir model. This was done in an effort to take a more conservative approach in modelling the effects of the proposed well duplet. A thinner reservoir would give more drawdown with the same production.

The physical parameters of the specific layers in the model were collected from:

- Well logs
 - Hungarian Mining and Geological Authority
 - Mining Property Utilization Company
- Technical data from existing hydrocarbon and thermal wells in the area
 - Regional Agency of the National Environmental
- Seismic data
 - Hungarian Mining and Geological Authority
- Hydrogeological reports
 - Environmental and Hydrological Research Institute (VITUKI)

2.2.2 Parameters

The *hydraulic conductivity* for each layer was defined from published values for similar rock types and calculated values from well tests performed on existing hydrocarbon and thermal wells. For the main hydraulic parameters, see Table 1.

The *faults and fractures* determine the amount of anisotropy in the reservoir and thus the flow of groundwater. In the model, they were defined from interpretation of various geological maps (Lengyel, 1957; Gyarmati, 1964; Haas et al., 2010) and are shown in Figure 5. The area's regional fault system direction is NE-SW (Frits, 1964). It was assumed that the hydraulic conductivity is 5 times greater in the direction of this regional fracture system than perpendicular to it. Within individual major fractures the anisotropy was assumed even greater, with defined hydraulic conductivity 10 times greater in the direction of the fracture than perpendicular to it. It was also assumed that the vertical hydraulic conductivity is 10 times lower than the horizontal hydraulic conductivity.

The temperature of the geothermal fluid was estimated from the temperature data from well testing and drilling logs. The assumed *thermal gradient* of 20°C/km was used to calculate the background temperature of the reservoir fluid within each layer of the model.

The reservoir's *rock compressibility* is used to calculate specific storage which controls groundwater level fluctuations. Porosity is also used to calculate specific storage. The estimated porosity values for each layer in the model can be seen in Table 1.

The Triassic carbonate formations do not outcrop within the model area and are overlain by several hundred meters of low-permeability caprock, mostly the above mentioned Miocene tuffs. Therefore, it was assumed that there is no *infiltration* recharge into the reservoir model.

2.2.3 Numerical model

Numerical modelling was done using Vatnaskil's self-developed software, Aqua3D (Vatnaskil, 2013). The program is a finite-element model used to solve three-dimensional groundwater flow and mass/heat transport problems. Vatnaskil has utilized Aqua3D over the past 30 years on a number of geothermal reservoirs all around the world and it has proven to be a reliable and accurate tool.

The software uses the following three-dimensional flow equation for describing the movement of groundwater flow with constant density:

$$\frac{\partial}{\partial x} \left(k_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_{zz} \frac{\partial h}{\partial z} \right) = S_s \frac{\partial h}{\partial t} - Q \quad (1)$$

where k_{xx}, k_{yy}, k_{zz} , are values of the hydraulic conductivities along the principal axes [m/s]
 h is the piezometric head [m]
 Q is a volumetric flux per unit volume [m³/s/m³]
 S_s is the specific storage coefficient [m⁻¹]
 T is time [s]

Specific storage is calculated for each layer in the model using the following formula:

$$S_s = \rho g (\alpha + \varphi \beta) \quad (2)$$

where ρ density of the reservoir fluid [kg/m³]
 g acceleration due to gravity (9.81 m/s)
 α rock compressibility [m²/N]
 φ porosity
 β fluid compressibility (4.4·10⁻¹⁰ m²/N)

The solution of the three-dimensional mass/heat transport problem is based on the following partial equation:

$$\begin{aligned} & \frac{\partial}{\partial x} \left(D_{xx} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_{yy} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(D_{zz} \frac{\partial T}{\partial z} \right) + \\ & + Q(T_w - T) - \left(V_x \frac{\partial T}{\partial x} + V_y \frac{\partial T}{\partial y} + V_z \frac{\partial T}{\partial z} \right) = \varphi R_h \frac{\partial T}{\partial t} \end{aligned} \quad (3)$$

where D_{xx}, D_{yy}, D_{zz} are dispersion coefficients along the principal axes
 t is time [s]
 T is the temperature of the reservoir water [°C]
 T_w is the temperature of the injected water [°C]
 Q is pumping/injection rate [m³/s]
 V_x, V_y, V_z are the velocity vectors taken from the solution of the flow problem [m/s]
 φ is porosity
 R_h is retardation coefficient

The retardation coefficient is calculated by:

$$R_h = 1 + \left(\frac{c_s}{c_l} \right) \frac{(1 - \varphi) \rho_s}{\varphi \rho_l} \quad (4)$$

where c_s is the specific heat capacity of the porous medium [J/g°C]
 c_l is the specific heat capacity of the liquid [J/g°C]
 ρ_s is the density of the porous medium [kg/m³]
 ρ_l density of the reservoir fluid [kg/m³]

The three-dimensional model of the Sárospatak reservoir constructed by Vatnaskil consists of 3808 nodes and 7419 finite elements, creating a mesh (Figure 5) in 7 layers in order to define depth-varying hydrological parameters. As mentioned previously, Vatnaskil assumed that the boundaries of the model are based on tectonic and lithological features and provide no-flow conditions to the reservoir.

2.3 Results

For the preliminary reservoir modelling, two different production/injection scenarios (Scenario A and Scenario B) were simulated (Table 2). A well duplet was defined in the reservoir as shown in Figure 3 and 5. It was assumed that all the production was reinjected back into the reservoir with lower temperature according to the scenario and the heating/summer season. The reservoir parameters for the two scenarios were the same.

TABLE 2: Production rates and the injection temperatures used for Scenarios A and B by Vatnaskil in 2013

Scenario	Production [m ³ /s]		Temperature of reinjection fluid [°C]	
	Winter	Summer	Winter	Summer
A	2.43×10^{-2}	4.86×10^{-3}	40.5	34
B	3.08×10^{-2}	9.71×10^{-3}	42.5	40

The results for Scenarios A and B are shown in Figure 6. The simulation for drawdown and upconing were calculated and shown after 20 years of hypothetical operation with the given production/injection rates. The cooling effect was calculated and plotted after 50 years of operation. As the figures show, the drawdown/upconing are visible, but not drastic. In the well's immediate vicinity the change in the water

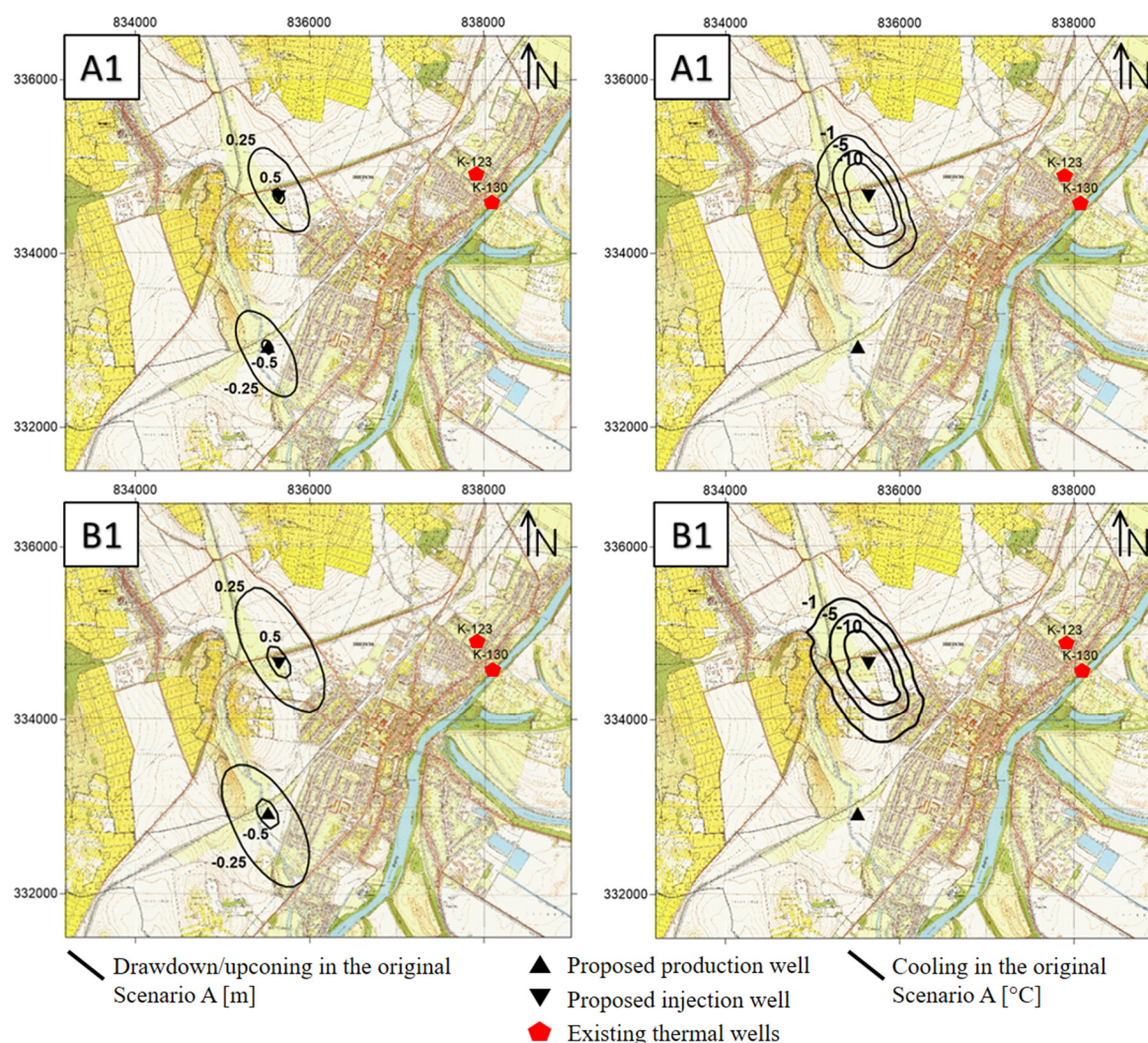


FIGURE 6: Results of the original model for Scenario A (top) and Scenario B (bottom). The drawdown/upconing effects are shown on the left and the cooling effects on the right

level is 50 cm, with a 25 cm change within roughly 1 km of each well. At a distance of greater than 1 km, the change in water level is negligible. In the case of the cooling effect around the well, the affected zone is similar. The cooling effects appear in the immediate vicinity of the injection well with a maximum cooling of 10°C, but a couple of hundred meters away from the well there is less than 1°C cooling. These areas are relatively small compared to the entire reservoir. The main conclusion of from the scenario runs is that the proposed well duplet, both in the case of the drawdown/upconing and cooling effects, has a negligible influence on the existing thermal wells in Sárospatak.

2.4 Collection of new data

As part of this study, additional research in the literature was done in order to investigate possible ways to improve the original Sárospatak model. The aim was to get a broader picture of the carbonate geothermal reservoirs abroad and in Hungary and then to gather as much information of the Sárospatak area as possible.

2.4.1 Hydraulic parameters

S. N. Ehrenberg and P. H. Nadeau (2005) collected data from 10,481 carbonate petroleum reservoirs and 30,122 siliciclastic reservoirs from all over the world. Although the petroleum industry can be quite different from the geothermal industry, from a hydrogeological point of view, the geological information can be useful for both industries. Ehrenberg and Nadeau plotted the average porosity vs. depth for all the carbonate reservoirs they investigated (Figure 7A). Although the carbonate reservoirs have less porosity than the sandstones, the average porosities above 2 km depth is between 10 and 17%. In the paper, they also plotted the average permeability vs. porosity in order to have an idea of the hydraulic conductivity (Figure 7B). It is certain that with decreasing porosity, the permeability also decreases. Below 15% porosity, the permeability varies between 10-100 mD. In order to compare these permeability values with values in the Sárospatak model, the relevant values from the paper were converted into hydraulic conductivities in units of m/s as shown in Equation 5 below. The conversion was based on Darcy's law presented in the book of Freeze and Cherry (1979). The converted hydraulic conductivities and the comparison can be seen in Tables 3 and 4.

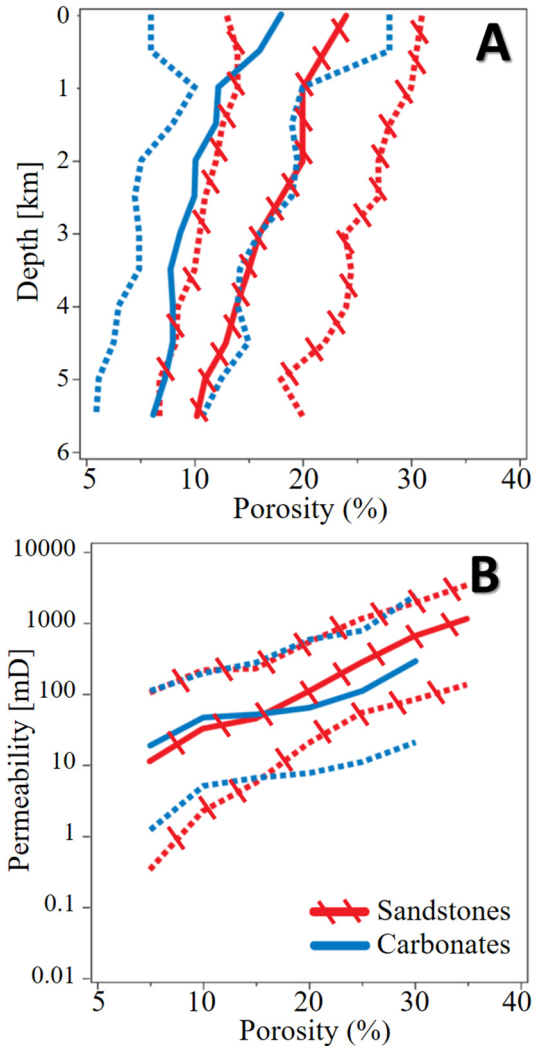


FIGURE 7: Depth vs. porosity (A) and permeability vs. porosity (B) in the sandstone and carbonate reservoirs from all over the world (Ehrenberg and Nadeau, 2005). The continuous lines represent the average values, whilst the dotted lines indicate the lower and upper 10% limits where 90% of the reservoirs fall within

$$K = \frac{k\rho g}{\mu} \quad (5)$$

where:

K is the hydraulic conductivity [m/s]
 k is the permeability [m²]
 ρ is the density [1000 kg/m³]

g is the gravitational acceleration [10 m/s^2]
 μ the dynamic viscosity [$0.5465 \text{ mPa}\cdot\text{s}$ at 50°C]

From Table 3, we can see that the average porosities of the carbonate reservoirs of the world are 10-100 times higher in the relevant depth range than in the case of the Sárospatak model, according to Ehrenberg and Nadeau. There is more similarity between the model and the values given by Ehrenberg and Nadeau for the hydraulic conductivity, however at shallower depths the model difference is roughly 2 orders of magnitude with the model values being higher.

TABLE 3: Average porosity values vs. depth of the carbonate reservoirs from all around the world (Ehrenberg and Nadeau, 2005). The highest and lowest porosities from the Sárospatak model are also shown for comparison

Depth [km]	Porosity [%]	Porosity from the Sárospatak model [%]
0.25–0.75	16	1.0 (highest)
0.75–1.25	12.2	
1.25–1.75	12	0.1 (lowest)

In 2014, Götz et al. directly examined and measured the hydraulic parameters of specific rock formations, collecting samples from the vicinity of Budapest. The work was done both in the field and in the laboratory. The one formation they investigated that exists in the Sárospatak reservoir is the Triassic Hauptdolomite. The measured permeability was $4.40\text{E-}15 \text{ m}^2$, which was converted to $8.05\text{E-}08 \text{ m/s}$ hydraulic conductivity with the same method mentioned above. This is around one order of magnitude less than the hydraulic conductivity of the unaltered Hauptdolomite defined in the Sárospatak model.

TABLE 4: Average permeability vs. porosity values, and the converted hydraulic conductivities from carbonate reservoirs from all over the world (Ehrenberg and Nadeau, 2005). The highest and lowest hydraulic conductivities from the Sárospatak model are also shown for comparison

Porosity (%)	Permeability [md]	Permeability [m^2]	Hydraulic conductivity [m/s]	Hydraulic conductivities from the Sárospatak model [m/s]
7.5–12.5	42	4.15×10^{-14}	7.58×10^{-7}	1.00×10^{-4} (highest)
12.5–17.5	46	4.54×10^{-14}	8.31×10^{-7}	1.00×10^{-7} (lowest)

In 2012, within the framework of the “T-JAM” project between Hungary and Slovenia, Nádor et al. (2012) made a geothermal reservoir model for the Mura-Zala basin which covers areas from both countries. In this model, based on their resources, they calculated hydraulic parameters for both the Dachstein Limestone and the Hauptdolomite Formations. The results can be seen in Table 5.

TABLE 5: Values of porosity and hydraulic conductivity from Nádor et al. (2012)

Rock type		Porosity [%]	Hydraulic conductivity [m/s]
Dachstein Limestone	min.	1	5.79×10^{-7}
	max.	3	1.16×10^{-6}
Hauptdolomite	min.	1	5.79×10^{-7}
	max.	3	1.16×10^{-6}

However, Péter Szűcs and György Ritter (2007) created a geothermal model for the Sárospatak (Végardó) Spa and they used slightly different parameters for the Triassic limestone. They also included the Miocene siliceous fractured rhyolite tuff layer into their model, where the spa's thermal wells are screened. The relevant parameters are shown in Table 6. Although Szűcs and Ritter modelled the same reservoir as Vatnaskil, their model covered only the area of Sárospatak and its immediate vicinity. This was probably made because of a lack of information on the lateral extent of the rhyolite tuff. The defined thickness of the karstified limestone and hydraulic conductivity are very similar to the values in the Vatnaskil model. However, the porosity is somewhat higher than the porosity defined in the Vatnaskil model.

TABLE 6: Hydraulic parameters used by Szűcs and Ritter (2007) in their model for the Sárospatak-Végardó Spa

Rock type	Thickness [m]	Hydraulic conductivity [m/s]	Porosity [%]
Miocene, siliceous, fractured rhyolite tuff	min. 40	1.16×10^{-5}	5
	max. 40	6.94×10^{-5}	
Triassic, karstified limestone	min. 100	2.31×10^{-5}	3
	max. 100	2.31×10^{-6}	

Using well data, Zoltán Fejes (2011) collected and calculated hydraulic parameters from the vicinity of the town Szerencs. This small city neighbours Sárospatak, so the reference is quite local. His calculations lead to 2.14×10^{-4} m/s hydraulic conductivity for the above-mentioned Miocene silicified and fractured rhyolite tuff. This value is very similar to the hydraulic conductivity defined in the heavily karstified limestone, which is the top layer in the Sárospatak value.

2.4.2 Existing thermal wells in the reservoir

The Sárospatak-Végardó geothermal spa operates two thermal wells which are supposedly exploiting from the reservoir. However, neither of them is actually screened within the Triassic limestone, but rather from slightly above it. The formation is often described as a silicified and fractured rhyolite tuff from the Miocene age and it overlays the Triassic carbonate rocks with an unconformity. The two formations are thought to be hydraulically connected with each other, and thus part of the same geothermal reservoir.

The first existing geothermal well was drilled in 1960 with the name Vé-27, and although it was initially very promising it had to be shut down in 1967 due to bad conditions of the well itself. In the same year, well Vé-2 (K-123) was drilled and started to operate with a temperature of 49°C and flow rate of 1000 l/min (1440 m³/day). The bottom of the well was at 290 m depth. Because the owners were experiencing significant pressure drop in the well, they drilled another well, V-3 (K-130), in 1984. This well reached a depth of 344 m and started to produce with a temperature of 45°C and flow rate of 700 l/min (1008 m³/day). Since 1984, a significant pressure drop has been experienced in both wells. In 2007, the maximum allowed production rate was 450 l/min for K-123 and 700 l/min for K-130.

After analysing the literature, it can be concluded that the values of the main hydraulic parameters used in the original Vatnaskil model of Sárospatak compare reasonably well with published values from other similar geothermal reservoirs. The exception is that the porosity values used in the Vatnaskil model are much lower than published values. Furthermore, in the Vatnaskil model, the bottom of the Miocene tuff layer from which the existing wells are producing is not included due to lack of information about the extent of the layer.

3. MODEL SENSITIVITY ANALYSIS

3.1 Overview

In order to determine which model parameters are most important with respect to their influence on the results of drawdown/upconing and cooling, a sensitivity analysis study was performed. The focus was on the parameters which have the largest variability and uncertainty (hydraulic conductivity and porosity). It was also decided to investigate the effects of the existing thermal wells on the reservoir.

The B scenario from the original Vatnaskil (2013) work was used as the base model from which all new sensitivity scenarios were constructed. Therefore, results from the new sensitivity analysis runs were plotted against the results from the B1 scenario in order to determine the effects of the changed parameters. The water level changes were plotted after approximately 20 years of production (7470 days), and the cooling effects after 50 years of production (18250 days). The results are described and shown in Section 3.3.

3.2 Altered parameters

In each scenario, only one parameter was changed at a time, with the exception of Scenarios 1-3. In total, 11 different scenarios were simulated which can be divided into three groups.

In the first group of scenarios, a new layer was added to the top of the model representing the Miocene siliceous and fractured rhyolite tuff. The parameters assigned to this new layer were based on the work of Fejes (2011) and are described in Table 7.

TABLE 7: The main hydraulic parameters of the extra layer in Scenario 1-3 (based on: Fejes, 2011)

Rock type	Thickness [m]	Hydraulic conductivity [m/s]	Porosity [%]
Siliceous, fractured rhyolite tuff	40	2.14×10^{-4}	1

In Scenario 1, the extra layer was added but no production from the existing thermal wells at the Sárospatak-Végardó spa was defined. In Scenarios 2 and 3 the production from the existing wells was defined in the model. Due to conflicting data on the actual production rates from these existing wells, two scenarios were run in order to account for this uncertainty (Table 8). For simplicity, constant production rates were defined.

TABLE 8: Production rates [m^3/s] in the first 3 scenarios

Layer	Screened Wells	Summer			Winter		
		Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Karstified limestone (Layer 2)	Production	-3.08×10^{-2}	-3.08×10^{-2}	-3.08×10^{-2}	-9.71×10^{-3}	-9.71×10^{-3}	-9.71×10^{-3}
	Injection	3.08×10^{-2}	3.08×10^{-2}	3.08×10^{-2}	9.71×10^{-3}	9.71×10^{-3}	9.71×10^{-3}
Rhyolite tuff (Layer 1)	K-123	-	-7.50×10^{-3}	-1.14×10^{-3}	-	-7.50×10^{-3}	-1.14×10^{-3}
	K-130	-	-1.17×10^{-2}	-7.57×10^{-4}	-	-1.17×10^{-2}	-7.57×10^{-4}

In the second group of the simulations, only hydraulic conductivities were altered, and in the third group only porosity values were altered. For the second and third group of scenarios, the original 7-layer model (without the silicified and fractured rhyolite tuff layer) was used. The altered parameters are shown in Table 9. In Scenarios 4 and 11, only the bottom layers were changed. Since the degree of karstification in the upper parts of the carbonates is relatively unknown, Scenarios 5-10 were used to alter parameters based on this factor. In Scenario 5 and 9, it was assumed that the top 3 layers were all poorly karstified,

TABLE 9: The altered parameters of Scenarios 4-11. The yellow cells show where the parameters were changed and the underlines show the parameters they were based on. For more details see text

Model layer	Rock type	Alteration	Thickness [m]	Hydraulic conductivity [m/s]					Porosity (%)				
				Original	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Original	Scenario 8	Scenario 9	Scenario 10	Scenario 11
1	Limestone	Heavily Karstified	100	1.00E-04	1.00E-04	1.00E-06	<u>7.28E-04</u>	<u>1.00E-04</u>	1.00	<u>3.00</u>	0.50	<u>12.00</u>	1.00
2		Karstified	100	1.00E-05	1.00E-05	1.00E-06	7.28E-05	1.00E-04	0.50	1.50	0.50	6.00	0.50
3		Poorly	100	1.00E-06	1.00E-06	<u>1.00E-06</u>	7.28E-06	1.00E-04	0.50	1.50	<u>0.50</u>	6.00	0.50
4		Limestone	100	1.00E-07	1.00E-07	1.00E-07	7.28E-07	1.00E-07	0.10	0.30	0.10	1.20	0.10
5	Dolomite	Fractured	30	1.00E-04	8.05E-06	1.00E-04	1.00E-04	1.00E-04	1.00	1.00	1.00	1.00	<u>12.00</u>
6		Dolomite	24	1.00E-06	<u>8.05E-08</u>	1.00E-06	1.00E-06	1.00E-06	0.25	0.25	0.25	0.25	3.00
7		Fractured	30	1.00E-04	8.05E-06	1.00E-04	1.00E-04	1.00E-04	1.00	1.00	1.00	1.00	12.00

and in Scenarios 5, 8 and 10 it was assumed that the top layers were all heavily karstified. In Scenario 6 the model was run with the highest hydraulic conductivity that has been found in the literature for the limestone. Similarly in Scenario 10, the model was run using the average porosity of the world's carbonate reservoirs according to Ehrenberg and Nadeau (2005). A summary of the 11 scenarios with the altered parameters are shown below.

Additional model layer

- Scenario 1** An extra layer added to the top of the model to represent the siliceous fractured rhyolite tuff. No production from the two existing thermal wells. Hydraulic parameters were taken from Fejes (2011).
- Scenario 2** An extra layer added to the top of the model to represent the siliceous fractured rhyolite tuff. Define production from the two existing thermal wells with the maximum allowed production (Szűcs and Ritter, 2007).
- Scenario 3** An extra layer added to the top of the model to represent the siliceous fractured rhyolite tuff. Define production from the two existing thermal wells with an estimated current production (Vatnaskil, 2013).

Hydraulic conductivity changes

- Scenario 4** Decrease hydraulic conductivity in model layer 6 from 1E-06 to 8.05E-08 m/s which is the average published value for the Hauptdolomite (Götz et al., 2014). Scale the hydraulic conductivity values for layers 5 and 7 down by the same factor as layer 6.
- Scenario 5** Assume model layers 1 and 2 are poorly karstified. Decrease hydraulic conductivity in those layers to the same value as layer 3 (1E-06 m/s).
- Scenario 6** Increase hydraulic conductivity in model layer 1 from 1E-04 to 7.28E-04 m/s which is the calculated value for Triassic limestone from Fejes (2011). Scale the hydraulic conductivity values for layers 2-4 up by the same factor as layer 1.
- Scenario 7** Assume model layers 2 and 3 are heavily karstified. Increase hydraulic conductivity in those layers to the same value as layer 1 (1E-04 m/s).

Porosity changes

- Scenario 8** Increase porosity in model layer 1 from 1 to 3% which is the value for Dachstein Limestone from the T-JAM model (2011). Scale the porosity values for layers 2-4 up by the same factor as layer 1.
- Scenario 9** Assume model layers 1 and 2 are poorly karstified. Decrease porosity in those layers to the same value as layer 3 (0.5 %).
- Scenario 10** Increase porosity in model layer 1 from 1 to 12% which is the value for the average values for carbonates found in reservoirs all over the world (Ehrenberg and Nadeau, 2005). Scale the porosity values for layers 2-4 up by the same factor as layer 1.
- Scenario 11** Increase porosity in model layer 5 from 1 to 12% which is the value for the average values for carbonates found in reservoirs all over the world (Ehrenberg and Nadeau, 2005). Scale the porosity values for layers 6 and 7 up by the same factor as layer 5.

Figure 8 shows the legend for Figures 9-19. The results from the scenario runs are shown in Figures 9-19, where they are compared with results from the original Vatnaskil model (Scenario B). The contours represent the difference in the water level and reservoir fluid temperature in the proposed producing layer (model layer 1) before and after the simulated production. In Figures 9-19, the drawdown/upconing effects are plotted after 20 years (7470 days) and shown on the left, and the cooling effects are plotted after ~50 years (18250 days) of simulated production and are shown on the right. The results from the original model are marked with continuous black lines and results from the sensitivity analysis runs are shown with red and blue dashed lines. The proposed well duplet and the existing thermal wells are also displayed. The coordinates are in the EOV system, which is the main projection system for Hungary.

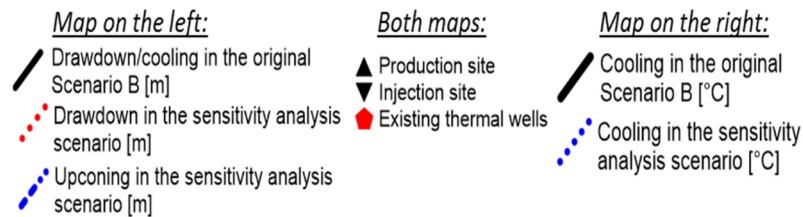


FIGURE 8: Legend of the maps showing the results in Figures 9-19

3.3 Results

Additional model layer

The results from Scenario 1 are shown in Figure 9. For this scenario, an additional layer, 40 m thick, was added to the top of the model in order to represent the siliceous, fractured rhyolite tuff formation. As a results show, the drawdown and upconing effects have significantly decreased compared to the original model. A few hundred meters away from the proposed wells, the change in the water level is less than 10 cm. Although the cooling effect has also decreased, the difference is not that large. In this scenario, adding an extra layer above the production layer of the proposed well duplet has in effect increased the thickness of the reservoir, and thus the storativity. The increased storativity clearly diminishes the drawdown effects and decreases slightly the cooling effects.

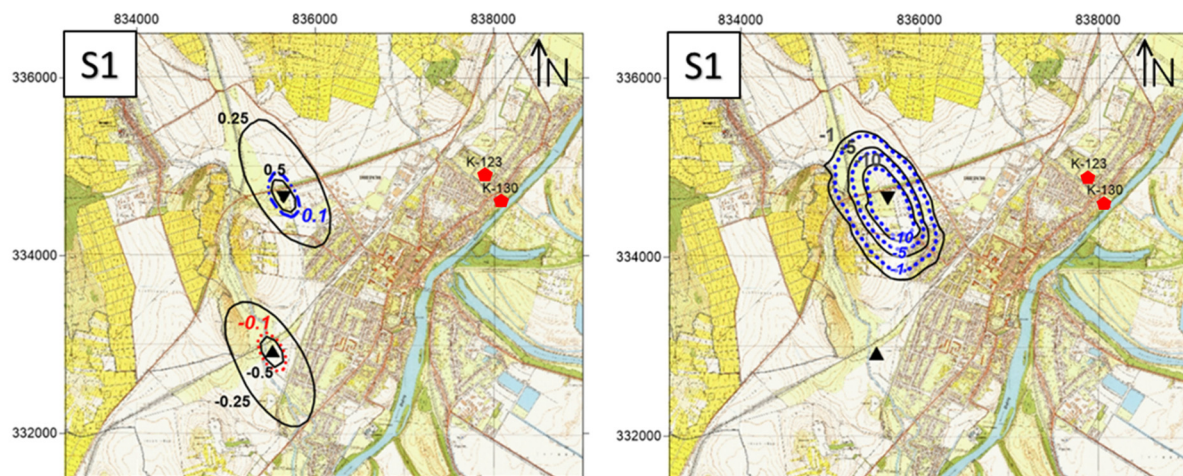


FIGURE 9: Calculated long-term effects of the proposed well duplet on the water level and temperature for Scenario 1

In Scenario 2 (Figure 10), the production from the existing thermal wells at Sárospatak was added to the model with their maximum allowed production rates. The change in the water level is significant for this scenario. The upconing has basically disappeared, and only the drawdown effect is visible now, which is drastically larger than it was in the original model. At a distance of several kilometres from the proposed production well, the water level change is 0.5 m. The effect is much less around the injection well. It seems that although adding an extra layer did increase the storativity, the drastic increase in production from the existing thermal wells outweighs this effect significantly, and they have an impact on the proposed wells (pressure decline). The magnitude of the cooling effect has not changed, it is still very small and is slightly shifted towards the existing thermal wells. This is probably due to changes in the flow direction in the system caused by the production from the existing thermal wells.

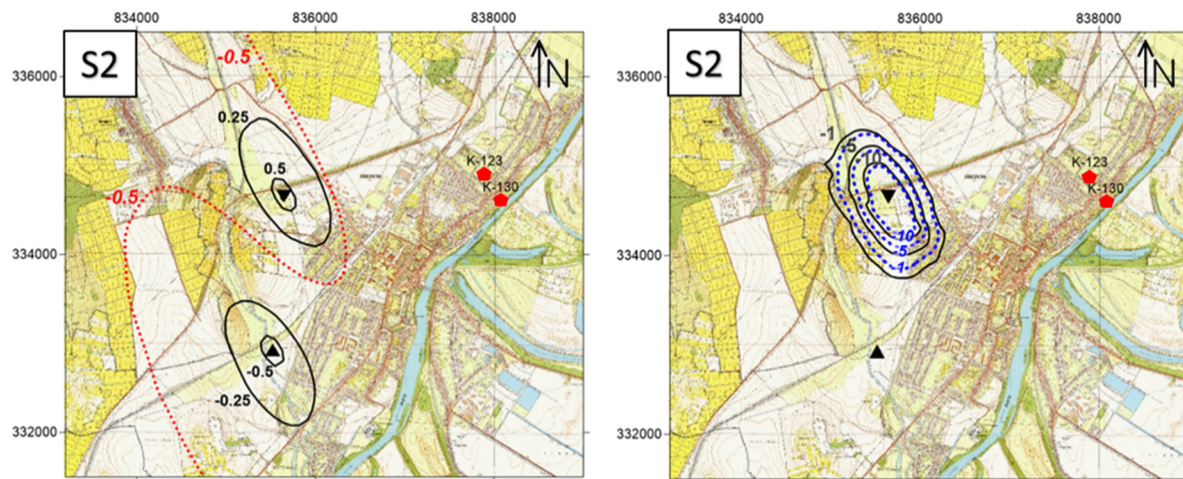


FIGURE 10: Calculated long-term effects of the proposed well duplet on the water level and temperature for Scenario 2

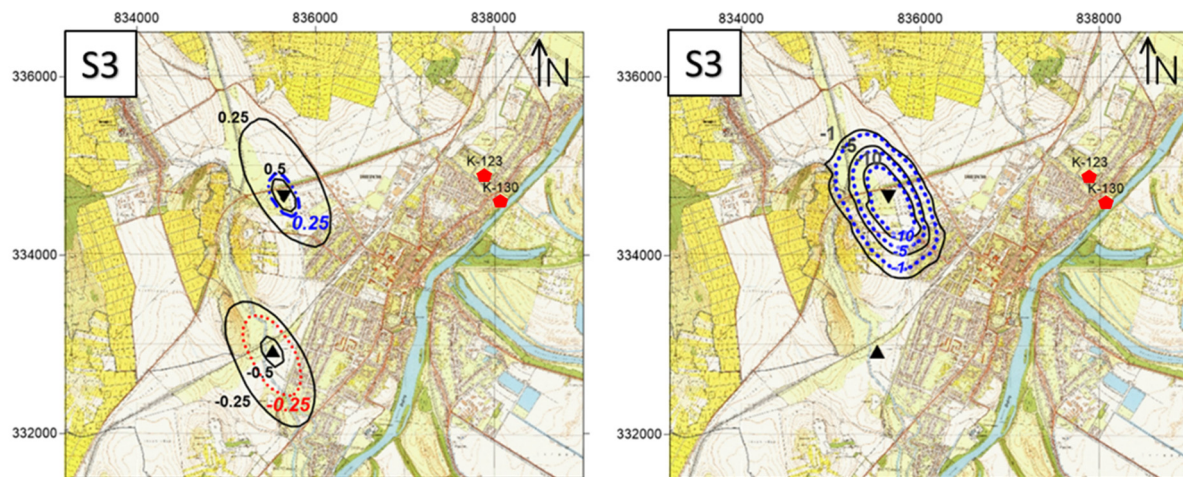


FIGURE 11: Calculated long-term effects of the proposed well duplet on the water level and temperature for Scenario 3

Figure 11 shows the results of Scenario 3. Production from the existing thermal wells was decreased by around one order of magnitude to more realistic rates. In this case, the influence of the increased storage from the extra layer outweighs the impact from the proposed wells on the water level and there is therefore less drawdown/upconing than in the original model. However, the effects on the water levels are still somewhat larger than in Scenario 1. The cooling effect of the reinjection is, however, very similar to Scenario 1.

Note that for all of Scenarios 1-3, there was some change in the cooling effect regardless of the production. The main reason for this is most likely the change in the thickness, and thus the storativity, of the reservoir.

Hydraulic conductivity changes

In Scenarios 4-11, neither the existing thermal wells of Sárospatak nor the extra layer were accounted for in the simulations. In Scenario 4 (Figure 12), the aim was to determine if the hydraulic conductivity of the lower, dolomite layers had any impact on the state of the producing layer. The results of the scenario show very little difference from the results of the original model. Thus, it can be concluded that the hydraulic conductivity of the lower dolomite layers do not influence the effects of the production/injection in the top model layer.



FIGURE 12: Calculated long-term effects of the proposed well duplet on the water level and temperature for Scenario 4

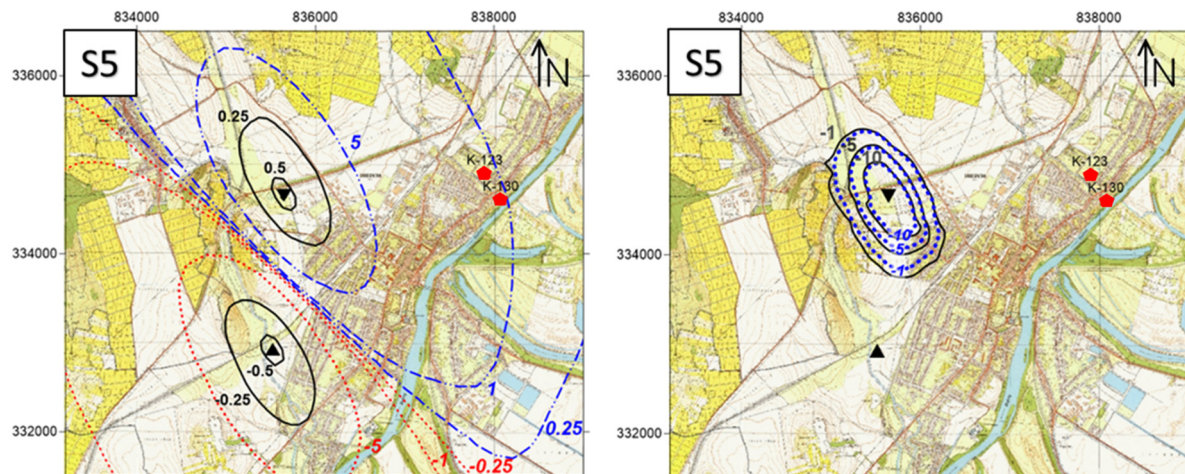


FIGURE 13: Calculated long-term effects of the proposed well duplet on the water level and temperature for Scenario 5

In Scenarios 5-7, the impact of the hydraulic conductivity of the limestone layers was investigated. In Scenario 5 (Figure 13), it was assumed that all the karstified limestone layers (layers 1-3) were poorly karstified. Accordingly, the hydraulic conductivity was lowered in layers 1 and 2 to the same value as layer 3. As a result, the amount of drawdown and upconing drastically increased as can be seen in Figure 13. Where the change in water level was ± 0.25 m in the original model, the calculated change in water level in Scenario 5 was 10 m. The influence from the well duplet reaches the existing thermal wells and causes roughly 1 m of upconing at the wells. The difference between the calculated cooling in Scenario 5 and the original model is minimal.

In Scenario 6 (Figure 14), hydraulic conductivity was increased in all the limestone layers (Table 9). The assumption was based on the highest hydraulic conductivity for limestones in the area, according to Fejes (2011). It is clearly apparent that even this relatively small change of the parameter ($\sim$ seven times) can significantly change the calculated effects of the well duplet on the water level. The results of the scenario show that both the drawdown and upconing are minimal. However, the cooling effect has remained the same as in the original model.

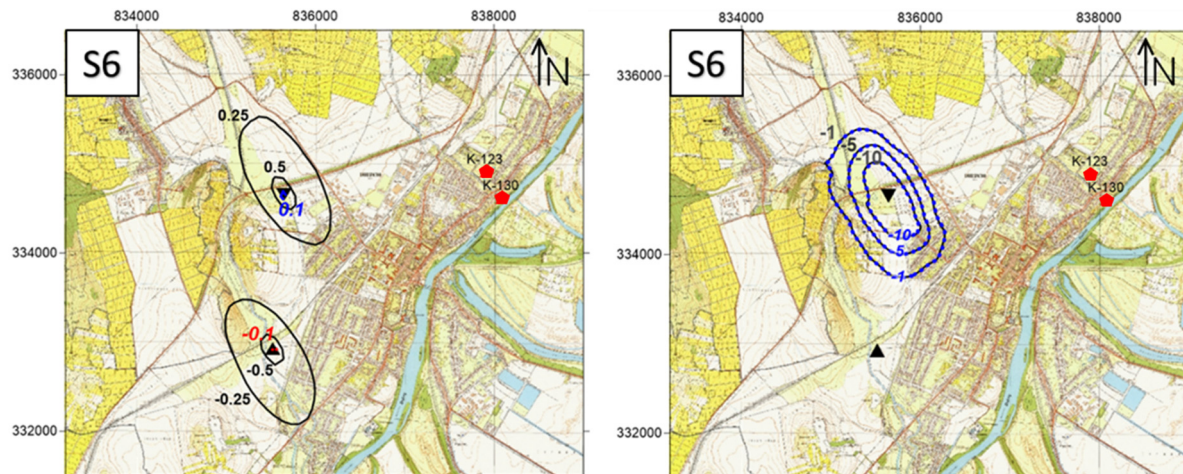


FIGURE 14: Calculated long-term effects of the proposed well duplet on the water level and temperature for Scenario 6

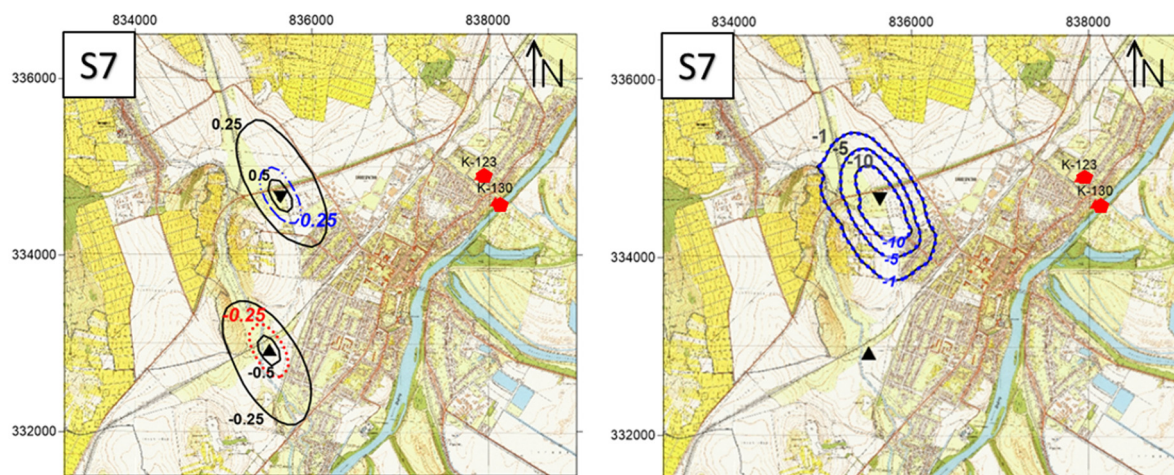


FIGURE 15: Calculated long-term effects of the proposed well duplet on the water level and temperature for Scenario 7

In Scenario 7, showed in Figure 15, the hydraulic conductivity was increased in layer 2 and 3 to the same value as layer 1, i.e. it was assumed that the upper three limestone layers were heavily karstified. In this way, the top three layers were actually unified and handled as one layer in the model, in terms of hydraulic conductivity. The drawdown and the upconing effects were very similar to the original model, although they have both slightly decreased. This is probably because the top 3 layers were behaving as one, in effect increasing the production layer's thickness and hence the storativity. There was very little change, however, in the cooling effects.

Note that among the 4 scenarios of the second group, only one (Scenario 5) caused any significant changes in the cooling effect from the original model. This fact suggests that the degree of cooling is not sensitive to the hydraulic conductivity in this model, or at least not significantly. On the other hand,

the water level change varied to a much larger degree with changes to the hydraulic conductivity. This point indicates that the water level change is sensitive to the hydraulic conductivity.

Porosity changes

In the last group of scenarios, porosity values were altered. In Scenario 8 and 10, the porosity values of the limestone layers were increased with different magnitudes. In Scenario 9 (Figure 17), they were lowered to the same level as the poorly karstified layer and in Scenario 11 (Figure 19) porosity was only altered in the lower, dolomite layers. The results from Scenarios 8-11 are shown in Figure 16-19. It is evident that in most of these cases, porosity changes made very little difference in the results for both the water level changes and the cooling effects, i.e. they gave the same results as in the original model. However, the only noticeable difference was in the case of Scenario 10 (Figure 18).

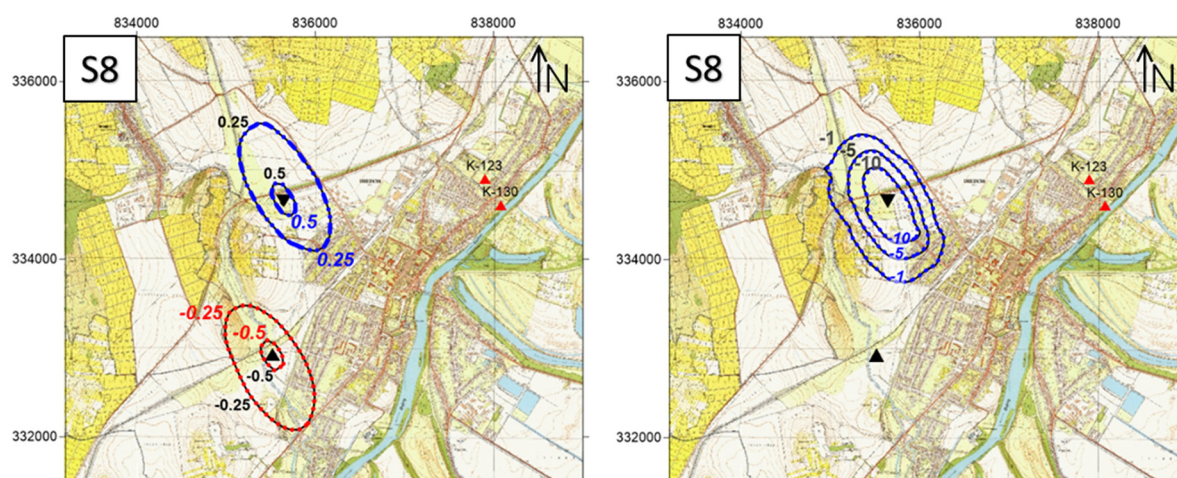


FIGURE 16: Calculated long-term effects of the proposed well duplet on the water level and temperature for Scenario 8

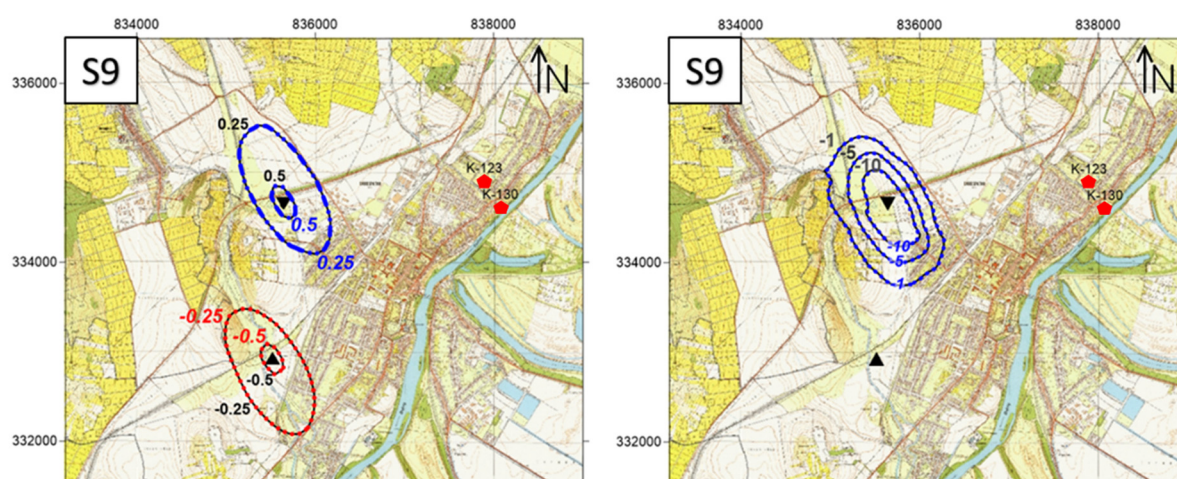


FIGURE 17: Calculated long-term effects of the proposed well duplet on the water level and temperature for Scenario 9

In this scenario, the porosity values of the limestone layers were actually increased by 12 times in layer 1. This was the largest alteration of the porosity value in all the scenarios. This was enough to cause a slight decrease in the cooling effect from the original model, although still to a very small degree. This fact indicates that the model is not sensitive to the porosity.



FIGURE 18: Calculated long-term effects of the proposed well duplet on the water level and temperature for Scenario 10

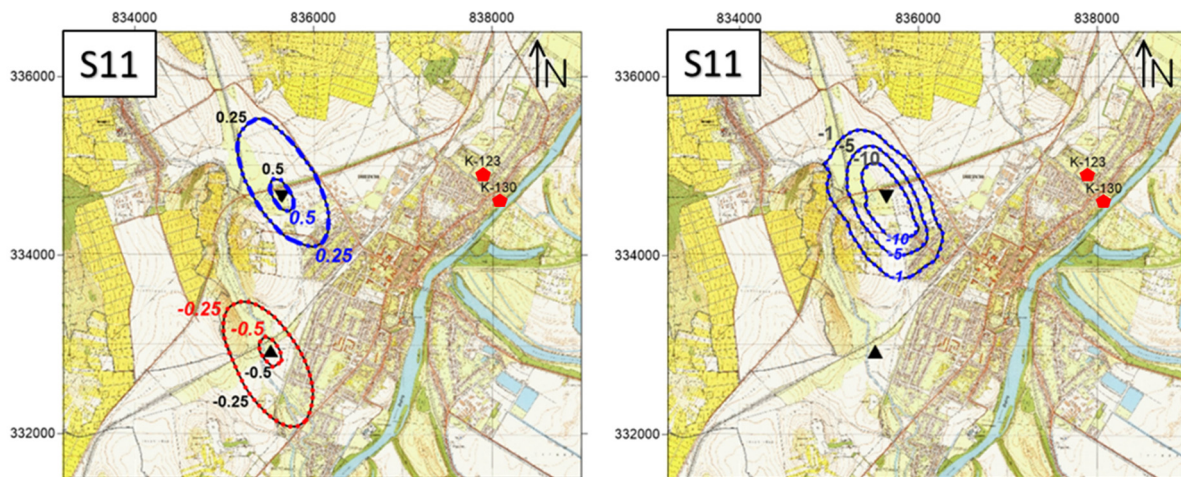


FIGURE 19: Calculated long-term effects of the proposed well duplet on the water level and temperature for Scenario 11

4. CONCLUSIONS AND RECOMMENDATIONS

The literature review showed that many of the parameters describing the geological conditions in the Sárospatak geothermal reservoir have a relatively large degree of uncertainty. After analysing the results of the sensitivity analysis, a prioritization of these parameters can be concluded.

The hydraulic parameters of the dolomite and the porosity of the limestone formation do not play key roles in the reservoir model because calculated changes in water level and cooling are not sensitive to these parameters. However, the model is sensitive to the hydraulic conductivity, hence the karstification, as well as the layer thicknesses, hence the storativity, of the top limestone layer. Therefore, these parameters have the greatest influence on the calculated drawdown/upconing and to a lesser degree on the cooling effect around the injection well. It can also be concluded that cooling is more sensitive to changes in thickness/storativity, less sensitive to changes in hydraulic conductivity and least sensitive to changes in porosity.

The main objective of the original modelling work by Vatnaskil was to determine if the proposed well duplet would have any negative impact on the existing thermal wells at Sárospatak. The results of the

sensitivity analysis indicate clearly that the production/injection of the proposed wells are very unlikely to have any impact on the existing thermal wells. Moreover, the only possible effect would be a positive change in the water level (upconing) as shown in Scenario 5 where a lower degree of karstification in the upper layers was assumed. On the other hand, it is more likely that the production from the existing thermal wells would rather have a negative effect (increased drawdown) on the water level around the proposed well duplet.

For further investigation of the use of geothermal district heating in Sárospatak, a carefully constructed numerical model is necessary. This model is a good base for that purpose, but it needs several careful improvements. In my opinion, the crucial aspects for future modelling work include the following:

- Acquire accurate historical production rates and expected future production from the existing thermal wells. Production from these wells has a high probability of negatively affecting the proposed wells.
- Future boreholes drilled into the Dachstein Limestone can provide crucial information for improving the model. Drill logs, borehole measurements and well testing can be used to determine more accurate values for hydraulic conductivity within the reservoir. This parameter mostly depends on the degree of karstification which is the central question. A better understanding of the hydraulic conductivity can also be attained by analysing the above-mentioned production history of the existing wells.
- Acquire a better understanding of the storativity of the producing layer. This mostly depends on the thickness and the horizontal extent of the Dachstein Limestone. Therefore, further geophysical investigations of the basement in the area would be advisable.

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