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Probabilistic Models of Booking the Geothermal Reserves (McKelvey Scheme) in Construction of Geothermal Potential Catalog for Slovakia – Case Studies for the Levoča Basin, S and W Part

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ABSTRACT

With already proven geothermal reserves R_{pv} = 35 MWt, the Levoča Basin – southern and western part is among most explored geothermal water bodies in Slovakia. Actual installed thermal output of all online wells, i.e. $P_{th,inst}$ = 25 MWt gives it highest ranks in the country too. In addition, new geothermal well in town of Kežmarok is under testing aimed for geothermal district heating system, plus another two wells apply for new geothermal water withdrawals, recalling actions to assess total and sustainable geothermal capacity to avoid reservoir depletion. Construction of probabilistic (sustainable) model of McKelvey scheme is based on Monte Carlo simulation of the USGS volume method later combined with modified reserve capacity ratio approach. The recovery factor is assessed through simulation of perspective reservoir volume method. Both, the guided (background models for setting PDFs) and conceptual (geothermal water regimes) approaches control the simulation. Thus, PDFs for western part are constructed from cumulative histograms of background data, while for the southern, reservoir units in different tectonic units are considered a single reservoir as they spatially alternate; then both parts are simulated individually, with products aggregated through arithmetical summation. The recovery factor is likely to vary R0 ϵ < 0.048 ; 0.19 > for its western and R0 ϵ < 0.042 ; 0.115 > for the southern part. The western part is more perspective in terms of thermal potential, i.e. 141 / 57 MWt for t_{prod} = 40 / 100 years, so that with sustainable capacity of $P_{th(S)}$ = 72 / 28 MWt, there is still a potential for development even on a sustainable (long-term) scale, i.e. $P_{th(D)}$ or $P_{th(D*)}$ = 21 MWt to 3 MWt respectively, whereas sustainable capacity for the southern part, $P_{th(S)}$ = 8 MWt is all available for development as this is not produced.

1. INTRODUCTION

Although utilization of geothermal energy in Slovakia dates far beyond Medieval to experience benefits of warm and thermal-healing springs, and the systematic research and prospection on deep geothermal resources followed late in 70's answering global energy resources concerns, a first catalog of geothermal potential occurred back in 90's with the Atlas of geothermal energy of Slovakia (Franko et al., 1995). Besides delineation of 26 perspective geothermal areas (PGAs) and basic description including drilling and borehole data, each was assigned with an estimate of a total geothermal potential of 5,538 MWt. The estimate was then modified for 6,653 MWt (Fendek – Fendeková, 2010; Fendek et al., 2011) and 6,582 MWt (Marcin et al., 2014), however, neglecting changes in number, areas and potential assessed for PGAs identified in this period. Data and procedure analysis of estimates shown, however, robust inconsistencies, such is mixing of various methods without a conceptual rationale, "wild use" of recovery factors lacking any background, balancing energy base to different lifetimes and use of discrete calculations based on averaged inputs. A pilot probabilistic approach (Fričovský et al., 2020a) used a limited data and best-guess intervals in setting density functions for Monte Carlo simulation of USGS volume method and locally-upscaled recovery factor, still suffering many generalizations. Recently, a new, probabilistic catalog is under construction based on booking the geothermal reserves. In total, all 31 geothermal water bodies – GWBs (Kullman et al., 2005; Fričovský et al., 2020b, 2022) are subjected to extensive data analysis, involving geological, hydraulic, hydrogeological and geothermal properties, and conceptual models, to guide the setup of probabilistic density functions in Monte Carlo simulation, as well forward processing that leads to aggregation and interpretation of PDFs and inverse distribution functions (IDFs) forming the model.

The southern and western part of the Levoča Basin (LEB) is among the most complicated GWBs. Two different parts form the LEB on a basin scale. On the west, two nappe tectonic units in superposition beneath the Paleogene sedimentary cover associate geothermal reservoirs within Mid Triassic carbonates in hydraulic connection along fault lines and swarms. In southern part, multiple nappes are reduced to tectonic slabs, expected to comprise only one reservoir unit independent on a provenience atop the crystalline bedrock. Geothermal waters do not, however, flow between the southern and western part.

This paper reviews workflow, methodology, processing and construction of probabilistic model of a complex GWB formed by different reservoir units of various conceptual models and settings, including both, definition of regionalized recovery factor and interpretation of a probabilistic model of a McKelvey scheme to address the geothermal potential. Now, upturn in search for energy diversification accelerates in Slovakia, plus multiple sites are already online within the LEB. Such models are then able not only to discuss potential available for further development, but can contribute in assessment of sustainable geothermal energy use at least on balance scales.

2. MODEL BACKGROUND – GEOLOGICAL AND HYDROGEOTHERMAL SETTINGS

As the LEB is part of a sustainable geothermal potential catalog for geothermal water bodies in Slovakia, following section describes basic features of a geothermal field based on literature and recently unpublished geological and geothermal model (Fričovský et al., 2024).

2.1 Geothermal field

A surface heat flow density in Slovakia varies 30 – 125 $mW.m^{-2}$, with a mean of 82.1 ± 20 $mW.m^{-2}$ (Bodiš et al., 2018). Local highs are related both to contribution of radiogenic-rich Neogene volcanic and volcanoclastic formations and crustal thinning in deep Neogene sedimentary basins. The geothermic activity ceases generally to the north, recording local lows within the core mountains (Majcin et al., 2017). According to a modeled range, i.e. 51-82 $mW.m^{-2}$ and a mean of 64 $mW.m^{-2}$, the LEB is well along the moderate geothermic activity in Slovakia, expressing visible trends of increase from the local core mountains (Tatra Mts., Volovské vrchy Mts. and the Nízke Tatry Mts.) towards the basin. The trend is most abundant along the N and E footslopes of the Tatra Mts. (Figure 1), implying a hydrogeothermal function of the Sub-tatric fault system for thermal waters propagation (Král et al., 2021), or rather vertical invasion into shallow positions, typical for basin constriction or lateral leakage systems identified in the Western Carpathians (Fričovský et al., 2016). Since no relation to active geodynamics and volcanism, the geothermal field is classified as conduction-dominated, associating orogenic belt-type geothermal plays (Moeck, 2014; Fričovský et al., 2016).

2.2 Geological settings

With app. area of 1,790 km^2 the LEB is one of the largest geothermal water bodies in the country, necessarily recalling a complex geological structure. For a sake of a following modelling, the settings were generalized into hydrogeologically-hydrogeothermally uniform complexes (Figure 1) characterized below.

2.2.1 Top insulator (IZO1)

The top insulator complex consists of the *Inner Western Carpathian Paleogene Basin Fill (IWCP)* in the entire LEB, plus the Late Carboniferous to Early Triassic siliciclastics and LG metamorphosed volcanoclastis of the Choč Nappe in the Hornádska kotlina Basin (HKB), i.e. the southern part of the LEB, as long as they are thrusted onto Mid Triassic carbonates due to geotectonic evolution. The IWCP represents a succession of basal coarse-grained siliciclastics and carbonate conglomerates or breccia (transgression), followed by claystones-dominated (flood progression) and flysch-type (flood culmination) and finally sandstones-dominated (flood termination and regression) formations (Král et al., 2021). The overall thickness varies 0 – 3,000 m in western and 0 – 2,000 m in southern part, except the Ružbachy block where Mesozoic formations crop out. The block is a continuation of pre-Tertiary elevation running SW – NE direction along Tatranské Smokovce – Vyšné Ružbachy line, separating the W part into the Popradská kotlina Basin to the SE and the Magura depression to the NW. A similar elevation is formed along the Poprad – Branisko Mts line, forming a sub-depression to the south and submerging basin to the north. The complex of siliciclastics and volcanoclastics is merged to the IZO1 only south from the Vikartovce – Široké line (Figure 1) (Jetel et al., 1990), otherwise is adjusted to the bottom insulator IZO2, reaching thicknesses of a few meters to 350 m (e.g. Gerenčérová, 1993, Haluška – Petrivaldský, 1993, Marcin, 2000).

2.2.2 Top reservoir (RES1)

The top reservoir groups Mid Triassic to Late Triassic carbonates of various proveniences (Figure 1) at a base of the IZO1 complex. While in the western part, the model continues towards other complexes, the RES1 complex forms a base of a model in the south.

Within the western part, the Choč Nappe dolomites, dolomitic breccia and limy dolomites form a top reservoir (Daniel et al., 1998) for a typical vertical succession of intramountain depressions of the Inner Western Carpathians, i.e. beneath Tertiary basin fill and atop Late Triassic – Mid Cretaceous profile of the Krížna Nappe (Fatricum) or other tectonic units. Overall reservoir thickness is up to 1,130 m, with maxima nearby the town of Kežmarok, where multiple duplexes are expected. In southern part, the model merges all carbonates beneath IWCP as RES1, although they differ in tectonic origin and lithology, recording all limestone – dolomite varieties. A total thickness reaches up to 1,100 m as given by a model, increasing towards the Košice Basin (E) or Šarišská vrchovina (NE). A model reflects tectonic segmentation of the HKB, since increase in reservoir thickness in N-S and SW-NE direction reflects ceasing of their erosion during pre-Tertiary paleokarst period (Jétel et al., 1990; Činčura – Köhler, 1995).

2.2.3 Bottom insulator (IZO2)

The complex is limited to the W part only. It is exclusively formed by Late Triassic – Mid Cretaceous formations of the Krížna Nappe, i.e. different pelite to organogene and organodetritic limestones, claystones and marlstones (Hanzel, 1992) that elevate in SW – NE direction and crop-out nearby the spas of Ružbachy (Štefanka et al., 2011). The thickness varies between a few meters up to 800 m, with a local maxima in the Kežmarok – Spišská Belá area.

2.2.4 Bottom reservoir (RES2)

The complex is limited to the W part only as a base of a model. A bottom reservoir is formed exclusively by Mid Triassic to Late Triassic carbonates, i.e. a variety of limestones and dolomites with their transient forms (Fendek et al., 1992), however, found only in few wells (Table 1). While drilled thickness varies 30 – 380 m (e.g. Mlynarčík - Petrivaldský, 1990; Fendek et al., 1996; Halás et al., 2008). Modeled thickness is 40 to 780 m.

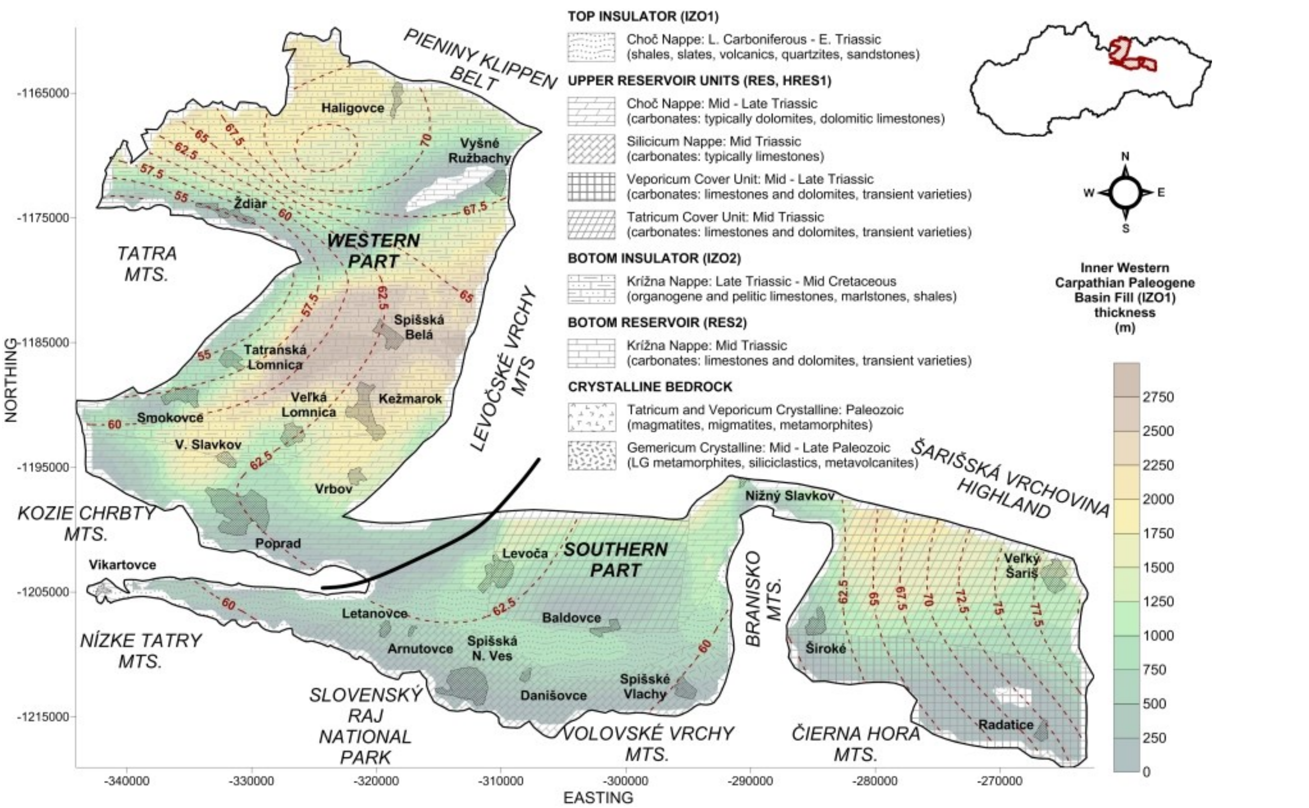

Figure 1: IWCP basin fill thickness, structural map of pre-Tertiary basement of the Levoča Basin – S and W part and the heat flow density map (mW.m^{-2})

Table 1: Relevant geothermal and deep hydrogeological wells proving geothermal resource

Locality	Well	IZO1 (m)	RES1 (m)	IZO2 (m)	RES2 (m)	T_{wh} (°C)	Q_{pv} (kg.s^{-1})	LEB part
Veľká Lomnica	GVL-1	1,553	547	not reached	not reached	62	34	western
Veľký Slavkov	VSČ-1	1,900	-	360	200	57	27	W
Vrbov	Vr-1	1,482	280	not reached	not reached	56	28	W
Vrbov	Vr-2	1,488	460	550	not reached	59	33	W
Poprad	PP-1	643	560	not reached	not reached	48	61	W
Stará Lesná	FGP-1	1,440	420	830	380	58	22	W
Vyšné Ružbachy	Izabela	spring	spring	spring	spring	20	20	W
Vyšné Ružbachy	VR-2	180	-	10	40*	20	1	W
Vyšné Ružbachy	VR-5	56	-	200	90*	24	3	W
Vyšné Ružbachy	VRŠ-1	5	-	165	35*	21	17	W
Gánovce	GA-1	40	230	not reached	not reached	23	3	W
Gánovce	GA-1A	50	not reached	not reached	not reached	27	2	W
Gánovce	ŠHG-1	25	125	not reached	not reached	26	3	W
Gánovce	ŠHG-2	30	70	not reached	not reached	25	2	W
Arnutovce	HKJ-3	450	680*	-	-	31	11	S
Letanovce	HKJ-4	410	200*	-	-	25	8	S
Lipovce	SAL-1	68	160*	-	-	19	2	S
Lipovce	SAL-6	240	230*	-	-	19	0.1	S
Bzenov	SH-2	297	130*	-	-	18	3	S
Kvačany	SH-4	317	50*	-	-	18	0.5	S

exp: "not reached" – the borehole terminated in the above horizon, not reaching base of the particular horizon, " * " – base of the bottom reservoir not reached, " – " – missing horizon or other impermeable bedrock, "T_{wh}" – wellhead temperature at proven deliverability, "Q_{pv}" – yields proven according to national legislation (i.e. at least 21-days long pumping tests.

2.3 Hydrogeothermal settings

Geological settings and tectonics initiated creation of multiple groundwater flow patterns in open to semi-open hydrogeothermal structures (Marcin, 2000; Daniel, 2005). Geothermal waters are meteoric in origin (Michalko – Fendek, 2002) and either spring out as in the Vyšné Ružbachy, Gánovce, Baldovce area (Fendek et al., 1992), or leak vertically or tectonically into shallow reservoir positions where they experience mixing and rapid cooling, such identified in Vrbov, as evidenced by transient-type chemistry of fluids in Choč Nappe dolomites (Daniel et al., 1998; Král et al., 2021). Basin-constriction systems should generally be expected north from the Smokovce – Spišská Belá line, where only one reservoir unit (RES2, i.e. the Krížna Nappe carbonates) is expected. Close to the Tatra Mts., bedrock-high hydrogeothermal structures are either proven or expected, typically along the Sub-tatric fault system. Between the Smokovce – Spišská Belá and the Poprad – Vrbov line, a combination of basin-constriction and lateral-leaking flow systems contributes on thermal waters movement in general S – N and SW – NE direction. Although there are no representative deep wells constructed in the HKB (southern part of the LEB), hydrogeothermal structures are considered (or expected) as basin-constriction to the north from the Levoča – Široké line, or bedrock-high south of it.

Sampled wellhead temperatures are listed in Table 1. Models constructed as background for guided probabilistic simulation expect reservoir temperatures in conduction-dominated, steady-state environment to vary T = 8 – 131 °C for RES2, T = 7 – 102 °C for RES1 in the western, and T = 7 – 80 °C for RES1 in southern part of the basin. It corresponds to modeled conductive gradients, generally in ranges of 20 – 47 $°C.km^{-1}$ for IZO1 (increasing in HKB due to Late Carboniferous – Early Triassic adjusted complex), 16 - 24 $°C.km^{-1}$ for RES1, 21 - 31 $°C.km^{-1}$ for IZO2 and 19 - 27 $°C.km^{-1}$ for RES2.

3. METHODOLOGY REVIEW

One of crucial triggers in construction of a probabilistic catalog of national geothermal potential is unification of assessment methods. In past, hydrogeothermal assessments used the so-called energy balance method (Fendek et al., 2005) for hydrogeologically open PGAs or later GWBs, that was, however, only a modification of magmatic heat budget method, what we consider improper. The USGS volume or stored-heat method applied only to hydrogeologically closed hydrogeothermal systems or where reinjection was considered mandatory (Franko et al., 1995). More was discussed already during a pilot model construction (Fričovský et al., 2020a).

3.1 The USGS volume method

The total thermal energy of a reservoir system is sum of energy stored in rock Q_R and fluid Q_W (Muffler – Cataldi, 1978; Garg – Combs, 2015). Geothermal reservoirs in the Western Carpathians are exclusively liquid-dominated, including several wet-steam zones, such is the Žiar Basin or the Košice Basin (Fričovský et al., 2016, 2019, 2020b). This reduces the fraction of heat in a fluid for the heat in water Q_W as this is the mobile reservoir phase (1)

$$H_T = Q_R + Q_W \left| \begin{array}{l} Q_R = A\,h\left[\rho_r\, c_r\,(1-\phi)\left(T_{res} - T_{ref}\right)\right] \\ Q_W = A\,h\left[\rho_r\, c_r\,\phi\left(T_{res} - T_{ref}\right)\right] \end{array} \right. \qquad (1).$$

Unlike for double-phase reservoirs, the (1) assumes a full water saturation. Obviously, this is a robust simplification, however, Table 1 and borehole data show only limited options for its assessment. Grouping (1) together gives a uniform formula of the stored heat (2). This allows also reservoir environment division into multiple blocks being evaluated separately or as a sum (3) in discrete or combined 2D / 3D models (e.g. Ciriaco et al., 2020):

$$H_T = A\,h\left[\left(\phi\, c_w\, \rho_w\right) + 1 - \phi\left(\rho_r\, c_r\right)\right]\left(T_{res} - T_{ref}\right) = \int \gamma_t \left(T_{res} - T_{ref}\right) \mathrm{d}V \qquad (2)$$

$$H_T = \sum_{i=1}^{n} \gamma_t\, V\left(T_{res} - T_{ref}\right) \qquad (3)$$

where γ_t (4) is the volumetric heat capacity as clear function of not only reservoir and fluid properties, but the porosity ϕ as well:

$$\gamma_t = \left[\left(\phi\, c_w\, \rho_w\right) + 1 - \phi\left(\rho_r\, c_r\right)\right] \qquad (4).$$

3.2 Recovery factor

By definition, the recovery factor accounts energy stored in reservoir environment available for extraction at current or expected conditions (e.g. Muffler – Cataldi, 1978; Ungemach et al., 2005; Garg – Combs, 2011; Williams, 2014). There is an extensive reading and discussion on setting proper methods to address or assume the recovery factor in terms of power production, considering not only natural, but technical conditions (i.e. lifetime, load factor) as well (e.g. Grant, 2000; Williams, 2004; Santoso et al., 2019; González-Garcia et al., 2021). In addition, many works (e.g. Grant, 2000, 2018; Williams, 2004, 2007; Sanyal – Butler, 2005; Sanyal – Sarmiento, 2005; Takahashi – Yoshida, 2016) aim to generalize recovery factor for given geological, geothermic or state conditions in terms of constants or simple parametric functions. According to the scope of a national probabilistic catalog, the recovery factor R0 is introduced and applied regionally per each GWB, addressing amount of thermal energy available to tap regardless of its future use. Thus, technical aspects are neglected and the focus is put on natural conditions and perspektivity of production only.

Following a pilot model (Fričovský et al., 2020a), we adhere to differentiation of R0 assessment according to hydrogeological conditions. Since locally all reservoir environments are considered open to semi-open (Fendek et al., 1992; Daniel et al., 1998; Marcin, 2000; Daniel, 2005), modification of effective reservoir volume method mentioned in Sanyal – Butler (2005) or Tester et al. (2006) was applied, though originally developed for EGS. Its principle is a volumetric comparison between what is called the effective reservoir area A_e – the part of reservoir under certain geothermal anomalies or increased temperatures, most perspective for geothermal development; and the total reservoir area A_t that also includes infiltration and descending transition zones at low temperatures (5):

$$\Phi_{res} = \frac{A_e \, \Delta z_e \, \gamma_{t,e}}{A_t \, \Delta z_t \, \gamma_t} \qquad (5)$$

where subscript e – properties of the effective and t – properties of the total area, while γ_t (4) is function of reservoir temperature T_{res} in effective or total area respectively.

Cooling of open hydrogeothermal systems may be triggered by cold water downflow from recharge/transition zones or invasion from shallow reservoir positions, if overproduced. Thus, recoverability becomes a function of initial reservoir gradient to reference conditions compared to a rate of tolerated cooling $T_{res,a}$ (6):

$$\Gamma_{R0} = \frac{T_{res,i} - T_{res,a}}{T_{res,i} - T_{ref}} \left| \begin{array}{l} T_{res,i} - T_{res,a} = T_{cool} \\ T_{ref} = \text{const.} = 15°C \end{array} \right. \qquad (6).$$

Setting the cooling temperature at 10 % of initial conditions (a few ideas on acceptable cooling are discussed e.g. in Tester et al., 2006; Sutter et al., 2011; Fox et al., 2013; Williams, 2007, 2014), a combination of (5) and (6) yields (7) consequently. The cooled temperature T_{cool} can be, however, approached through predictive reservoir response modeling for a given period of time:

$$R0 = \Phi_{res} \frac{T_{res,i} - 0.1 T_{res,a}}{T_{res,i} - T_{ref}} = \Phi_{res} \frac{T_{cool}}{T_{res,i} - T_{ref}} \qquad (7).$$

Then, (7) approaches not only effect of areas perspective for production compared to a total reservoir area including blind zones, but a rate of heat extractable upon breakthrough occasionally leading to production optimization or shut-in.

3.3 McKelvey scheme review

For a geothermal potential catalog, we follow a McKelvey scheme and its modifications (e.g. Muffler – Cataldi, 1978; Williams et al., 2010; Lawless et al., 2010) combined with the probabilistic geothermal reserves booking concept (Sanyal – Sarmiento, 2005), adding:

- total thermal potential TTP – summing up drilling-proven and probable reserves as long as $P(R_{pv}) > P90$, i.e. part of energy that can be extracted under high certainty
- probable thermal potential $TTP_{(p)}$ – a part of thermal energy at a critical rate of risk, i.e. $P(TTP_{(p)}) = P50$ – see Table 2.

4. PROBABILISTIC MODEL SETUP

Prior creating probabilistic density functions entering Monte Carlo simulations (Table 3), defining criteria were summarized:

- geothermal waters between the western and southern part of LEB do not communicate = modeled / set-up separately
- reservoirs of different tectonic proveniences are considered a single, shallow (RES1) reservoir = modeled / set-up as a single unit
- reservoirs of the western part communicate together, i.e. production of one effects the other = modeled / set-up as a single unit.

4.1 Recovery factor

4.1.1 Effective (perspective) area

Considering (5) and (7), defining the effective area becomes crucial. By its description in 3.2, the national catalog model (Fričovský et al., 2024) uses anomaly hunting principles (Cumming, 2009), i.e. analysis of a surface heat flux or reservoir top temperature to address part of reservoir where production is expected to develop or increase. Recalling (Figure 1), there is no distinguished heat flux anomaly, rather it is trend-like distributed in both parts, so that the reservoir top temperature is used (Figure 2). A general catalog-proposed procedure using background geothermal models is:

- A_e_min = area where T_{res} at top > $P95(T_{res})$ or $P95(T_{res})$ coverage if reservoirs communicate together
- A_e_max = area where T_{res} at top > $P50(T_{res})$ for single or $P50(T_{res})$ for bottom reservoir unit if reservoirs communicate together
- A_e_ml = area where T_{res} at top > $P75(T_{res})$ for single or $P75(T_{res})$ for a top reservoir unit if reservoir communicate together

Table 2: Review of probabilistic McKelvey scheme concept

Class	Computation	Eq.
Geothermal resources	$RS_T = \frac{P10(H_T) - P10(H_0)}{t_{prod}}$	(8)
Geothermal reserves	$RE_T = \frac{P90(H_0) - P10(H_0)}{t_{prod}}$	(9)
Inferred reserves	$R_{inf} = \frac{P10(H_0) - Md(H_0)}{t_{prod}}$ if $Md(H_0) < X(H_0)$ $R_{inf} = \frac{P10(H_0) - X(H_0)}{t_{prod}}$ if $Md(H_0) > X(H_0)$	(10)
Probable reserves	$R_{pb} = \frac{Md(H_0) - P90(H_0)}{t_{prod}}$ if $Md(H_0) < X(H_0)$ $R_{pb} = \frac{X(H_0) - P90(H_0)}{t_{prod}}$ if $Md(H_0) > X(H_0)$	(11)
Proven reserves	proven by long-term production / sufficiently long and representative pumping tests	-
Total thermal potential	$TTP = \left[\frac{Md(H_0) - P90(H_0)}{t_{prod}}\right] + R_{pv} \rightarrow TTP = R_{pv} + R_{pb}$ if $Md(H_0) < X(H_0)$ $TTP = \left[\frac{X(H_0) - P90(H_0)}{t_{prod}}\right] + R_{pv} \rightarrow TTP = R_{pv} + R_{pb}$ if $Md(H_0) > X(H_0)$	(12)
Probable thermal potential	$TTP_{(p)} = \frac{P90(H_0)}{t_{prod}} + \left[\frac{P50(H_0) - P90(H_0)}{t_{prod}}\right] \rightarrow TTP_{(p)} = R_{pv(p)} + R_{pb} \rightarrow TTP_{(p)} = P50\frac{(H_0)}{t_{prod}}$	(13)

where "t_{prod}" represents a period the catalog is balanced for, i.e. 40 years (short-term) and 100 years (sustainable) production, and:

$$H_0 = H_T \, R0 \quad (14).$$

4.1.2 Total reservoir area

Unlike a previous case, the total reservoir area in R0 assessment is considered constant, i.e. given by tectonic margins of reservoir bodies or GWB definition. In case of two to more reservoir units in hydraulic communication, the total area is given as extension of the deeper reservoir, that is, due to tectonic evolution of the Western Carpathians, more preserved than the shallow.

4.1.3 Reservoir thickness and other parameters

Since LEB is divided into its S and W part, construction of PDFs is derived from individual histograms for a fist, and cumulative histograms for the later. This is same for inputs entering the (7), plus: a) PDFs are constructed individually for the perspective and total area, and; b) initial reservoir temperatures are taken from perspective area, including a set cooling at 10 %.

4.2 USGS volume method

4.2.1 Total reservoir area

Unlike for the R0, the A_t is set as dynamic variable. The general methodics for catalog gives its PDF set-up concept as:

- A_t_min = area where T_{res} at top > P95(T_{res}) or P95(T_{res}) coverage if reservoirs communicate; i.e. equal to Ae_min
- A_t_max = delineated margins of a single reservoir unit or the bottom reservoir unit if communicate
- A_t_ml = area where T_{res} at top > P50(T_{res}) for single or P50(T_{res}) for bottom reservoir unit if reservoirs communicate, i.e. A_e_max.

As such, this simulates availability of geothermal waters in all reservoir parts, but recalls also a predictable positioning of recent and future geothermal installations in its most perspective parts, plus allows simulation of reservoir temperature to indicate parts of geothermal energy close to boundary conditions (T_{ref}) or even beneath, thus not usable.

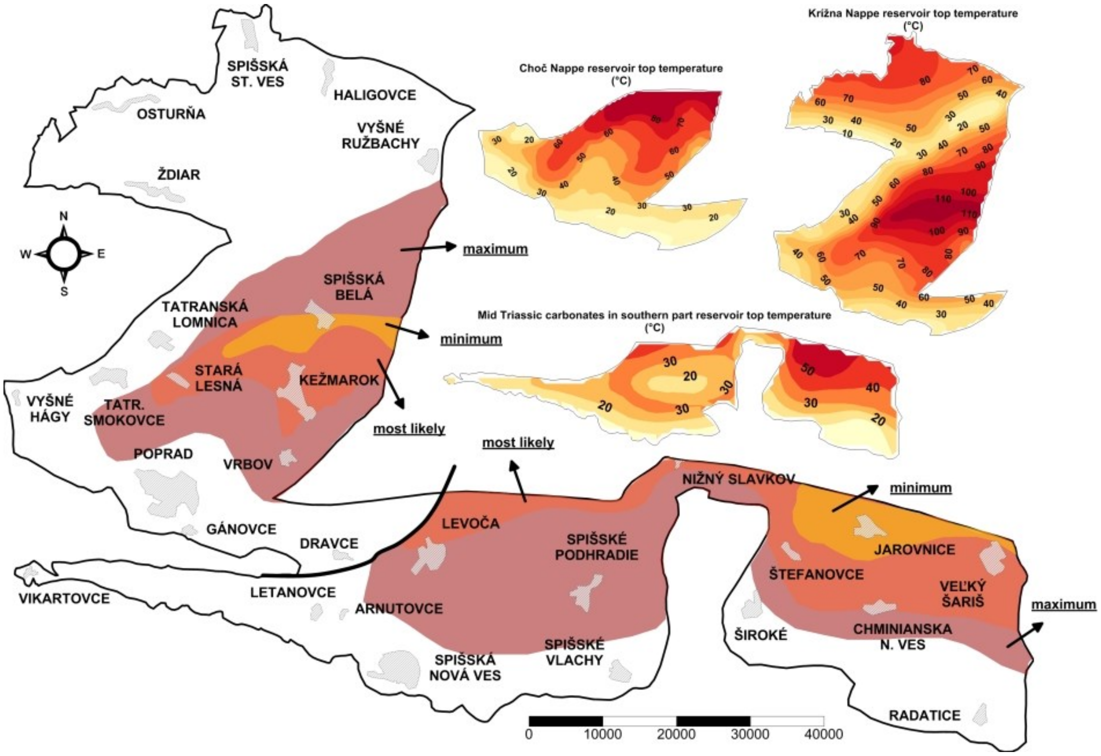

Figure 2: Definition of effective (perspective) area for R0 probabilistic assessment

Table 3: Input parameters and PDFs setup

parameter	unit	min	max	ave	med	ml	PDF function
			LEB – southern part				
A_t for R0	km^2	827.5	827.5	n/a	n/a	n/a	constant / fixed
A_t for USGS	km^2	47	827.5	n/a	n/a	197.4	Δ right
A_e	km^2	47	197.4	n/a	n/a	122	Δ center
Δz	m	25	1100	462	465	n/a	polymodal
Δz_e	m	250	1100	533	524	n/a	bimodal
$z_{(DP)}$	m	0	2730	1007	1004	n/a	bimodal
$z_{(DP)e}$	m	945	2730	1703	1695	n/a	normal
$T_{res,i}$	°C	15	80	32	31	n/a	bimodal
T_{res}	°C	9	80	30	29	n/a	bimodal
			LEB – western part				
A_t for R0	km^2	946	946	n/a	n/a	n/a	constant / fixed
A_t for USGS	km^2	27	946	n/a	n/a	402	Δ right
A_e	km^2	27	315	n/a	n/a	197	Δ left
Δz	m	50	1130	457	442	n/a	polymodal
Δz_e	m	120	1130	579	569	n/a	bimodal
$z_{(DP)}$	m	0	5200	n/a	n/a	1700	Δ right
$z_{(DP)e}$	m	1198	5200	n/a	n/a	2900	Δ right
$T_{res,i}$	°C	15	135	61	61	n/a	polymodal
T_{res}	°C	7	135	60	59	n/a	bimodal
			functions applied in both parts				
$\phi(z)$	-	n/a	n/a	n/a	n/a	n/a	function of $z_{(DP)}$
$\phi(z)_e$	-	n/a	n/a	n/a	n/a	n/a	function of $z_{(DP)e}$
ρ_w	kg.m^{-3}	n/a	n/a	n/a	n/a	n/a	function of T
c_w	J.kg^{-1}.K^{-1}	n/a	n/a	n/a	n/a	n/a	function of ρ_w
ρ_r	kg.m^{-3}	n/a	n/a	n/a	n/a	n/a	function of $\phi(z)$
c_r	J.kg^{-1}.K^{-1}	n/a	n/a	n/a	n/a	n/a	function of ρ_r
T_{cool}	°C	n/a	n/a	n/a	n/a	n/a	function of T
T_{ref}	°C	15	15	n/a	n/a	n/a	constant / fixed

where $z_{(DP)}$ is depth of definition point, i.e. derived depth of simulated reservoir according to its top and half the thickness

4.2.2 Reservoir temperature and other parameters

Generally, PDFs of many input parameters created for R0 assessment are used in Monte Carlo simulation of the USGS volume method (2), including parameters identified as functions. Unlike the R0 procedures, where initial reservoir temperature was provided by the model and then limited to the effective area, here the reservoir temperature PDF is constructed from the entire reservoir environment.

4.2.3 Recovery factor

The recovery factor is applied to yield recoverable energy H_0 (14) individually for W and S. Recalling typical lognormality in distribution of geological or geothermal parameters, the R0 is set as lognormal by default.

5. MODEL INTERPRETATION

The probabilistic model is constructed based on 10,000 Monte Carlo iterations both for the R0 and the USGS volume method per each part of the LEB. Since randomized picks from PDFs, the population was reclaimed to a logical interval, i.e. R0 ϵ < 0 ; 1 >.

5.1 Recovery factor model

The R0 was subjected to locally-defined simulation to address probability of energy recovery in both parts for two purposes: a) to adjust recoverability of geothermal energy at particular conditions; b) to correct for randomly used R0 constants in previous hydrogeothermal assessments in Slovakia, nor respecting geological, hydrogeological or geothermal specifications (i.e. R0 = 0.075 or 0.1).

For the entire probabilistic catalog, i.e. including the LEB, R0 adjusted for consecutive USGS volume method simulations is with a range R0 ϵ < P90(R0) ; P50(R0) > bearing respective moderate-low to low risk rate. The representative R0 for LEB is from the R0 ϵ < P90(R0) ; P50(R0) > as a median value, where the subpopulation is taken after grouping both simulated populations together.

5.1.1 Levoča Basin – southern part

A result of individual simulation of (7) with Table 3 data yields R0 ϵ < 0.005 ; 0.997 > interval of a clear lognormal distribution, with skewness ς = 2.293 (Figure 3), subjected to consecutive USGS volume method simulation. After extracting the given subpopulation, i.e. R0 ϵ < 0.042 ; 0.115 > defined above, the median value accounts Md(R0) = 0.077, much less than a typical R0 = 0.1 applied to regional hydrogeothermal assessments in Slovakia (e.g. Fendek et al., 2005). Apparently low R0 is, however, not only a picture of although highly permeable, but rather thin carbonates, but also their shallow burial depth in major part of HKB (Figure 2), and limited perspective area for a geothermal development, given by extensive recharge and transition zones prior final invasion into reservoir.

5.1.2 Levoča Basin – western part

Simulation of cumulated PDFs for the western part with 10,000 iterations gives a primary population of R0 ϵ < 0.002 ; 0.999 >, less skewed, i.e. ς = 1.225 (Figure 3), yet of obvious lognormality. Picking the desired interval range R0 ϵ < 0.048 ; 0.19 > gives a mean of R0 = 0.109. A point to remember is, that this is a result for connected reservoir environments, as model expects that production of one is of consequent impact on another, hence they communicate hydraulically. As for a complex reservoir environment, its deliverability appears among moderate in the Western Carpathians, as combination of both, good permeability, but also increased temperatures, even more for the bottom reservoir unit in the Krížna Nappe. In fact, the deliverability may partially be increased also by hydraulic communication between both reservoirs itself, supplying energy or reducing water withdrawal up to a limit of onset of depletion.

5.1.3 Levoča Basin – representative R0 value

This section describes determination of representative R0 for the entire Levoča Basin for a sake of national geothermal catalog purposes. Unlike in previous cases, merging simulated populations of R0 for both parts yields the primary population for the entire GWB, i.e. the primary interval is R0 ϵ < 0.002 ; 0.99 >. Although we only apply a simple arithmetic merging, taking the GWB as a single body, the subpopulation R0 ϵ < P90(R0) ; P50(R0) > is clearly affected by skewed R0 for HKB, i.e. R0 ϵ < 0.044 ; 0.145 >. Recalling that the representative R0 for the entire GWB is again a mean value of the subpopulation, it gives R0 = 0.088. When projected onto IDF curves, this value lies on P65(R0) for southern and P79(R0) for its western part, for both, yielding a acceptable rate of certainty. However, since this is only a value for general comparison between GWBs in a national catalog, we rather recommend to adhere to the locally specified recovery rates.

5.2 Probabilistic McKelvey scheme model

A probabilistic McKelvey (MCK) scheme model was constructed combining Monte Carlo simulation of the volumetric method (2) including lognormally-distributed correction with the R0 (7) with later balancing for a desired period of production (Table 2), i.e. the short-term (40 years) and long-tern or sustainable (100 years). The MCK for both, the southern and western part are then aggregated by a simple arithmetic summation, although this is usually applied if required correlation is sufficient.

5.2.1 Levoča Basin – southern part

According to Table 1 the proven reserves count R_{pv} = 1.6 MWt. Owing to skewness of distribution, i.e. $X(H_0/t_{prod})$ = 73 MWt > $Md(H_0/t_{prod})$ = 46 MWt, the probable reserves are assumed R_{pb} = 39 MWt as long as $P90(H_0/t_{prod})$ = 7 MWt for t_{prod} = 40 years. Thus, comparing (12) and (13), the total thermal potential for consideration equals rather the TTP = 40 MWt since $P(R_{pv}) > P90(H_0/t_{prod})$, scoring 55 % certainty on IDF. Even under prolonged period of production, the $R_{pv} < P90(H_0/t_{prod})$. So that with R_{pb} = 15 MWt as a product of $P90(H_0/t_{prod})$ = 3 MWt and $P50(H_0/t_{prod})$ = 18 MWt, the total thermal potential is again rather the TTP = 17 MWt.

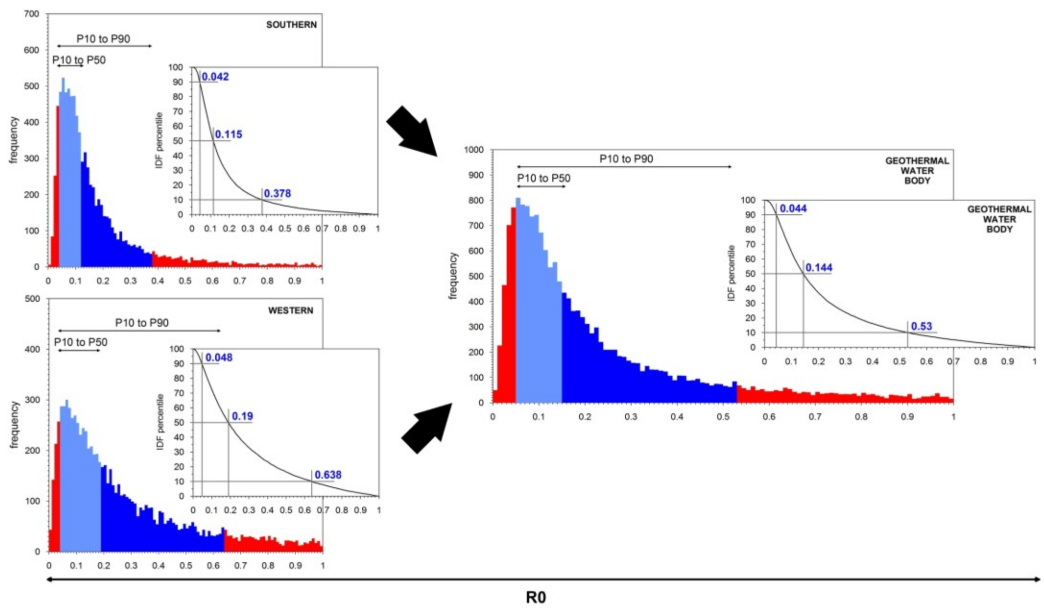

Figure 3: Recovery factor determination

5.2.2 Levoča Basin – western part

The western part is not only geothermally more active when compared to the previous (including a considerable effect of stratified reservoirs in hydraulic communication and greater reservoir temperatures not only in the bottom unit), but is among most explored (R_{pv} = 35 MWt / 436 MWt in Slovakia) and produced, with installed capacity $P_{th,inst}$ = 25 MWt / 229 MWt and a mean yearly thermal output of P_{th} = 7 MWt / 57 MWt (Fričovský et al., 2020b, 2022). Construction of a probabilistic model gains, then, a value.

When considering t_{prod} = 40 years, the balance is given as $P90(H_0/t_{prod})$ = 21 MWt, $Md(H_0/t_{prod})$ = 141 MWt, $X(H_0/t_{prod})$ = 237 MWt and $P10(H_0/t_{prod})$ = 565 MWt. Probable reserves thus represent R_{pb} = 120 MWt. Since $R_{pv} > P90(H_0/t_{prod})$, the assumed total thermal potential is given by $TTP_{(p)}$ = 141 MWt, otherwise $P(TTP) < P50(H_0/t_{prod})$ expressing less confidence and greater risk consequently. This is more for what we recall a sustainable production period, i.e. t_{prod} = 100 years, as $P90(H_0/t_{prod})$ = 8 MWt, $Md(H_0/t_{prod})$ = 57 MWt, $X(H_0/t_{prod})$ = 95 MWt and $P10(H_0/t_{prod})$ = 226 MWt. With probable reserves (11) R_{pb} = 48 MWt, and with the $R_{pv} > P90(H_0/t_{prod})$ kept valid, the total thermal potential is given rather by probabilistic assessment (13), i.e. as $TTP_{(p)}$ = 57 MWt. If hunting for a total thermal potential (12), i.e. TTP = 84 MWt, the risk rate would rapidly increase since $P(TTP) \approx P37(H_0/t_{prod})$ projected onto IDF curve.

5.2.3 Geothermal water body catalog

The aggregated geothermal potential catalog for both, the short-term and long-term period of production is presented in Table 4. For a sake of the catalog itself, the potential to explore and tap, not considering any sustainability criteria is, thus 73 MWt for t_{prod} = 100 years and 181 MWt for t_{prod} = 40 years. The western part of the LEB is by far of greater perspektivity with 77 – 78 % contribution.

5.3 Sustainability and perspectivity of geothermal potential

Recent rising concern on energy independency possess a risk of uncontrolled exploration, drilling, and production of geothermal energy in Slovakia, since the resource is, unfortunately, considered renewable and sustainable lacking any discussion on its limits. Since first study of sustainable potential (Fričovský et al., 2020a) on a national scale set several limits based on unguided and uncalibrated simulation, the national catalog targets this issue admittedly. We recall the presented method in the pilot model that is a modification of original reserve capacity ratio proposed by Bjarnadottir (2010). Based on therein mentioned methodology, both authors considered the sustainable capacity as 50 % of probable reserves, yet substituted as (probable) total thermal potential corresponding to amount of energy at a given certainty level – be that marked $Pth_{(S)}$. This gives $P_{th(S)}$ = 8 MWt / 20 MWt for southern and $P_{th(S)}$ = 28 MWt / 71 MWt for the western part respectively for 100/40 years.

Perspectivity analysis is based on finding an energy potential that is available for further development under recent mean thermal output of online wells – $P_{th(D)}$ (15) or under installed capacity, i.e. the maximum energy withdrawal wells are able to provide – $P_{th(D^*)}$ (16):

$$P_{th(D)} = P_{th,(S)} - P_{th} = 0,5.TTP_{(P)} - P_{th,ref} = 0,5.\left[P50\left(\frac{H_0}{t_{prod}}\right)\right] - \left[Q\,.c_{wh}.\left(T_{wh} - T_{ref}\right)\right] \quad (15)$$

$$P_{th(D^*)} = P_{th,(S)} - P_{th,inst} = 0,5.TTP_{(P)} - P_{th,inst} = 0,5.\left[P50\left(\frac{H_0}{t_{prod}}\right)\right] - \left[Q_{pv}.c_{wh}.\left(T_{wh} - T_{ref}\right)\right] \quad (16).$$

Table 4: Probabilistic model of a McKelvey scheme (in MWt)

McKelvey scheme	Symbol	western part (40 / 100 years)	southern part (40 / 100 years)	Levoča Basin, S and W part – cumulative (40 / 100 years)
Total geothermal resources	RS_T	5,850 / 2,340	1,805 / 719	7,655
Total geothermal reserves	RE_T	597 / 253	169 / 68	748
Inferred (possible) reserves	R_{inf}	424 / 170	129 / 51	553
Probable reserves	R_{pb}	120 / 48	39 / 16	156
Proven reserves	R_{pv}	35.3	1.6	37
Total thermal potential	TTP	155 / 84	40 / 17	181 / 73
Total thermal potential (probabilistic)	$TTP_{(p)}$	141 / 57	46 / 18	
Sustainable thermal capacity	$P_{th(S)}$	71 / 28	20 / 8	91 / 36
Recovery factor (interval / representative)	R0	0.042 – 0.115 / 0.077	0.048 – 0.19 / 0.109	0.044 – 0.144 / 0.088

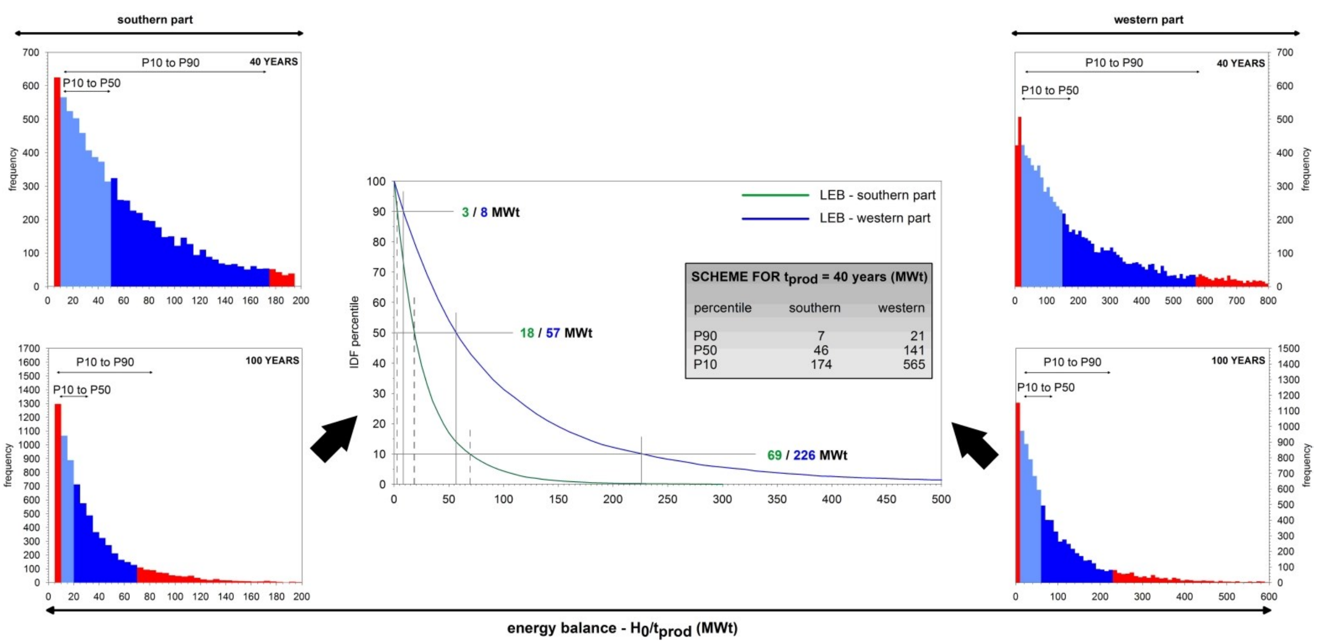

Figure 4: USGS volume method – energy base simulation

We consider botch approaches an optimistic (15) and pessimistic (16) developable potential assessment, since the first is a function of a current thermal output that is typically much less than the installed in the latter case. There is no geothermal water production in the southern part of the basin (e.g. Fričovský et al., 2022). Consecutively, both developable potentials equal then the sustainable capacity, so that $P_{th(D)} = P_{th(D^*)} = P_{th(S)}$ regardless the time scale. For the western part, P_{th} = 7 MWt and $P_{th,inst}$ = 25 MWt (Fričovský et al., 2020), i.e. $P_{th(D)}$ = 64/21 MWt and $P_{th(D^*)}$ = 46/3 MWt for 40/100 years-long production. Cumulatively, there is a potential in between 65 – 80 MWt for t_{prod} = 40 years and 12 – 26 MWt for t_{prod} = 100 years for the entire GWB. Comparing actual production in both, the short- or long-term horizon, the entire LEB is clearly perspective although we would recommend to focus future prospection rather to regions N from the Žiar – Vyšné Ružbachy line in the western, or to the region SE from the Nižný Slavkov – Radatice line, including revitalization of existing deep geothermal boreholes in the Arnutovce and Letanovce area.

6. CONCLUSIONS AND REMARKS

This paper presents principles and methodology of a probabilistic model construction addressing total and sustainable geothermal potential and the McKelvey scheme of geothermal water bodies in Slovakia recently in progress and scheduled for introduction by 2024. Combination of guided approach in setting PDFs with a conceptual approach in performing simulations and result aggregation is typical for all geothermal water bodies where at least two reservoir units are hydraulically connected and the water body consists of at least two parts that with different geothermal water flow regimes, while reservoirs are considered open in terms of natural recharge. Analogous situation is e.g. with the Žilina Basin / Ilava Basin in northern and the Bátovce – Rykinčice depression in central part of the country. Moreover for a sake of the catalog itself, definition of a "representative" or what is considered most likely recovery factor is presented above. Geothermal potential is assessed both for short-term (40 years) and long-term (100 years) production.

The Levoča Basin W and S part is among largest GWBs in Slovakia, comprising two reservoir units within Mid Triassic carbonates of the Choč Nappe and the Krížna Nappe separated by Late Triassic – Mid Cretaceous succession of pelitic / organogene carbonates, typically in basin-constriction and lateral-leaking arrangement along open fault systems in the western part. To the south, Mid Triassic carbonates of different tectonic provenience form what is generalized a single reservoir unit beneath the Paleogene siliciclastic basin fill since they laterally alternate atop a crystalline bedrock.

In the western part, the recovery factor is likely to vary between R0 ϵ < 0.048 ; 0.19 > (a subpopulation median value is R0 = 0.109). Since already proven geothermal reserves count R_{pv} = 35 MWt and the probable reserves are assessed for R_{pb} = 120 / 48 MWt for t_{prod} = 40 / 100 years respectively, the overall potential should rather be addressed as following a probabilistic model (13), i.e. $TTP_{(p)}$ = 141 / 57 MWt as sum of P90(H_0/t_{prod}) + R_{pb}, otherwise P(TTP = R_{pb} + R_{pv}) < P50(H_0/t_{prod}), thus of increased risk, both on a model uncertainty and a reservoir capacity scale. Applying modification of simple balance-based resource capacity approach, i.e. the critical sustainable capacity is up to a half of a thermal potential ensuring greater than 50 % probability rate according to a model, the $P_{th(S)}$ = 71 / 28 MWt on a short- and long- term scale. Concerning actual on-site thermal output (7 MWt) and installed capacity (25 MWt), the potential to develop under sustainable conditions is still $P_{th(D)}$ = 64 / 21 MWt to $P_{th(D^*)}$ = 45 / 3 MWt. Since there is no actual geothermal production in the southern part of the basin, both, the $P_{th(D)}$ and $P_{th(D^*)}$ are equal to assessed sustainable potential, i.e. 20 / 8 MWt for considered balance periods, as long as TTP = 40 / 16 MWt under the R0 ϵ < 0.042 ; 0.115 >. Cumulatively, the total thermal potential of the LEB is 181 MWt for short- and 73 MWt for a long- term production, turning it among most perspective in Slovakia.

Presented model bears, however, all uncertainties regarding probabilistic models applying the Monte Carlo simulation to both, the R0 assessment or booking the geothermal reserves. Although we used guided approach and conceptual modeling in setting PDFs, the model remains sensitive to future changes in input data, likely to change upon prospection north from the Tatranská Lomnica – Vyšné Ružbachy line (W part) or east from the Nižný Slavkov – Široké line (S part). Use of a simple arithmetic aggregation may then be another issue, while both parts of the basin can still be considered correlative, at least in terms of geothermal field patterns and geology. While there is a new borehole drilled in town of Kežmarok for geothermal district heating, the model assumes no significant risk for reservoir geothermal capacity, as long as concerns of interference with neighboring sites (such is Vrbov) are refuted. However, construction of geothermal (sustainable) potential catalog becomes a critical factor under expected triggering of geothermal prospection and production to avoid reservoir depletion in all geothermal water bodies in Slovakia.

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