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A Reviewed Hydrogeothermal Evaluation of the Ďurkov Depression Hydrogeothermal Structure: Insights from Probabilistic Assessment and Sustainable Production Optimization

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ABSTRACT

Although geothermal structure of the Ďurkov depression is by many considered the most prospective for a large-scale direct geothermal energy production, no project has been launched yet at the site. Revision of hydrogeothermal evaluation took part to introduce a concept of probability-based assessment and sustainable production into a topic. Both, a conservative t = 40 years and t = 100 years balance period has been quantified, the latter corresponding to a minimum production period meeting sustainability concept as defined by Axelsson et al. in 2001. Combination of specified recovery factor based on a production-efficiency method, volumetric (heat-in-place) USGS method and reserve capacity ratio approach has been applied to both, Monte Carlo based quantification and Turning-bands derived spatial distribution of energy base. According to 10,000 iterations, the median for H_T = 5.8 EJ. At calculated R_0 = 0.053, the mean value of H_0 = 305 PJ. Following the booking concept, $P90(H_0) = R_{pv}$ = 37 MWt for t_{prod} = 100 years and $P90(H_0) = R_{pv}$ = 92 MWt when balanced for 30 years only. This leaves R_{pb} = 60 MWt or R_{pb} = 150 MWt to prove under a probabilistic concept (50 % probability). However, the modified reserve capacity ratio yields a critical limit of P_{th} = 49 MWt and P_{th} = 121 MWt respectively, if turning to a sustainable geothermal production. With a reference to a pioneering hydrogeothermal evaluation, 42 MWt were proven through free-flow and 92 MWt modeled for pumping. To quantify the first, it appears that as long as a model is valid, there is 88 % probability of a long-term production at a given rate even balanced for 100 years. For both periods, the resultant reserve capacity ratio for such an installed capacity would count r_{cap} = 0.58 and r_{cap} = 0.83 respectively, implying a sustainable character of the production.

1. INTRODUCTION

Although national economy of the Slovak Republic is still fossil-fuels oriented, the country ranks as a low-AHSs country, recording mean yearly emissions at 25 % below a ratified level. Indeed, renewables contribute only with 23 % on domestic electricity and 19 % on heat primary energy consumption. The total geothermal energy potential in Slovakia accounts for 6,234 MWt, with 347 MWt classified as proven reserves. Up to a year 2018, the online capacity is only 181 MWt, explaining a barely 1 % share of geothermal energy on a total heat production in the country.

The conceptual research and prospection of geothermal energy in Slovakia dates back to the 70's of the last Century, simultaneous to a prospection of oil and gas. The Košice Basin has been studied widely, with first prospection wells on oil and gas drilled in 1973-1975, identifying geothermal waters in Mesozoic carbonates. In 1999, a pilot hydrogeothermal evaluation of the site installing three geothermal wells GTD-1, GTD-2 and GTD-3 identified proven reserves associated with the Ďurkov Depression of 41.8 MWt for a free-flow (Vranovská – Bodiš, 1999) and 92.6 MWt (Giese, 1998) for a pumping scenario, whilst 113.4 MWt were classified as probable reserves, when balanced for 40 years (Vranovská et al., 1999). A heat plant working at a desired 100 MWt installed output soon came into consideration, including 7 doublets (Vranovská et al., 2000). However, no project has been set into operation yet.

The Ďurkov Depression hydrogeothermal structure (DDHS) is the most prospective amongst all the geothermal water bodies in Slovakia. Now, the country is called to update for quality and quantity of geothermal resources according to the Water Framework Directive No. 2000/60/EC of the European Parliament and the Council. Instead of a point-source (well data) based evaluation, the reviewed evaluation turns to a probabilistic resources and reserves assessment. A reconstructed geological and geothermal model forms a background. A Monte Carlo simulation was applied to assess the USGS volumetric method (Muffler – Cataldi, 1978; Williams et al., 2008; Williams, 2004, 2007) derived heat in place (HIP; H_T), corrected with the recovery factor R_0 according to the reservoir extraction efficiency method (Ungemach et al., 2005, 2009). Because of a spatial unstationarity in data, conditioned Turning-bands method took place for 3D distribution simulation. The recoverable HIP (H_0) has been balanced for both, the t_{prod} = 40 years (a convectional balancing period in Slovakia) and t_{prod} = 100 years, according to a concept of sustainable production discussed in Axelsson et al. (2001), to address the resources and reserves expected at the site. Because of a pilot stage, we used the reserve capacity ratio approach (Bjarnadottir, 2010) to delineate classes of reservoir production in terms of depletive and sustainable management.

2. BACKGROUND

1.1 Site definition and deep geological structure

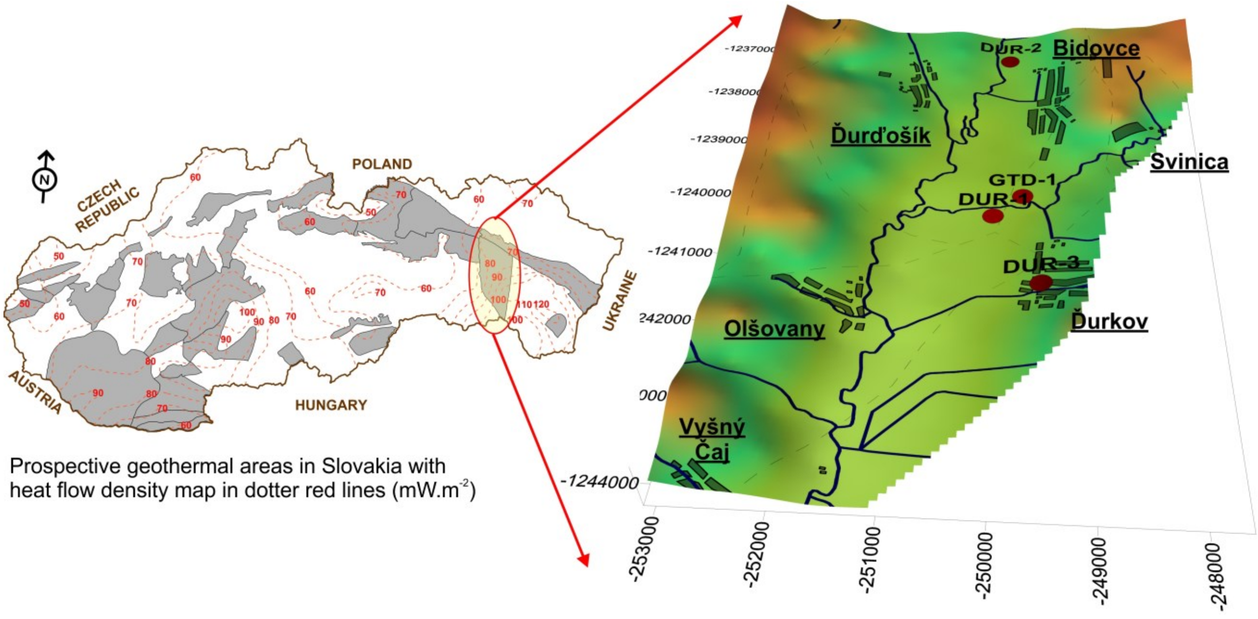
The Ďurkov Depression hydrogeothermal structure (DDHS) represents a depressed morphostructure of Mesozoic carbonates dissected into several blocks beneath Neogene sedimentary basin fill of the Košice Basin, that is the NE promontory of the Pannonian Basin (Pereszlenyi et al., 1999). The E margin corresponds with the subsurface extension of the Neogene-aged volcanic Slanské vrchy Mts. A northern limit corresponds to the tectonic contact with the Bidovce pre-Tertiary depression. To the W, the structure terminates along the N-S fault zone parallel with the Vyšný Cas – Oľšovany – Ďurďošík junction (Figure 1) while to the south the limit is set arbitrary to the uplifting block of Mesozoic carbonates along a Ruskov – Vyšný Čaj line (Vranovská et al., 1999, 2000). The area is app 33.6 km^2.

The deep geological structure reflects a typical vertical profile of Neogene sedimentary basins in the Western Carpathians. Quaternary accumulations (fluvial, proluvial and deluvial forms) are only several meters thick; thus are usually neglected in construction of deep structural models. Neogene profile thickness reaches up to 2,000-3,000 m. At a top, Sarmatian clays with rare strata of products of andesite and rhyolite volcanism (200 to1,000 m thick) transit to Badenian carbonate sandy clays with rare tuffites and shales (thickness up to 1,500 m). Carpathian basal conglomerates beneath carbonate clays with evaporate intercalations (thickness of 400-600 m) form a base (Pereszlenyi et al., 1999; Beňovský et al., 1999; Vranovská et al., 1999, 2000). Mesozoic carbonates form a primary geothermal reservoir body, identified as an analogue to the Krížna Nappe series of the Western Carpathians (Vranovská – Bodiš, 1999). Thickness of the profile increases quasi-axially in the NW-SE and SW-NE direction from 200 m (N, W) to 2,200 m in the central depressed block and to the south (Vranovská et al., 1999). Tectonic dissection of the morphostructure owes to three generations of faults in the SW-NE, NW-SE and N-S direction (Bodiš – Vranovská, 2012). A few is known about pre-Mesozoic underbed, however, analogously to the Western Carpathians, crystalline complex (magmatites and metamorphites) of the Veporic unit is expected instantly beneath (Pereszlenyi et al., 1999). The entire crust is roughly 30 km thick (Bielik, 1999).

1.2 Briefnote on reservoir hydrogeothermics

The geothermal field of the structure is classified as of an increased activity (Franko et al., 1995) with a surface heat flow density of 105-115 mW.m^{-2}. In well samples (Bodiš – Vranovská, 2012) the thermal conductivity of Neogene profile varied 2.1-2.45 W.m^{-1}.K^{-1}, increasing to 3.4-4.2W.m^{-1}.K^{-1} in Mesozoic carbonates. A mean geothermal gradient differs for 51.2 °C.km^{-1} for Neogene and 29.4 °C.km^{-1} for Mid Triassic horizon (Vranovská et al., 2015).

Geothermal resource – thermal brines associate with a single reservoir involving Mid Triassic carbonates and shallow, tens meters thick basal conglomerates of the Karpatian. At a top (1,800-2,600 m) temperatures vary 87-142 °C, increasing to 95-180 °C to the base at 1,960-4,000 m (Fričovský et al., 2018a). According to thermodynamic model, the reservoir enthalpy has been calculated for 390-740 kJ.kg^{-1} for a top and 440-1,660 kJ.kg^{-1}, indicating a low (SExI = 0.04-0.06) to moderate-low (SExI = 0.1-0.25) thermodynamic quality of geothermal brine (Fričovský et al., 2018b). Geothermal waters are of Na-Cl type, with TDS of 20.4 to 33.1 g.l^{-1} and extreme in arsenic concentrations (cAs = 19-36 mg.l^{-1}) (Bodiš – Vranovská, 2012). According to a reviewed conceptual model (Vranovská et al., 2015) the waters originated as infiltrated meteoric that seeped to Neogene strata, dissolving evaporates and reacted with Hg-As-Sb type mineralization prior accumulation in Mid Triassic dolomites.



Prospective geothermal areas in Slovakia with heat flow density map in dotter red lines (mW.m^{-2})

Figure 1: The Ďurkov depression hydrogeothermal structure: site definition.

Hence no geochemical indices on degradation were found, the system is considered a closed-type. For both, the horizontal (Fričovský et al., 2018b) and inclined (Fričovský et al., 2018c) porous media model, only a weak, separate convection cells were identified to the reservoir base, fairly limited in only a few meters height and extend. Analogously to geothermal systems worldwide, geodynamic evolution, lithology and geothermic activity define the site as conduction-dominated orogenic belt-type geothermal play (Moeck, 2014).

3. METHODOLOGY AND APPROACH

During geothermal energy exploration and assessment, two concepts developed in Slovakia. Open-type hydrogeothermal structures with natural recharge are assessed through the energy balance method (1) in category of possible reserves (Franko et al., 1995). It identifies a balance between the energy extracted at the wellhead over the energy present in the reservoir, at given energy flux over the area of a structure. The volumetric USGS method is addressed to a complex geothermal assessment for cases of closed-type systems including reinjection (Fendek et al., 2005). This is, however, a robust obfuscation, hence such a limit lacks any methodological ratio:

$$R_{pb} = A.q_0.\frac{T_{wh} - T_{ref}}{T_{res} - T_n} \tag{1}$$

where: R_{pb}: probable reserves (W), q_0: surface heat flow density ($W.m^{-2}$), A: surface areal extension of a system (m2), T_{wh}: wellhead temperature (°C), T_{ref}: reference temperature (°C), T_{res}: reservoir temperature (°C), T_n: neutral zone temperature (°C).

In a reference hydrogeothermal evaluation (Vranovská et al., 1999, 2000), the USGS volume method (White – Williams, 1975; Muffler – Cataldi, 1978) has been applied. Input data were, however, given by mean values obtained from the structure, and the recovery factor was taken constant at R_0 = 0,75 (Fendek et al., 2005), missing any reasonable derivation. Therefore, under a task of the Ministry of Environment of the Slovak Republic, re-evaluation of the hydrogeothermal assessment is carried using a calibrated geological and geothermal model, including probabilistic concepts in stored heat and recovery factor estimation and spatial delineation.

3.1 USGS volume (stored-heat, heat-in-place) method

The USGS volume method (syn. stored-heat) is amongst approaches in geothermal resource assessment not requiring a field production data and matching (Sanyal, 2007), at least in early stages of evaluation process. The method computes the total thermal energy stored in the reservoir H_T as a sum of a heat stored in the rock H_R and associated reservoir fluid (Muffler – Cataldi, 1978); be it a single-phase geothermal water H_W in conditions of the Ďurkov depression; i.e. $H_T = H_W + H_R$ or (2)

$$H_T = A.\Delta z.\left[\phi.\rho_w.c_w + (1-\phi).\rho_r.c_r\right].\left(T_{res} - T_{ref}\right) \tag{2}$$

More general, the equation (2) can be re-arranged into the integral (3) or simplified (4) form (e.g. Grant, 2014; Garg – Combs, 2015), defining the reservoir volumetric heat capacity (5) as a function of porosity and thermal properties of matrix and associated reservoir fluid:

$$H_T = \int \gamma_a.\left(T_{res} - T_{ref}\right)\mathrm{dV} \tag{3}$$

$$H_T = \gamma_a.V.\left(T_{res} - T_{ref}\right) \tag{4}$$

$$\gamma_a = \phi.\rho_w.c_w + (1-\phi).\rho_r.c_r \tag{5}$$

The H_T, however, accounts not only a heat contained in the reservoir fluid and matrix. The H_T sums also the heat accumulated in the reservoir and the heat in flow through the reservoir (Axelsson et al., 2005). A risk of overestimates on a scale of multiples (Grant, 2000) to folds (Grant, 2014) may arise from apparent simplicity of the method, not only considering substitution of "representative" (e.g. mean) values. Most of questions address use of a reservoir volume, porosity (Doveri et al., 2010) and reference (base) temperature as critical uncertainties (Grant, 2014). The critical weakness of the volume method is formulation (6) of the recoverable heat (in place) - H_0, i.e. the part of a heat that can reasonably be exploited:

$$H_0 = R_0.H_T \tag{6}$$

3.2 Recovery factor

The standard method on recovery factor R_0 estimation compares an energy exploited at the wellhead over that accumulated in the reservoir (7). In USGS standards the reference state is described at the mean ambient (T_{ref} = 15 °C) or a mean condenser (T_{ref} = 40 °C) temperature. The wellhead flow (8) is assumed isenthalpic (Garg – Combs, 2011):

$$R_0 = \frac{q_{wh}}{H_T} \tag{7}$$

$$q_{wh} = m_{wh} . \left(h_{wh} - h_{ref} \right) \tag{8}$$

This method has been subjected to multiple conceptual revisions, including concept of energy availability or exergy (Garg – Combs, 2010, 2011, 2015; Williams, 2014) for power potential estimation. Thermodynamic aspects were discussed in terms of a reference and a definition state (Takahashi – Yoshida, 2016, 2018). The latter provided a solid basis to recognize between the reference temperature for reservoir potential (q_R) and the reference (abandonment) temperature for a wellhead state (q_{wh}).

A concept of production-based estimation of recovery factor has been introduced by Ungemach et al. (2005, 2007, 2009), designed for doublet or reinjection-including geothermal resources. The efficiency of production (η_{prod}) measures energy produced during a period of time (t_{prod}) over the energy stored in the reservoir (9). Then, the accessible recovery (R_0) is given by a gradient between production (T_{ref}) and reservoir (T_s) conditions at a current efficiency (10):

$$\eta_{prod} = \frac{Q_{prod}}{A.\Delta z} . \frac{\gamma_f}{\gamma_a} . t_{prod} \tag{9}$$

$$R_0 = \eta_{prod} \cdot \frac{T_{res} - T_{ref}}{T_{res} - T_s} \tag{10}$$

Realistic recoverable heat assessment (6) can be partially approached through substitution of Q_{prod} yielded from a history-matching and observations on well(s). A productivity can also be addressed setting a maximum Q_{prod} limited at critical pressure decline or water level drawdown. The question of production period can be answered in both, the real time the resource has been produced or by the period the reservoir is desired for exploitation.

3.3 Reserves and resources: booking and scheme

Review and revision of a reference hydrogeothermal evaluation of the Ďurkov geothermal structure (Vranovská et al., 1999, 2000) is carried through a probabilistic Monte Carlo simulation (Rubinstein – Kroese, 1991) of H_T and R_0 (eqs. 9 and 10) instead of using arbitrary constants $R_0 = 0.1$ (Fendek et al., 2005) or $R_0 = 0.075$ (Vranovská et al., 1999, 2000). The procedure adopts a McKelvey's scheme for classification of geothermal resources and reserves (Muffler – Cataldi, 1978) with consequent modifications (Clotworthy et al., 2006; Falcone et al., 2013, 2015). These are calculated through balancing the respective H_0 given by its IDF (Sanyal – Sarmiento, 2005) for a certain period of time; i.e. for $t_{prod} = 40$ years (convention in Slovakia) and $t_{prod} = 100$ years to reflect a minimum period of long-term production considered within a concept of sustainable geothermal production (Axelsson et al., 2001).

Extended reading is available on the classification in cited literature (Muffler – Cataldi, 1978; Clotworthy et al., 2006; Williams et al., 2011; Falcone et al., 2013, 2015; Sarmiento et al., 2013). Assessment of total resources - RS_T, inferred reserves - R_{inf}, probable reserves - R_{pb} and proven reserves – R_{pv} is fairly inspired by categories defined in booking the geothermal reserves (Sanyal – Sarmiento, 2005). Basic formulations and computations according to cited materials (see above) are listed in Table 1.

3.4 Reserve capacity ratio approach

The reserve capacity ratio approach is based on a balance evaluation between the accessible energy stored in reservoir and an energy that is extracted under existing or realistic conditions. The original reserve capacity ratio r_{cap} approach accounts on a reserve capacity $R_{cap} = R_{pb} - R_{pv}$ value over the probable reserves, R_{pb}. The ratio has then been applied to classify 5 states of reservoir production, ranging from sustainable and overexploitation state towards massive overexploitation. Proven reserves in the scheme substitute the installed or produced geothermal energy by all existing wells (Bjarnadottir, 2010).

No wells operate at the Ďurkov geothermal structure. Original concept $r_{cap} = R_{cap} / R_{pb}$ (Bjarnadottir, 2010) is re-arranged into a form respecting Monte Carlo simulation of H_0 (17). The scope of carried hydrogeothermal evaluation revision is also to optimize proven reserves (installed capacity / thermal output) towards future onset of reservoir production. Thus, we use the reservoir capacity ratio to find a critical R_{pv} (Tab. 2) at which a future exploitation meets a modified sustainable production class (Fričovský et al., 2014). Note that instead of probable reserves R_{pb} (Eqs. 14 and 15) in setting the definition of reserve capacity R_{cap}, we used a mode (M) or 50-th percentile (P50) of H_0 as given by the IDF. According to the IDF and booking concept, $R_{pv} + R_{pb} \leq \mathrm{P50}(H_0)/t_{prod}$, that corresponds to a level of accessibility and confidence in evaluation process.

$$r_{cap} = \frac{R_{cap}}{R_{pb}} = \frac{\left(\mathrm{P50}(H_0) / t_{prod} \right) - P_{th}}{\left(\mathrm{P50}(H_0) / t_{prod} \right)} ; \text{or } r_{cap} = \frac{R_{cap}}{R_{pb}} = \frac{\left(\mathrm{M}(H_0) / t_{prod} \right) - P_{th}}{\left(\mathrm{M}(H_0) / t_{prod} \right)} \tag{17}$$

Table 1: Review on concept of geothermal resources and reserves assessment and classification.

Class	Definition	Computation	Eq. number in text
Geothermal resources	Energy accumulated in the reservoir, accessible for near-future economical and legal extraction, less than 100 years	$RS_T = \frac{\mathrm{P10}(H_T) - \mathrm{P10}(H_0)}{t_{prod}}$	11
Inferred reserves	Part of energy and a resource accumulated in the reservoir that is soundly indicated by analogy with other geothermal systems at comparable conditions, however, susceptible to a robust re-evaluation when additional exploration is carried	$R_{\mathrm{inf}} = \frac{\mathrm{P10}(H_0) - \mathrm{M}(H_0)}{t_{prod}} \text{ if } \mathrm{M}(H_0) < \mathrm{P50}(H_0)$ $R_{\mathrm{inf}} = \frac{\mathrm{P10}(H_0) - \mathrm{P50}(H_0)}{t_{prod}} \text{ if } \mathrm{M}(H_0) > \mathrm{P50}(H_0)$	12 13
Probable reserves	Part of energy and a resource accumulated in the reservoir that is indicated by both, the direct and indirect manifestations, and relevant results from geophysical, geochemical and numerical modeling. A change of re-evaluation with additional exploration carried is significantly less than that by inferred reserves.	$R_{pb} = \frac{\mathrm{M}(H_0) - \mathrm{P90}(H_0)}{t_{prod}} \text{ if } \mathrm{M}(H_0) < \mathrm{P50}(H_0)$ $R_{pb} = \frac{\mathrm{P50}(H_0) - \mathrm{P90}(H_0)}{t_{prod}} \text{ if } \mathrm{M}(H_0) > \mathrm{P50}(H_0)$	14 15
Proven reserves	Part of energy and a resource accumulated in the reservoir that is successfully proven and sampled through realized wells. Proven reserves represent installed or online capacity of geothermal fields. Probability of re-calibration after carrying another stages of exploration is relatively weak.	$R_{pv} = \frac{\mathrm{P90}(H_0)}{t_{prod}}$	16

Table 2: Reserve capacity ratio: modified production sustainability scheme.

Class	Definition	Critical R_{pv} limit (if MH_0) < P50 (H_0) substitute M (H_0))	r_{cap} range
Intense reservoir depletion	Massive overexploitation of the system. At this R_{pv}, the system is supposed to produce above level of probable reserves and at high risk of collapse.	$r_{cap} < 0 = \frac{\left(\mathrm{P50}(H_0)/t_{prod}\right) - R_{pv}}{\left(\mathrm{P50}(H_0)/t_{prod}\right)} \to R_{pv} \succ \left(\mathrm{P50}(H_0)/t_{prod}\right)$	$r_{cap} < 0$
Reservoir depletion	Overexploitation of the system. Up to all of the probable reserves are utilized, increasing a risk of a collapse. No capacity for more installations.	$0 = \frac{\left(\mathrm{P50}(H_0)/t_{prod}\right) - R_{pv}}{\left(\mathrm{P50}(H_0)/t_{prod}\right)} \to R_{pv} = \left(\mathrm{P50}(H_0)/t_{prod}\right)$	$r_{cap} \in < 0 ; 0.5 >$
Sustainable production	Sustainable use of the system. Up to a half of probable reserves are utilized. A system is capable to operate for a desired production period with only a weak risk of collapse.	$0.5 = \frac{\left(\mathrm{P50}(H_0)/t_{prod}\right) - R_{pv}}{\left(\mathrm{P50}(H_0)/t_{prod}\right)} \to R_{pv} = 0.5\left(\mathrm{P50}(H_0)/t_{prod}\right)$	$r_{cap} \in < 0.5 ; 0.75 >$
Well sustainable production	Sustainable use of the system. Less than a quad of probable reserves are utilized. A system may be left for prolonged production or there is a potential for geothermal development at the site.	$0.75 = \frac{\left(\mathrm{P50}(H_0)/t_{prod}\right) - R_{pv}}{\left(\mathrm{P50}(H_0)/t_{prod}\right)} \to R_{pv} \prec \left(\mathrm{P50}(H_0)/t_{prod}\right)$	$r_{cap} > 0.75$

4. INPUT MODEL AND DATA

4.1 Interfaces

For revised hydrogeothermal assessment of the Ďurkov depression hydrogeothermal structure, several setups are combined:

- *structuralized gross grid (SGG)*: set of 150 points in 500x500 m cells horizontally; welltops at each top / base of stratigraphical horizon; plus 10 nodes per each point for reservoir body at $z = 0.1.\Delta z_i$ m vertical resolution; 900 nodes on a gross grid, 1650 nodes for reservoir grid. The grid is used to calculate required inputs for geological and stationary geothermal model. Each node provides information on geometry (A_i, z_i, Δz_i), geothermics ($T_{res,i}$, $\rho_{w,i}$, $c_{w,i}$, $\rho_{r,i}$, $c_{r,i}$, $\phi_{z,i}$), and calculated $H_{T,i}$, $H_{W,i}$, $H_{R,i}$, $H_{0,i}$, $H_{T,i}/A_i$, $H_{0,i}/A_i$

- *refined model grid (RMG)*: derived for geothermal reservoir in Mid Triassic carbonates + Karpatian basal conglomerates only; resolution of the cell: 50x50x10 m along stable surfaces. Used for simulation of input geothermic data. Expecting unstationarity, the 3D distribution of H_T and H_0 is carried through conditioned Turning-bands (TBS) method based on structuralized variograms (constructed based on a gross grid) and 100 iterations per each cell to qualitative evaluation of the structure

- *Monte Carlo simulation (MSC)*: uses data from structuralized gross grid (geometry) and refined model grid (geothermic data) in probabilistic simulation, carries up to 10,000 iterations per H_T and R_0; functions given by distribution of input variables.

4.2 Reservoir geometry

4.2.1 Area

Total areal coverage of the structure at a surface is app. 33.6 km^2. Thus, it represents a maximum value for MSC. Distribution of the heat flux gives elevated values in eastern part of the structure $q_{HF} > 100$ mW.m^{-2} that is above the local mean. Thus, the area of heat flux anomaly ($A = 16.3$ km^2) is the minimum coverage considered in MCS.

4.2.2 Thickness and depth

The structure involves eight identified tectonic blocks of various vertical tendency (Fig. 2). The top of the strata is in depths of 1,660-2,650 m, with base at 1,960-4,035 m. Thus, the z = 1660-4,035 m for MCS. According to a model, overall thickness counts $\Delta z = 250$-2,200 m. A cut-off for MCS is, thus, $z + \Delta z \leq 4{,}035$ m. The criterion applies in formation (T_{res}) temperature calculations for MCS.

4.3 Reservoir geothermics

Model of temperature distribution in the entire structure has been constructed within the SSG interface, applying conduction-dominated environment model (Haenel et al., 1988). Consequently, the SSG geothermal model served construction of structuralized variograms necessary for TBS based distribution. Calibration of the model took part according to static temperature profiles of GTD-1 to GTD-3 wells (Vranovská et al., 1999).

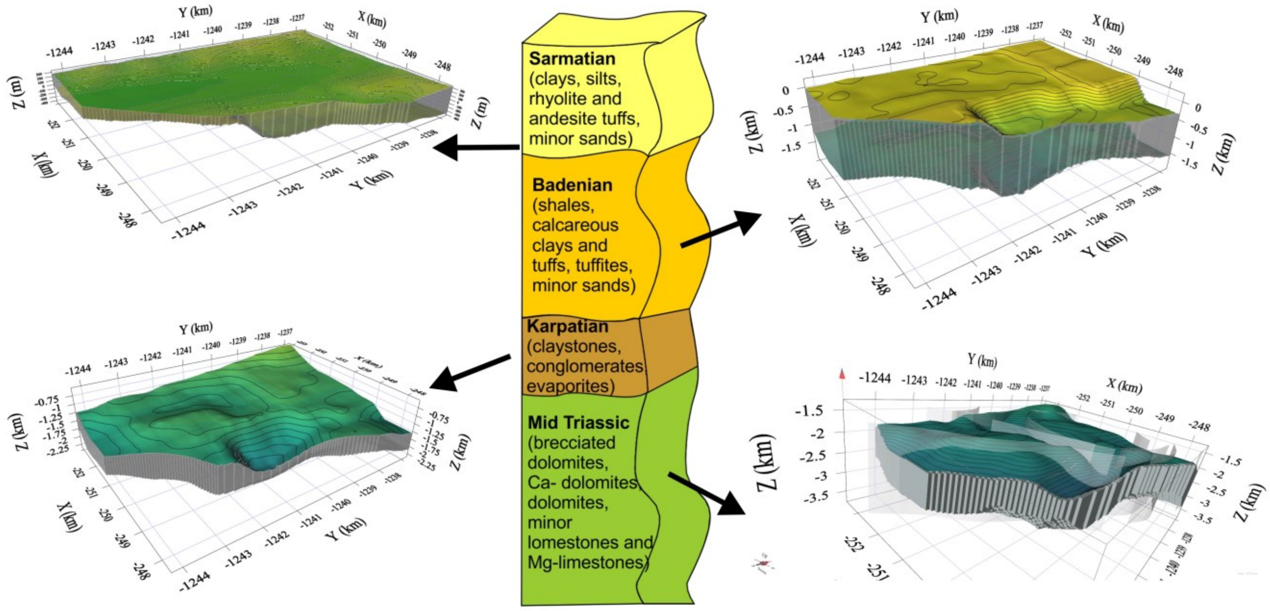


Figure 2: The Ďurkov depression hydrogeothermal structure: deep geological structure and geometry.

4.3.1 Formation and surface temperature

A mean temperature of the soil is T_s = 8-10 °C, decreasing in the W-E direction with elevating surface. Neglecting base of Quaternary, temperature at the base of Sarmatian is $T_{(z)}$ = 16-53 °C, increasing to $T_{(z)}$ = 43-128 °C for Badenian and $T_{(z)}$ = 87-142 °C for base of Karpatian, that is a top of the Mid Triassic. It increases up to T_{res} = 95-180 °C at a base (Fig. 3). In the reservoir, the mean temperature is T_{res} = 123 °C, increasing to $T_{(z)}$ = 147 °C when considering deepest horizons only. Distribution of temperature is asymmetric, decreasing axially to the NW and SE along a NE-SW line that intersects the Ďurkov depressed tectonic block. Extended temperature range T_{res} = 80-198 °C has been substituted as cut-off for T_{res} calculation in MCS using $T_{res} = [0.0478 \,.\, (z + \Delta z) + 3,9]$ function.

4.3.2 Specific heat capacity, specific density and porosity

A little data on ρ_w, ρ_m, c_w and c_m are available from a structure, except those measured during completion of GTD-1 to GTD-3 wells. Approximations become, thus, necessary, to fit thermos-physical parameters to respective T_{res} or $T_{(z)}$ or reservoir geometry. Specific density for water $\rho_w = 1 \pm [\, \beta_{vw}.(T_{wh}\text{-}T_{(z)}) \,]$ (Lipsey et al., 2016) and specific heat capacity $c_w = [4,245 - 1.841 \,.\, (T_{(z)} + 273.15)]/\rho_w$ (Pasquale et al., 2013) were adjusted strictly to SGG temperature distribution. For rock, both, the specific density and specific heat capacity, thus $\rho_r = [\, (4,806.7 \,.\, \phi) + 2,832 \,]$ and $c_r = [\, (-0.0026 \,.\, z_{(i)}\,) + 889 \,]$ were derived from borehole data and related to geometry.

4.3.3 Porosity

Qualified estimation of porosity is necessary in γ_a calculation, crucial for H_T calculation. Instead of global approximations, porosity logs from GTD-1 and GTD-2 well were taken and related to depth and thickness of Mid Triassic carbonates. Exponential function $\phi = 0.396e^{-0.001.\,(\,z\,+\,\Delta z\,)}$ was incorporated in MCS.

4.3.4 Deliverability and reference temperature

Deliverability is necessary for R_0 MCS estimate under reservoir production efficiency approach (9-10). We set the Q_{prod} = 55-235 $l.s^{-1}$ interval for MCS, that corresponds to accessible discharge by either overflow (Vranovská et al., 1999) or pumping (Giese, 1998). The latter value is considered critical to maintain pressure conditions off an enormous scaling potential of exploited and cooled fluid.

The reference temperature was set constant for T_{ref} = 65 °C. This corresponds to a carried reference hydrogeothermal evaluation (Vranovská et al., 1999), considering reinjection. The reinjection at local conditions is necessary, referring to a closed type of the system, high TDS and arsenic content, and absence of a potential surface stream to discharge waste water (heat).

5. RESULTS: HYDROGEOTHERMAL EVALUATION

5.1 Recovery factor

In conditions of geothermal assessments in Slovakia, R_0 is obviously set as constant R_0 = 0.1 or R_0 = 0.075, the latter applied in case of planed reinjection. Some reservoir engineering rationale is, however, absent. The recovery factor plays, however, crucial role for assessment, invoking a need for its site-discretization. A primary question on R_0 application is selection of the appropriate method to represent local steady-state and production characteristics. To assess recoverable heat associated with the structure, a method based on production efficiency (Eqs. 9-10) has been applied. The selection is justified due to a doubled-based scheme of production wells, tectonic dissection of the reservoir and closed-type character of the structure in terms of hydrogeological regime.

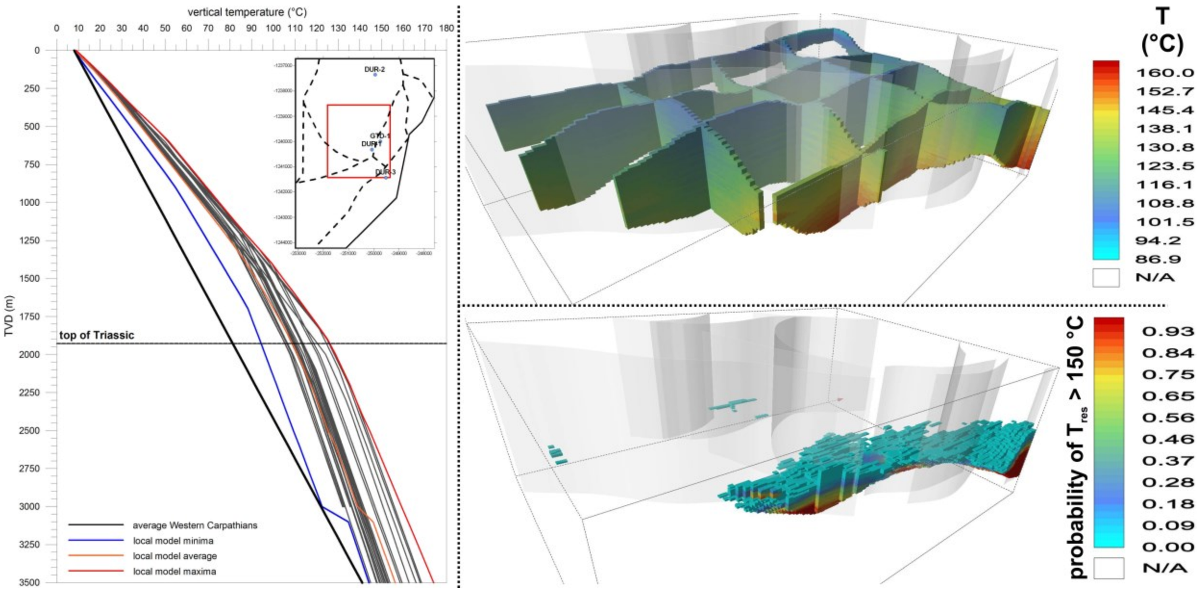


Figure 3: The Ďurkov depression hydrogeothermal structure: reservoir temperature distribution.

The MCS carried 5,000 iterations, with T_{ref} and t_{prod} set constant; T_{res}, ϕ, c_w, c_r, ρ_w, ρ_r defined as functions of T_{res} or $T_{(z)}$; and A_t, Δz and T_s as variables. Ranges used are described above. The resultant interval is $R_0 \epsilon < 0.008 ; 0.45 >$ skewed left. To set a representative value, we use distribution of R_0 from $R_0 \epsilon < P90(R_0) ; P50(R_0) >$ or $R_0 \epsilon < 0.016 ; 0.092 >$ range, yielding a unimodal distribution. Selection of $R_0 = 0.053$ refers then both to a mode of primary and median of selected population. It may, thus, be considered a conservative estimate when compared to a uniform value for the Western Carpathians, or $R_0 = 0.075$ accepted in a reference evaluation (Vranovská et al., 1999). However, it is thought that the resultant R_0 meets better local natural and production conditions.

5.2 Geothermal energy distribution

To evaluate geothermal energy distribution, the USGS volume method (Eqs. 2-5) has been applied to each of 1650 nodes on SGG, serving a base for structuralized variograms and consequent TBS simulations (Fig. 4). Dimensions per each SSG block are A = 500x500 m, Δz = 20-250 m. A relative H_W / H_T ratio is 0.88-1.61 % with 1.45 % in average. As the $H_W = f(\phi)$ and $\phi = f(z, \Delta z)$, the ratio increases slightly to the W and NW, where the Mid Triassic carbonates elevate. Energy density distributes, however, inversely. The $H_T = H_W + H_R$, and the H_T increases with ΔT, where $T_{res} = f(z, \Delta z)$ assuming stationary thermal environment.

At $H_{T,i}/A_i$ = 0.7-38 GJ.m^{-2} (a mean of 13 GJ.m^{-2}), the highest density extends well according to a distribution of temperature; i.e. ceases axially to the NW and SE from the Ďurkov depressed block. The calculated HT,I / Vi = 0.04-0.107 GJ.m^{-3} (a mean of 13 GJ.m^{-3}) is of arc-based distribution of maxima in the eastern part of the structure, where carbonates sink deep due to tectonic dissection and where thickness of the strata is greatest. In local conditions, it appears that the Ďurkov depressed block (see Fig. 1 and 3) and its periphery along the Bidovce depression, the Ďurkov – Olšovany and Olšovany block are most promising in terms of energy density available per unit reservoir area and volume.

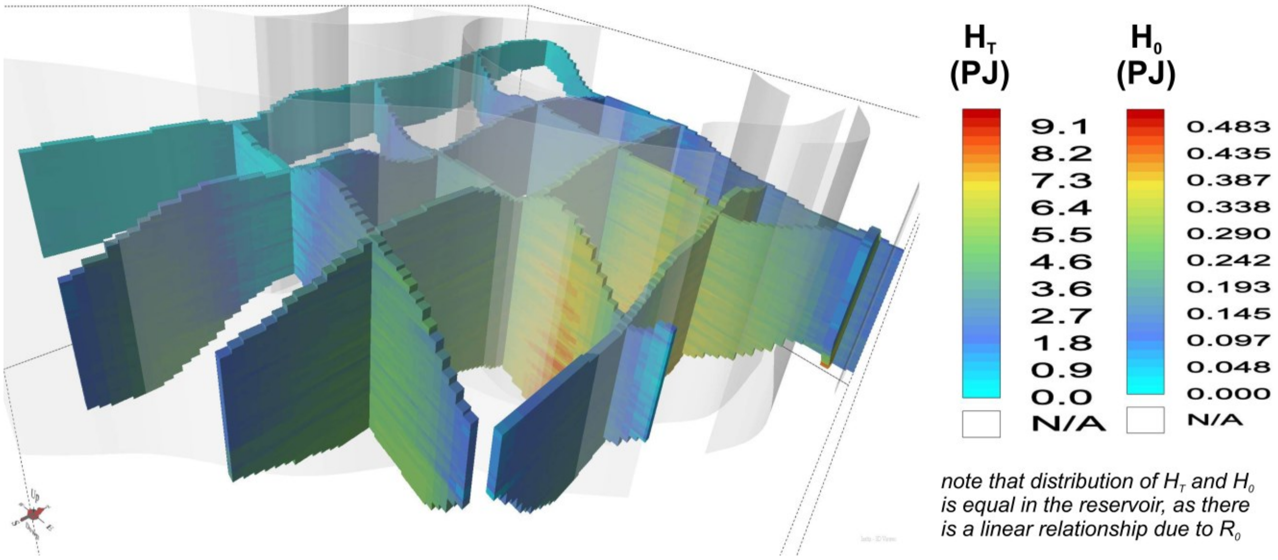
5.3 Energy base and recoverable heat in place

With setup described in section 4, where A and Δz were variables, ϕ, T_{res}, c_w, ρ_w, ρ_r and c_r referred with a function to a respective Δz or z and T_{res} ($T_{(z)}$ respectively); and T_{ref} was set constant, 10,000 iterations took part. Simultaneously, the constant $R_0 = 0.053$ corrected H_T for H_0 (Eq. 6). The total heat stored as based on MCS is H_T = 0.2-15 EJ. At a given setup, the average $X(H_T)$ = 6.2 EJ, the median $MD(H_T)$ = 5.8 EJ and the mode $M(H_T)$ = 4.2 EJ (Fig. 5). When corrected for recoverable heat in place, the H_0 = 10-759 PJ. Considering the inverse cumulative distribution function to the H_0, the $H_0 \ \epsilon < P95(H_0) ; P5(H_0) >$ equals $H_0 \ \epsilon < 81 ; 646 >$ PJ, with $P10(H_0)$ = 567 PJ, $X(H_0)$ = 329 PJ, $MD(H_0)$ = 305 PJ and $M(H_0)$ = 276 PJ (Fig. 5).

5.4 Classification of geothermal resources

Probabilistic H_0 distribution at the IDF curve is used to balance the recoverable heat in place for a desired (syn. balanced, production) period of time, in this case, the t_{prod} = 100 years and t_{prod} = 40 years (see Tab. 1; Eqs. 11 to 16). Resources and reserves according to the McKelvey's scheme are then compared to results obtained in a first, reference hydrogeothermal evaluation of the system (Vranovská et al., 1999) in terms of probability.

Classification of geothermal resources and reserves is depicted on Figure 6, with calculations carried as in Table 3. Because of skewing the IDF distribution, we decided to use the median (MD) of recoverable heat in place instead of using P50 or mode to rate R_{inf} and R_{pb}. With the same H_0, it is apparent that balanced reserves and resources increase with shortening the time for production. Yielded probabilistic model assumes 90 % probability on proving and sustaining 37 MWt for t_{prod} = 100 years, Then, increase of future installation to 97 MWt ($R_{pb} + R_{pv}$) appears possible for a long-term production only at 50 % probability.



note that distribution of H_T and H_0 is equal in the reservoir, as there is a linear relationship due to R_0

Figure 4: H_T and H_0 distribution based on conditioned Turning-bands simulation.

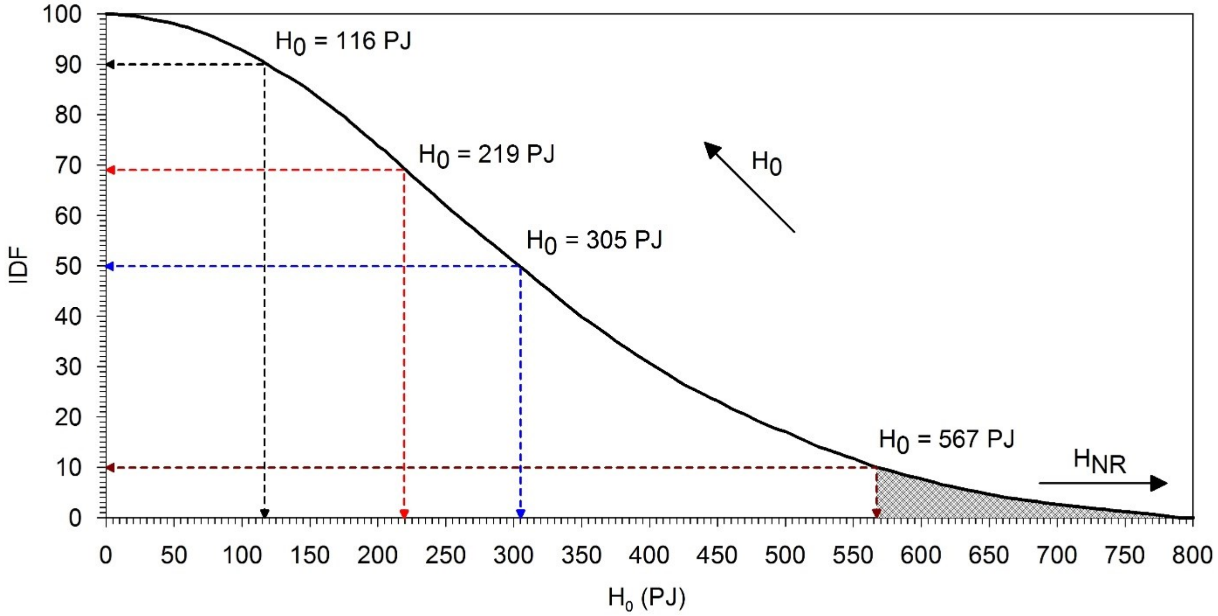


Figure 5: Cumulative inverse distribution function for H_0 based on 10,000 Monte Carlo iterations.

Table 3: Overview on classification of geothermal resources and reserves as based on desired production period balance.

Class	balance period: t_{prod} = 40 years	balance period: t_{prod} = 100 years
Geothermal resources RS_T (MWt)	$H(RS_T) = P10H_{T(IDF)} - P10H_{0(IDF)}$ $\Rightarrow RST = 10075(\text{PJ}) - 576(\text{PJ}) = 9508(\text{PJ})$ $RS_T = \frac{H(RS_T)}{t_{prod}} = \frac{9508(\text{PJ})}{60.60.24.365.40(\text{s})} = 7537(\text{MWt})$	$H(RS_T) = P10H_{T(IDF)} - P10H_{0(IDF)}$ $\Rightarrow RST = 10075(\text{PJ}) - 576(\text{PJ}) = 9508(\text{PJ})$ $RS_T = \frac{H(RS_T)}{t_{prod}} = \frac{9508(\text{PJ})}{60.60.24.365.100(\text{s})} = 3015(\text{MWt})$
Geothermal reserves RE_T (MWt)	$RE_T = R_{\inf} + R_{pb} + R_{pv} \approx\sim 450(\text{MWt})$	$RE_T = R_{\inf} + R_{pb} + R_{pv} \approx\sim 180(\text{MWt})$
Inferred reserves R_{inf} (MWt)	$P10(R_{\inf}) = \frac{567.10^{15}(\text{J})}{60.60.24.365.40(\text{s})} = 449{,}5(\text{MWt})$ $\Rightarrow R\inf = 449{,}5(\text{MWt}) - 242(\text{MWt}) = 207{,}5(\text{MWt})$	$P10(R_{\inf}) = \frac{567.10^{15}(\text{J})}{60.60.24.365.100(\text{s})} = 179{,}8(\text{MWt})$ $\Rightarrow R\inf = 179{,}8(\text{MWt}) - 96{,}7(\text{MWt}) = 83{,}1(\text{MWt})$
Probable reserves R_{pb} (MWt)	$MD(R_{pb}) = \frac{305.10^{15}(\text{J})}{60.60.24.365.40(\text{s})} = 242(\text{MWt})$ $\Rightarrow R_{pb} = 242(\text{MWt}) - 92(\text{MWt}) = 150(\text{MWt})$	$MD(R_{pb}) = \frac{305.10^{15}(\text{J})}{60.60.24.365.100(\text{s})} = 96{,}7(\text{MWt})$ $\Rightarrow R_{pb} = 96{,}7(\text{MWt}) - 36{,}8(\text{MWt}) = 59{,}9(\text{MWt})$
Proven reserves R_{pv} (MWt)	$R_{pv} = \frac{116.10^{15}(\text{J})}{60.60.24.365.40(\text{s})} = 92(\text{MWt})$	$R_{pv} = \frac{116.10^{15}(\text{J})}{60.60.24.365.100(\text{s})} = 36{,}8(\text{MWt})$

To remind, reference study declared R_{pv} = 42 MWt for free flow and R_{pv} = 93 MWt for pumping, balanced for t_{prod} = 40 years. Considering the actual IDF of H_0, there is 97 % probability for t_{prod} = 40 years and 88 % probability for t_{prod} = 100 years the system can be produced at the referenced rate, as actual assessment gives R_{pv} = 37 MWt or R_{pv} = 92 MWt respectively. Probability of proving additional 113 MWt declared as probable yields, however, significantly less probability, as $R_{pv} + R_{pb}$ = 150 MWt (free-flow) corresponds to 18 % for t_{prod} = 100 years and 74 % for t_{prod} = 40 years. The probability decreases dramatically when considering the pumping scenario, i.e. $R_{pv} + R_{pb}$ = 206 MWt, implying 4 % and 59 % respectively.

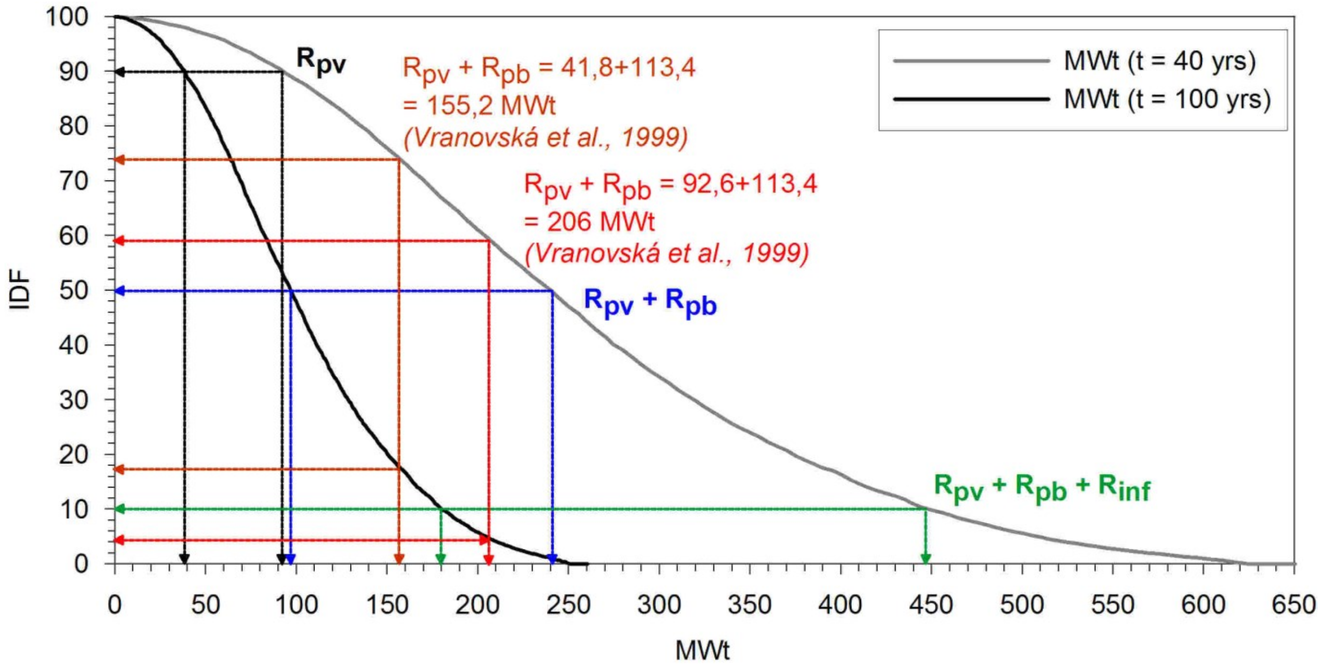


Figure 6: Booking geothermal reserves for the Ďurkov depression hydrogeothermal structure: a probabilistic concept.

6. RESULTS: RESERVE CAPACITY RATIO ANALYSIS

In a pioneering work on use of the reserve capacity ratio, sustainability is evaluated through a relation of installed (online) capacity over probable reserves on several geothermal fields in Iceland (Bjarnadottir, 2010). No wells operate at the DDHS. Thus, instead of approaching classification of sustainable use for any current production strategies, the concept of reserve capacity ratio is modified to set limits for geothermal energy withdrawal according to a conception scheme (Tab. 2).

The reference base to which the optimized installed thermal output is defined as sum of probable (R_{pb}) and proven (R_{pv}) reserves assessed from recoverable heat in place cumulative IDF curve. When balancing MD(H_0) = 305 PJ for a given period of time t_{prod}, this counts for R_{pv} + R_{pb}, with 50 % probability of proving. For t_{prod} = 100 years, the R_{pb} + R_{pv} = 97 MWt, increasing to R_{pb} + R_{pv} = 242 MWt if balanced for t_{prod} = 40 years. Another modification is rewriting proven reserves (R_{pv}) to (desired) installed thermal output (P_{th}) when setting sustainability intervals, not confusing with what part of energy has already been proven (Tab. 4).

The r_{cap} = 0.5 identified that the highest thermal output for sustainable production is roughly P_{th} = 49 MWt, which corresponds to probability of 85 % to prove due to hydrogeothermal assessment balanced for t_{prod} = 100 years. Accepting this value as a threshold, each exploitation below this limit can possibly sustained for a long time. Reducing the production can, however, prolong the reservoir operation, or allow other parties (projects) to operate the field. The critical installed output for t_{prod} = 40 years is P_{th} = 121 MWt (Fig. 7).

Considering a reference hydrogeothermal evaluation for t_{prod} = 40 years (Vranovská et al., 1999), proven reserves R_{pv} = 42 MWt obtained from free-flow tests equal to r_{cap} = 0.83 compared to R_{pv} = 92 MWt documented through pumping and numerical modeling scoring r_{cap} = 0.62. Even under a different amplitude of probability, both can be considered (well) sustainable. If there is another 113 MWt to prove, so that R_{pb} + R_{pv} = 42 + 113 = 155 MWt, the r_{cap} = 0.36. Due to an energy balance, this can not be considered a sustainable production. The ratio drops more for a pumping scenario, i.e. $_{b}$ + R_{pv} = 92 + 113 = 205 MWt where r_{cap} = 0.15. Apparently, even after such an amount of energy is proven, this can not be sustained for a long. Obviously, increase in t_{prod} reduces critical limits for classification of production sustainability. Consequently, when calling for prolonged period of production, at t_{prod} = 100 years, the proven reserves yielded from free-flow tests would score r_{cap} = 0.58, identifying still sustainable production at a given balance, however, if the potential of probable reserves is proven (installed), this can turn the production towards depletive operation.

In 2016, a single pumping test has been executed on GTD-2 (Halás Sr. et al., 2016), proving R_{pv} = 24 MWt according to Commission on Classification of Groundwater Resources and Reserves by the Ministry of the Environment of the Slovak Republic. This corresponds to probability above 95 % at the IDF scheme for both, t_{prod} = 40 and 100 years, scoring r_{cap} = 0.75 and r_{cap} = 0.9 respectively.

Table 4: Overview on classification of production sustainability based on a reserve capacity ratio.

Class	r_{cap} interval	balance period: $t_{prod} = 40$ years	balance period: $t_{prod} = 100$ years
Intense reservoir depletion	$r_{cap} < 0$	$r_{cap} < 0 = P_{th} \succ \left(305PJ/40yrs\right)$ $\to P_{th} \succ$ [illegible]t	$r_{cap} < 0 = P_{th} \succ \left(305PJ/100yrs\right)$ $\to P_{th} \succ$
Reservoir depletion	$r_{cap}\ \epsilon < 0\ ;\ 0.5 >$	$r_{cap} = 0 \to P_{th} = \left(305PJ/40yrs\right)$ $\to P_{th} = 242MWt$ $r_{cap} < 0.5 \to P_{th} = 0.5\left(305PJ/40yrs\right)$ $\to P_{th} = \frac{1}{2}.242MWt \approx 121MWt$	$r_{cap} = 0 \to P_{th} = \left(305PJ/100yrs\right)$ $\to P_{th} = 97MWt$ $r_{cap} < 0.5 \to P_{th} = 0.5\left(305PJ/100yrs\right)$ $\to P_{th} = \frac{1}{2}.97MWt \approx 49MWt$
Sustainable production	$r_{cap}\ \epsilon < 0.5\ ;\ 0.75 >$	$r_{cap} = 0.5 \to P_{th} = 0.5\left(305PJ/40yrs\right)$ $\to P_{th} = \frac{1}{2}.242MWt \approx 121MWt$ $r_{cap} < 0.75 \to P_{th} = 0.25\left(305PJ/40yrs\right)$ $\to P_{th} = \frac{1}{4}.242MWt \approx 60.5MWt$	$r_{cap} = 0.5 \to P_{th} = 0.5\left(305PJ/100yrs\right)$ $\to P_{th} = \frac{1}{2}.97MWt \approx 49MWt$ $r_{cap} < 0.75 \to P_{th} = 0.25\left(305PJ/100yrs\right)$ $\to P_{th} = \frac{1}{4}.97MWt \approx 24MWt$
Well sustainable production	$r_{cap} > 0.75$	$r_{cap} > 0.75 \to P_{th} \prec$ [illegible] $\left(305PJ/40yrs\right)$ $\to P_{th} \prec \frac{1}{4}$ [illegible]MWt ≈ 60.5MWt	$r_{cap} > 0.75 \to P_{th} \prec$ [illegible] $\left(305PJ/100yrs\right)$ $\to P_{th} \prec \frac{1}{4}$ [illegible]Wt ≈ 24MWt

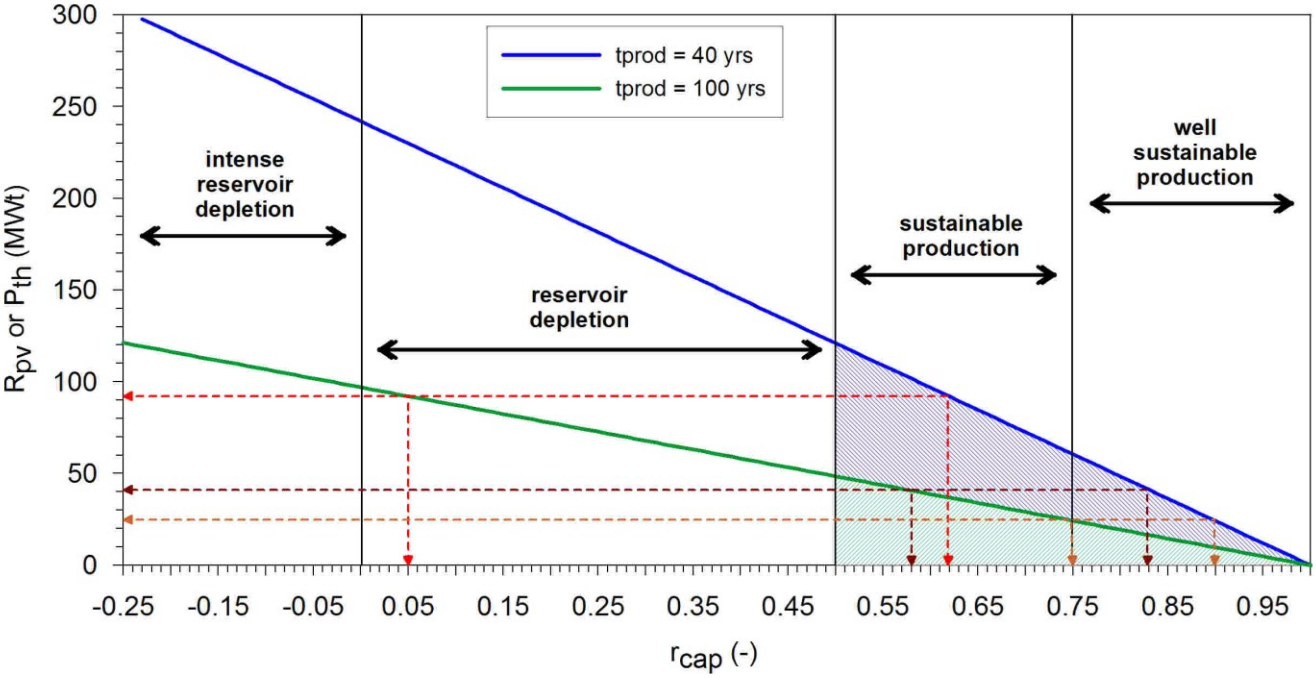


Figure 7: Sustainable production classification: booking energy withdrawal intervals.

7. DISCUSSION AND FUTURE PROSPECTS

The hydrogeothermal assessment revision for the DDHS has been carried based on structure geometry and stationary temperature model. Yet for app. 33.6 km^2 only 6 wells at an area of rougly 8 km^2 are available. Construction of site geometry used thus combination of previously published atectonic model (Pachocká et al., 2010), structural maps of pre-Tertiary basement and several seismic lines. Meanwhile, approximations on vertical and spatial distribution of variables, e.g. ρ_w, c_w, ρ_r, c_r, ϕ, or q_0 became necessary taken as function of temperature, thickness, porosity and depth, simply because spatially representative data are absent. This may cause some uncertainties to hydrogeothermal evaluation of the site and resources / reserves assessment that must be kept in mind. The recoverable heat in place probabilistic distribution recognizably refers to the recovery factor estimate, subjected to same uncertainties as with the volumetric method inputs. Application of Monte Carlo and conditioned Turning-bands simulation was also selected to narrow the effect of uncertainties. However, the following reserve capacity ratio method introduced to preliminary assess intervals of sustainable / depletive production is fairly dependent on results from booking the geothermal resources and reserves. Yielded capacities must, however, definitely by subjected to a precise proving, including long-term monitoring and pumping.

Recently, the Ministry of Environment of the Slovak Republic supports a detailed study of the DDHS realized at the Dionýz Štúr State institute of Geology. Among the others, this includes geological and geothermal models, hydrogeological assessment based on geological certainty, technical potential, reservoir capacity, thermodynamic evaluation, models of reservoir response to desired production and environmental aspects analysis based on rapid impact assessment matrix construction. This is carried to support a complex understanding of the DDHS and to provide a wide overview on its prospectiveness interaction with principles of the sustainable development and sustainable reservoir production.

8. CONCLUSIONS

Indeed, the DDHS is repeatedly reported as the most prospective geothermal area (geothermal water body) in Slovakia. Since 70's, research and prospection on geology and geothermal energy took consistently place with a subsequent pioneering hydrogeothermal evaluation carried in 1999, identifying available 42 MWt for free-flow and 92 MWt (numerical model) for pumping (therein referred as proven) strategies, adding 113 MWt for onward proving (Vranovská et al., 1999; Giese, 1999). Since, several visionary projects came to a plan or consideration, including district heating or cogeneration plant based on a binary cycle. However, because of law, economics, and property rights issues, no project runs online at a site yet. In 2016, a long-term pumping proved 24 MWt available per GTD-2 well.

Hydrogeothermal evaluation revision at the DDHS combines the USGS volumetric (heat-in-place) method (e.g. Muffler – Cataldi, 1978) for energy base and production-efficiency method for recovery factor derivation (e.g. Ungemach et al., 2005) in probabilistic booking the geothermal resources and reserves (Sanyal – Sarmiento, 2010) before proceeding towards estimation of installed capacity limits for sustainable production using the reserve capacity ratio approach (Bjarnadottir, 2010). Conditioned Turning-bands method (Chiles – Delfiner, 1999) based on structuralized variograms provided by a structuralized-gross-grid calculations served to interpret spatial distribution of energy density at the site. Instead of balancing the heat capacity in the reservoir for only t = 40 years, this study recalls the period of 100 years according to concept of sustainable reservoir production (Axelsson et al., 2001).

In comparison to a previous hydrogeothermal evaluation, we used a median of MCS derived $R_0 = 0.053$ that shall represent site-specific conditions more precisely. Then, according to the IDF distribution of recoverable heat in place, when balanced for 40 years, the estimate of proven reserves is $R_{pv} = 92$ MWt, with some probability of proving $R_{pb} = 242$ MWt up to 50 %. Apparently, for that short period of time production, estimates provided in a reference study fit well with our model. However, extending a production towards $t_{prod} = 100$ years to meet a concept of sustainability, $R_{pv} = 37$ MWt at P90(H_0). Additionally, there is a 50 % probability that there are 60 MWt available to prove for such a long term production. With projection to a probabilistic approach, previously free-flow supplied production ranked as proven reserves (Vranovská et al., 1999) would correspond to P88(H_0) for $t_{prod} = 100$ years and P97(H_0) for $t_{prod} = 40$ years respectively. Probability of proving additional 113 MWt (R_{pb}) yields P18(H_0) and P74(H_0) respectively.

A concept of reserve capacity ratio has been introduced to local conditions, as a first-guess attempt to evaluate sustainability criteria for geothermal energy production at the site, with a clear focus on thermal energy balance between a capacity and a potential production. For a 100-years long period of production, a critical installed output at $r_{cap} = 0.5$ yields $P_{th} = 49$ MWt, increasing to $P_{th} = 121$ MWt for $t_{prod} = 40$ years. The estimated rates corresponds to 85 % probability of success in proving and maintaining. Evaluation of previous results ranks $R_{pv} = 42$ MWt (Vranovská et al., 1999) as a (well) sustainable strategy for both periods, with $r_{cap} = 0.83$ and $r_{cap} = 0.58$ respectively. Proven reserves of $R_{pv} = 24$ MWt obtained through realized pumping test (Halás Sr et al., 2016) reach, obviously, a greater score. A considerable difference is when classifying $R_{pv} = 92$ MWt (Vranovská et al., 1999; Giese, 1999), ranked as sustainable ($r_{cap} = 0.62$) to depletive ($r_{cap} = 0.05$) scenario respectively, depending on a desired production period.

The presented study provides an alternative hydrogeothermal evaluation to a "representative values" approach frequently used in conditions of the Western Carpathians. A focus has been paid to evaluate probability of proving installed capacity at a site for a different period of desired production along with first insights on sustainable reservoir exploitation. Admittedly, any advanced studies on the latter topic shall then aim at reservoir prediction forecasting. However, the presented analysis should contribute to a complex knowledge on one of the most prospective geothermal areas in Slovakia, hopefully stimulating such actions elsewhere in the country, where there is an urgent need to approach geothermal resources as sources of energy.

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