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Estimating The Total Thermal, Sustainable And Developable Geothermal Potential For The Liptov Basin Geothermal Field, Northern Slovakia: Combining Probabilistic Resource Assessment Approach With Real Production Data

Branislav Fričovský[1], Ladislav Vizi[2] , Klement Fordinál[3] , Radovan Černák[1] , Katarína Benková[1] , Daniel Marcin[1] ,
Marta Kalabová[1] , Jana Fričovská[4]

1 – Dept. of Hydrogeology and Geothermal energy, Dionýz Štúr state institute of geology, Mlynská dolina 1, 817 04, Bratislava, Slovakia

2 – Dept. of 3D/4D geological modeling, Dionýz Štúr state institute of geology, Jesenského 8, 040 01, Košice, Slovakia

3 – Dept. of Younger geological units, Dionýz Štúr state institute of geology, Mlynská dolina 1, 817 04, Bratislava, Slovakia

4 – Dept. of Environmental geochemistry, Dionýz Štúr state institute of geology, Mlynská dolina 1, 817 04, Bratislava, Slovakia

branislav.fricovsky@geology.sk, ladislav.vizi@geology.sk

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ABSTRACT

The Liptov Basin is among most developed geothermal water bodies in Slovakia, with 5 active sites producing low enthalpy geothermal waters from 9 active wells. Though the most recent in Liptovský Mikuláš has not been evaluated yet, the proven reserves count 32 MWt with a respective deliverability of 288 kg.s^{-1}. For both, the regionalized recovery factor and definition of a McKelvey scheme, the Monte Carlo simulation was applied to the effective reservoir volume and the USGS volume method respectively. The regionalized recovery factor yields R0 = 0,021 – 0,125 with R0 = 0,061 as a mean to the P50(R0) – P90(R0) interval. Following a concept of sustainable reservoir production, as presented by prof. Axelsson and his team since 2001, the McKelvey scheme was constructed for a period of 100 years and 40 years, terming the sustainable and amortized life-time interval. For the first case, the total (probabilistic) thermal potential equal to P50(E0) is assessed for $TTP_{(p)}$ = 66 MWt. Applying the reserve capacity ratio approach, setting the r_{cap} = 0,5 as critical sustainable reservoir capacity rate, this counts $P_{th(S)}$ = 33 MWt. Projecting the cyclic production regime, with a thermal output in a range of $P_{th,ref}$ = 6,7 – 13,6 MWt within 2011 – 2022 period, and a normalized mean of $P_{th,ref*}$ = 10 MWt, the developable potential is assessed for $P_{th(D)}$ = 20 MWth, as cumulative for both reservoir units, or $P_{th(D)}$ = 69 MWt for 40 years of production respectively. This accounts the Liptov Basin as one of most prospective for further development, still under considerably sustainable conditions.

1. INTRODUCTION

A first catalog of geothermal potential of 26 geothermally prospective areas in Slovakia was published in mid 90s (Franko et al., 1995), accounting a total thermal potential of 5,538 MWt; modified later for 6,653 MWt (Fendek – Fendeková, 2010; Fendek et al., 2011) and 6,582 MWt (Marcin et al., 2014), yet multiple drawbacks. Some of these include: inconsistency in application of assessment methods, mixing different production time scales, use of constants for the recovery factor setting, or substitution of discrete values given by a certain (yet questionable in conceptual representativeness to the reservoir body) number of wells, although addressing the reservoir environment in general (e.g. Fričovský et al., 2020a,b, 2023a). Ongoing upsurge of interest in geothermal energy exploration and production for both, the heat and power, shifts a period of almost stagnation in between 2005 – 2020, now triggered through multiple EU funds and programs, such is the Just Transition Fund by the Ministry of Investment, Regional Development and Informatics of the Slovak Republic, or calls recently prepared by the Ministry of Economy of the Slovak Republic or Slovak Innovation and Energy Agency, to be summoned in 2025. To face risks of uncontrolled installations, a new catalog of geothermal resources is recently introduced (Fričovský et al., 2024), based on application of conditioned Monte Carlo simulations for regionalized recovery factor and thermal potential assessment, guided through geological and geothermal models for 31 identified geothermal water bodies (e.g. Fričovský et al., 2023b). A question of sustainability is addressed using a reserve capacity ratio approach to the (probabilistic) total thermal potential assessment, while developable sustainable potential – $P_{th(D)}$ is assumed normalizing a mean of production history, taken 2011 – 2022. This makes the $P_{th(D)}$ a variable, reflecting production changes with updating data and progress in development.

The Liptov Basin is located in northern part of Slovakia, and was recognized as prospective geothermal area (geothermal water body - GWB) since early 70s, with total area of 609.9 km^2. Geothermal waters, being the reservoir / borehole mobile phase, have already been proven by 23 wells, out of which 9 are recently operated for balneotherapy (Lúčky), recreation cascaded with space heating (Bešeňová, Liptovský Trnovec, Liptovský Ján, Kalameny), and heat supply to industrial fur-processing (Liptovský Mikuláš), as the latest increment as of 2023/2024. However, as described in following section, most of wells intercepted the shallow reservoir unit (the Choč Nappe), with only few installations within elevated morphostructures, making geothermal conditions in the deep reservoir unit (the Krížna Nappe) still a robust uncertainty, whether in terms of reservoir geometry, geothermics, resource availability, hydraulics etc.

2. LIPTOV BASIN – OVERVIEW

The Liptov Basin forms a typical intramountain depression of the Western Carpathians, owing to tectonics-driven Neogene relief inversion during formation of the Tatry Mts. As such, it is in tectonic contact with surrounding mountains, forming hydrogeological massifs of the Tatry Mts. and the Chočské vrchy Mts. (N), Nízke Tatry Mts. (S), Velka Fatra Mts. (W) and the Poprad Basin (E).

2.1 Geological settings

A total delineated area of the Liptov Basin is roughly 610 km^2. For a sake of a following guided probabilistic modelling, the settings were generalized into hydrogeologically-hydrogeothermally uniform complexes (Figure 1) characterized below.

2.1.1 Top insulator – IZO1 – the Sub-tatric group (Inner Western Carpathian Paleogene); Mid Paleocene - Oligocene

The IWCP represents a complete marine succession of basal coarse-grained siliciclastics and carbonate conglomerates / breccia (transgression) of the Borové Fm., followed by claystones-dominated (flood progression, high stand) Huty Fm., flysch-type Zuberec Fm. (high-stand, flood termination) and relics of sandstones-dominated Biely Potok Fm. (regression) atop (e.g. Gross et al., 1980; Fendek et al., 2017). A basin model (Figure 1) defines the overall thickness in a range of $\Delta z_{(IZO1)}$ = 0 – 2 210 m, with a mean of $\Delta z_{(IZO1)}$ = 450 m and an average of $\Delta z_{(IZO1)}$ = 595 m (Fričovský et al., 2024).

2.1.2 Shallow reservoir – RES1 – the Choč Nappe; Mid Triassic – Late Triassic

The reservoir links with extension of Mid to Late Triassic carbonates, where dolomites prevail over limestones, including transient varieties (Remšík et al., 1998). Owing to a pre-Tertiary paleokarst period (Franko – Bodiš, 1989; Činčura – Köhler, 1995; Franko – Melioris, 1999) and a domain's tectonic evolution, superposition of the Choč Nappe after a final setting triggered both, its weathering and reduction. Thus, unlike to deep / bottom reservoir, the RES1 consists of a few, insulated blocks, with the main dominant in western and southern part of the basin (Remšík et al., 1998). At modeled (Figure 1) thickness of $\Delta z(_{IRES1})$ = 30 – 1,030 m, with a mean of $\Delta z_{(RES1)}$ = 720 m the reservoir base is expected to extend in z = 80 – 2,900 (Fričovský et al., 2024).

2.1.3 Bottom insulator – IZO2 – the Krížna Nappe; Late Triassic – Mid Cretaceous

The complex includes variable sequences of organogene to organodetritic limestones, carbonate sandstones, radiolarites, nodular limestones, clayey carbonates and (calcareous) marlstones, terminated rarely with a flysch-type formations (Remšík et al., 1998). Obviously, the complex plays a significant barrier to a free-flow between both reservoir bodies, available only along open fault systems (Fričovský et al., 2015; Fendek et al., 2017), reaching overall thickness of $\Delta z_{(IZO2)}$ = 20 – 1,900 m (Fričovský et al., 2024).

2.1.4 Deep reservoir – RES2 – the Krížna Nappe; Mid Triassic

Unlike the shallow reservoir, it is expected (Remšík et al., 2005; Fendek – Remšík, 2005; Fendek et al., 2017) that the unit forms a solid body extended through the basin. The complex is formed by carbonates, where likely limestones or transient varieties prevail over dolomites (Remšík et al., 1998). A geological model (Fričovský et al., 2024) identifies the deep reservoir with a top dept at z = 40 – 3,600 m, a bottom in z = 300 – 4,000 m, and a thickness range of of $\Delta z_{(IRES2)}$ = 150 - 860 m, with a mean of $\Delta z_{(RES2)}$ = 480 m.

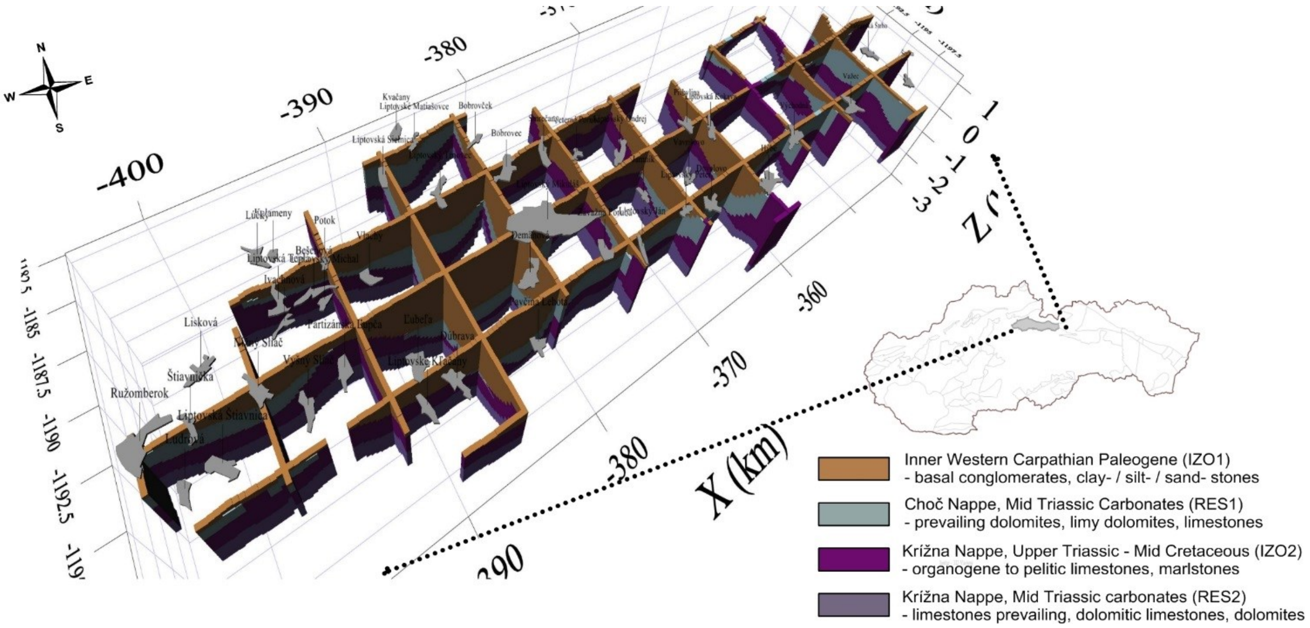

Figure 1: Liptov Basin – vertical structure based on function of complexes in conceptual model

2.1.5 Bedrock

The model (Figure 1) assumes the deep reservoir is insulated at its base. According to a typical profile (e.g. Remšík et al., 1998). Beneath, only FGL-1 well Pavčina Lehota intercepted the Tatricum Envelope Unit, reduced to Early Triassic quartzites and shales, though the profile could originally correspond to a profile of the Krížna Nappe. Beneath, Tatricum Crystalline Unit consists of magmatic and metamorphic complexes.

2.2 Hydrogeothermics

2.2.1 Heat flow distribution

A surface heat flow density varies $q_S = 49 – 76$ mW.m^{-2}, with a mean of q_S – 60 mW.m^{-2} (Fendek – Remšík, 2005), classified as moderate (Franko et al., 1995) according to the surface heat flow distribution in Slovakia ($q_S = 35 – 125$ mW.m^{-2}, a mean $q_S = 70$ mW.m^{-2} ± 14), Local highs (Figure 2) in the western part that correspond to the Bešeňová elevation hydrogeothermal structure, interpreted a major discharge zone (Remšík et al., 1998) with intense basin constriction flows and vertical evasion between RES2 and RES1 (Fričovský et al., 2015, 2016). Since the same patterns are generally modeled for the entire profile, a system is generally ranked conduction-dominated.

2.2.2 Steady-state reservoir temperatures

The yearly mean ambient temperature for the Liptov Basin is $T_S = 6$ °C. For the steady-state conditions, the temperature at a top of the RES1 varies $T_{(RES1)} = 6 – 67$ °C with a mean of $T_{(RES1)} = 27$ °C, increased to $T_{(RES1)} = 7 – 83$ °C with a mean of $T_{(RES1)} = 30$ °C at z = 80 – 2,900 m. Because of conduction-dominated environment, the increase in temperature for the RES2 is fairly proportional to its geometry and depth. At a top, models (Fričovský et al., 2024) yield a range of $T_{(RES1)} = 8$ - 96 °C with a mean of $T_{(RES1)} = 46$ °C at z = 40 – 3,600 m and $T_{(RES1)} = 15$ - 106 °C with a mean of $T_{(RES1)} = 57$ °C at z = 300 – 4,000 m (Figure 2). Generally, local highs for both, the RES1 and RES2 correspond to the depressed pre-Cenozoic morphostructures, not related to the heat flux patterns.

2.2.3 Hydrogeochemistry

Geothermal waters in the Liptov Basin are typically of carbonatogene (Ca-Mg-HCO_3), transient (Ca-Mg-HCO_3-SO_4, Ca-Mg-SO_4-HCO_3) and sulphatogene (Ca-(Mg)-SO_4) type, with SO_4 compound typical for RES2 due to a contact with Late Triassic evaporates within the Karpatian Keuper Fm., that is among crucial indicators of vertical communication between both reservoir bodies, when occurring in samples from RES1 (Fendek – Remšík, 2005; Remšík et al., 2005). Geothermal waters sampled at ZGL-2/A well are most likely of polygenetic origin, expressing Ca-Na-Mg-Mg-HCO_3-SO_4 type (Remšík et al., 1998). In general, hydrogeothermal systems are rather open to semi-open (Remšík et al., 2005), recharged in major from south – for the central and western part, and rather from north, when considering structures in the eastern part of the basin (e.g. Fričovský et al., 2015, 2016; Fendek et al., 2017).

2.2.4 Play-type classification

Applying the play-type classification (e.g. Moeck, 2014), the basin is the CD2b type, i.e. conduction-dominated, adjacent orogenic belt type, in intramountain depression tectonic settings, and hydrothermal geologic habitat, where distribution of lithofacies prevails over tectonics. According to a national scheme, the system is then ranked CD2ba, i.e. intramountain depressions (Fričovský et al., 2023a,b).

3. HYDROGEOTHERMAL POTENTIAL – A GUIDED PROBABILISTIC APPROACH

One of crucial triggers in construction of a probabilistic catalog of national geothermal potential (Fričovský et al., 2020a, 2024) is unification of assessment methods and introduction of guided / conditioned approach to Monte Carlo simulations according to respective conceptual models. This, mainly, includes, e.g.:

- reading geological, hydraulic and geothermal model data in setting simulation ranges and distribution functions
- adjusting R0 assessment methods according to prevailing reservoir hydrogeological regime; i.e. use of effective volume method (e.g. Sanyal – Butler, 2005) for rather open systems; production efficiency method (e.g. Ungemach et al., 2005) for closed-systems or for systems where reinjection is mandatory according to a national legislation
- post-processing for R0 model construction and McKelvey scheme construction guided according to a conceptual model; i.e. use of a single simulation (10,000 iterations) for layered and single-reservoir systems, use of unique simulation on cumulative histograms for multiple reservoir bodies when hydraulically or heat-and-mass flow connected, or use of numerous simulations when two or more reservoirs are stratified / not connected
- setting area as constant (A_t = const.) for systems with expected / mandatory reinjection, or as variable for open systems to simulate effect of potential reduction through recharge and downflow transition zones, obviously experiencing cooling at peripheries
- every GWB is evaluated for a sustainable (100 years) and short-term (40 years) period of production
- priorizing effective / prospective area definition: using a concept of anomaly hunting (Cumming, 2009) as follows: surface heat flow anomalies → reservoir top heat flow anomalies → reservoir top temperature anomalies → reservoir top temperature percentile distribution

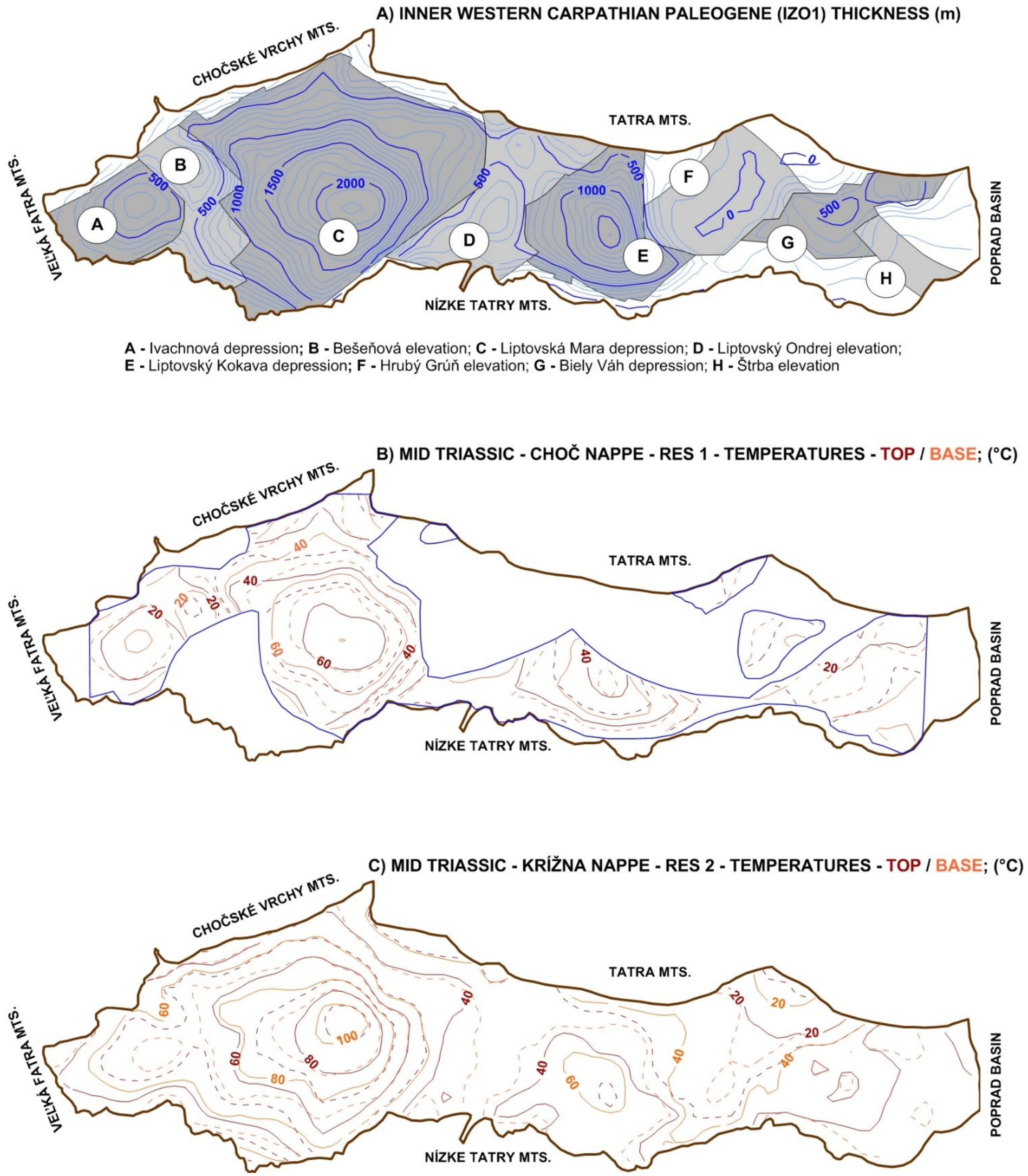

Figure 2: Liptov Basin – distribution of pre-Cenozoic basement and reservoir temperatures

Following the concept of national geothermal resources catalog construction, the following applies to the Liptov Basin model:

- reservoir bodies RES1 and RES2 are considered rather connected, with multiple vertical evasions, lateral leakages, downflows (Remšík et al., 2005; Fričovský et al., 2016; Fendek et al., 2017), thus:
    - recovery factor is guided by cumulative histograms according to data from both complexes
    - one R0 model applies to both reservoir bodies
- McKelvey scheme and geothermal potential assessment is given for the whole systems, expecting changes in one of complexes causes changes in another, i.e. the potential is not considered cumulative

Model inputs are presented in Table 1.

3.1 Recovery factor – R0

3.1.1 Effective volume method

The recovery factor accounts portion of energy stored in reservoir, available for extraction at current or expected conditions (e.g. Ungemach et al., 2005; Garg – Combs, 2011), including technical as well (e.g. Grant, 2000, 2018; Williams, 2004; González-Garcia et al., 2021). For the effective reservoir volume method, technical conditions are given by a tolerated rate of reservoir cooling (e.g. Fox et al., 2013; Aghahosseini – Breyer, 2020) here for 10 % compared to the initial state. The method accounts for a proportion of effective / prospective area delineated according local heat or thermal anomalies – V_e over the system extension – V_t. Since reservoir cooling of open hydrogeothermal systems may be triggered by cold water downflow from recharge/transition zones or invasion from shallow reservoir positions, if overproduced, recoverability becomes a function of initial reservoir gradient to reference conditions compared to a rate of tolerated cooling $T_{res,a}$, i.e. 10 % drop (1)

$$R0 = \frac{A_e \, \Delta z_e \, \gamma_{t,e}}{A_t \, \Delta z_t \, \gamma_t} \cdot \frac{T_{res,i} - T_{res,a}}{T_{res,i} - T_{ref}} \tag{1}$$

where γ_t is the volumetric heat capacity as function of temperature at initial state.

Table 1: Liptov Basin – input parameters and PDFs setup

parameter	unit	min	max	ave	med	ml	PDF function
functions given by geological and geothermal models							
A_t for R0	km^2	610	610	n/a	n/a	n/a	constant / fixed
A_t for USGS V.M.	km^2	333	610	n/a	n/a	540	Δ left
A_e	km^2	19	174	n/a	n/a	130	Δ right
Δz	m	36	1132	n/a	n/a	986	Δ left
Δz_e	m	36	1031	n/a	n/a	795	Δ left
$z_{(DP)}$	m	53	3890	1524	1539	n/a	normal
$z_{(DP)e}$	m	71	3890	1719	1768	n/a	normal
$T_{res,i}$	°C	15	106	n/a	n/a	48	Δ right
T_{res}	°C	6	106	n/a	n/a	47	Δ right
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

3.1.2 Recovery factor model

According to the catalog concept (described at the beginning of this section), the recovery factor is modeled as joint for both, the shallow and deep reservoir, as hydraulic or thermal connectivity of both complexes applies to recoverability of accumulated energy available for production, and so do reservoir limits. According to a workflow applied for every geothermal water body, irrespective of its conceptual setup, the procedure in constructing the dynamic R0 model is as follows:

1) primary population is given by 10,000 iterations of setup intervals and parametric distribution functions (Table 1), i.e. for the Liptov Basin the interval varies R0 = 0.001 – 0.997, with a mean of R0 = 0.21 a median of R0 = 0.125 (Figure 3)

2) the primary population is then reduced to a subpopulation of P90(R0) – P50(R0) interval according to IDF constructed on primary population, to account for rather locally respective values, i.e. R0 = 0.021 – 0.122, with the count of N = 4,411 samples (Figure 3)

3) according to a normality test, the subpopulation of a given count is rather of lognormal distribution, i.e. after transposition, the X(R0) = -2.832 and the σ(R0) = 0.495

4) the R0 is then simulated again, with N = 10,000 iterations, to yield a representative population according to its lognormal distribution, and then re-transponed, so that a final R0 model yields R0 = 0.021 – 0.125, with a mean of R0 = 0.061

5) the recovery factor model is then applied simultaneously to the USGS volume method (subsection 3.2) to address the recoverable heat in place.

A representative R0 = 0.021 – 0.125 assumes the rate of energy available in reservoir at a rate of 2 – 13 %. Because of intense basin dissection into several depressed and elevated pre-Cenozoic morphostructures corresponding to extension of hydrogeothermal systems, such interval indicates limits given by burial depths, permeability drops with depth and ceasing of the karstification related weathered zone, as well as with energy consumed in regional flow patterns and reservoir dynamics.

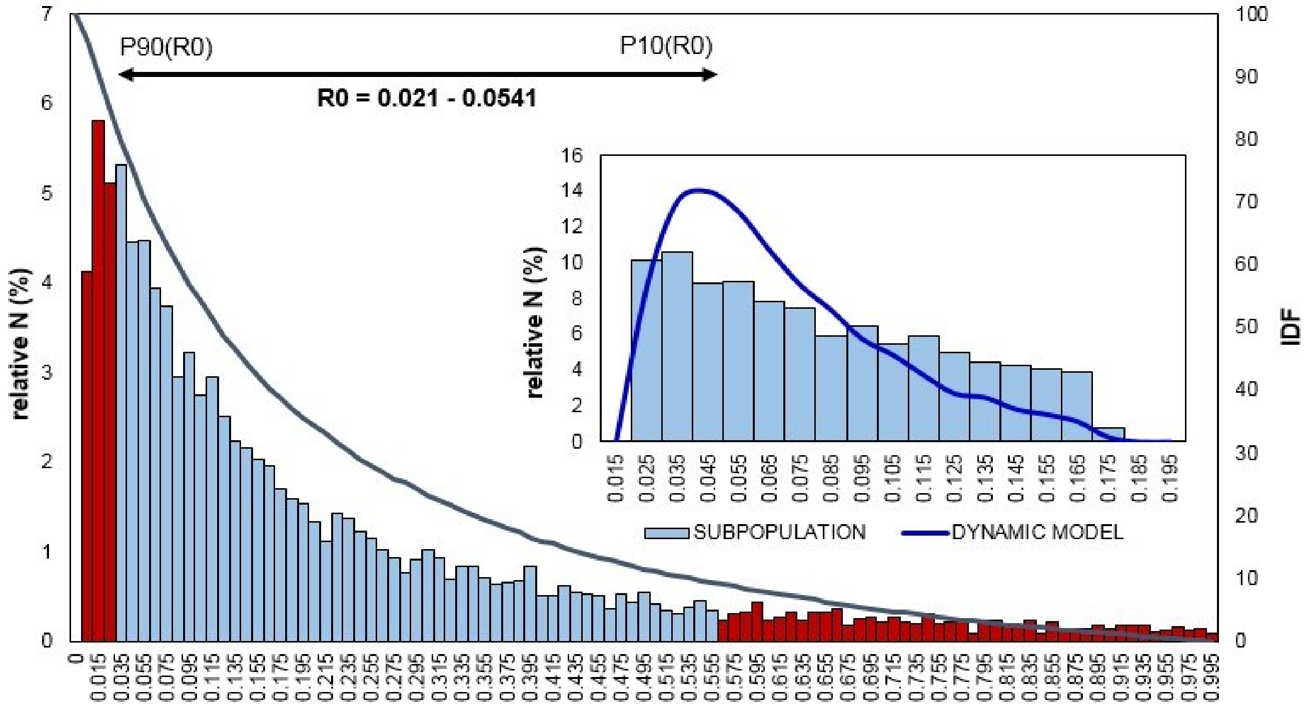

Figure 3: Liptov Basin – recovery factor analysis – primary population, subpopulation and dynamic R0 model

3.2 Geothermal potential

3.2.1 USGS volume method

Out of numerous approaches to assess geothermal potential, such is the USGS heat-in-place method, power density method, magmatic heat budget method etc. (Ciriaco et al., 2020), the USGS volume method (Muffler – Cataldi, 1978; Garg – Combs, 2015) was selected according to unifying national catalog concept and applied to every GWB in Slovakia. The relation (2) accounts for a rock / matric “r” or water “w” component, and a temperature difference between reservoir T_{res} and ambient T_{ref} conditions for open hydrogeothermal systems or reinjection temperature Tinj, where this is mandatory according to a national legislation.

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

3.2.2 Total and recoverable heat stored model

According to unifying guides in the catalog construction, the procedure in probabilistic model is as follows:

1) the total heat stored H_T is modeled through Monte Carlo simulation applied to (2) for N = 10,000 iterations using setup intervals and parametric distribution functions (Table 1), still yielding a unique population for both reservoir bodies, as these are classified as connected according to the Liptov Basin conceptual model. According to the model, the H_T = 31 – 28,050 PJ, and HT = 4,300 PJ as average

2) the H_T is simultaneously corrected by recovery factor according to (3) to yield the recoverable heat H_0, to account for available energy stored in both geothermal reservoirs, using a lognormal R0 distribution or representative population. At a given H_T and recovery factor, the recoverable heat is simulated for $H_0 = 1.1 – 3.305$ PJ, with an average of $H_0 = 297$ PJ and a median of $H_0 = 205$ PJ. There is, however, a considerable skew of the N = 10,000 population, i.e. Y(H) = 2.62. Besides the effect of R0 distribution on the total skew, this is also given by basin dissection and RES1 mass reduction into several blocks, when compared to the RES

$$H_0 = H_T \, . R_0 \tag{3}$$

3) setting the At as dynamic variable, with minimum equal to minimum effective area, most likely value according to a maximum effective area and maximum as high as the total GWB area (Table 1), the energy density, i.e. the recoverable heat over the area, is assumed to generally vary between $H_0/A_t = 0.002 – 6$ $GJ.m^{-2}$ at a mean of $H_0/A_t = 0.6$ $GJ.m^{-2}$.

3.2.3 Geothermal resources and reserves – McKelvey scheme

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 a class of (probabilistic) total thermal potential according to $TTP_{(p)} = P50(E_0)$, i.e. the energy balance / likely thermal output at the critical risk rate of success. The procedure is, however, straightforward:

1) balancing the recoverable heat in place H0 to the desired production period, the sustainable $t_{prod} = 100$ years (Axelsson et al., 2001), and the short-term $t_{prod} = 40$ years according to (4); that yields $E_0 = 10 – 280$ MWt for tprod = 100 years at 90 % confidence interval or $E_0 = 26 – 694$ MWt for $t_{prod} = 40$ years (Figure 4):

$$E_0 = \frac{H_0}{t_{prod}} \tag{4}$$

2) substitution of IDF percentiles into (5) to (9), reflecting the booking principles (Sanyal – Sarmiento, 2005)

According to borehole data (Table 3), the total proven reserves count $R_{pv} = 32$ MWt at respective deliverability of $Q_{pv} = 288$ $kg.s^{-1}$. In 2023, a new installation in the Liptovský Mikuláš was finished, yet undergoing a test phase and production data are not available. Considering a sustainable production period, i.e. $t_{prod} = 100$ years, probable reserves are assessed for $R_{pb} = 49$ MWt at $P61(E_0)$ according to IDF, thus proving additional 17 MWt is reasonable to expect at a moderate risk rate. Since the (probabilistic / probable) thermal potential is defined by $P50(E_0)$, i.e. corresponds to a critical risk of success when proving or producing, regardless of reservoir sustainable capacity, the reservoir potential increases to $TTP_{(p)} = 66$ MWt, with 3 % share on total TTP in Slovakia. Total reserves are then assessed for $RE_T = 218$ MWt, however, at considerable risk of failure. Shortening the period of production to $t_{prod} = 40$ years decreases a load on energy balance of the reservoir, subsequently increasing the amount of energy available at certain quality. Thus, while probable reserves are assessed for $R_{pb} = 122$ MWt at $P63(E_0)$ on IDF, the probable total thermal potential increases up to $TTP_{(p)} = 164$ MWt, with cumulative total reserves estimated for $RE_T = 498$ MWt.

There are, however, several uncertainties of the probabilistic assessment, due to its conceptual model, that may be of significant impact during future model updating:

- hydraulic / thermal connectivity between RES1 and RES2 on a regional scale (recently, lack of data exist, especially from geothermal water samples from RES2 in depressed morphostructures, so that compositional conceptual model based on thermochemistry and geothermometry applies to local systems only – e.g. Fričovský et al., 2015, 2016) – reconstruction of conceptual model towards "stratified" system would cause both reservoirs to be simulated separately, i.e. would most likely increase the geothermal potential associated with the basin

Table 1: Geothermal reserves booking – a national geothermal catalog scheme. Modified after: Sanyal – Sarmiento (2005)

Class	Computation	Eq.
geothermal resources	$RS_T = P5(E_0)$	(5)
geothermal reserves	$RE_T = P10(E_0)$	(6)
inferred reserves	$R_{inf} = \begin{matrix} P10(E_0) - Md(E_0) \text{if } Md(E_0) < X(E_0) \\ P10(E_0) - X(E_0) \text{if } Md(E_0) > X(E_0) \end{matrix}$	(7)
probable reserves	$R_{pb} = \begin{matrix} Md(E_0) - P90(E_0) \text{if } Md(E_0) < X(E_0) \\ X(E_0) - P90(E_0) \text{f } Md(E_0) > X(E_0) \end{matrix}$	(8)
proven reserves	proven by long-term production / sufficiently long and representative pumping tests	-
(probable) total thermal potential	$TTP_{(p)} = P90(E_0) + \left(P50(E_0) - P90(E_0)\right) \rightarrow TTP_{(p)} = P90(E_0) + R_{pb} \rightarrow TTP_{(p)} = P50(E_0)$	(9)

- relation between the basin and its NW periphery is still questionable, i.e. a relation between the Bešeňová elevation hydrogeothermal structure and the Lúčky – Kalameny structure; while geophysics (Fendek et al., 2017) in combination with geothermometry and thermochemistry (Fričovský et al., 2016) prefer both systems insulated; hydrogeothermal balance shows decent indications on mass transfer between (e.g. Remšík et al., 1998, 2005) – solving the uncertainty will change total area of the geothermal water body and histograms of reservoir properties.

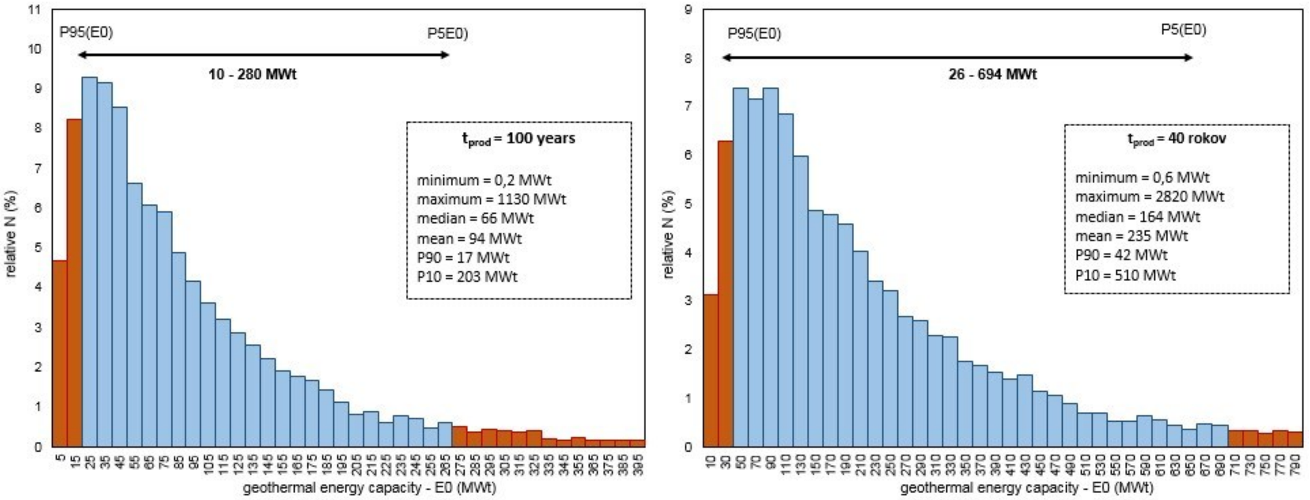

Figure 4: Liptov Basin – geothermal energy capacity simulations histograms for t_{prod} = 100 years and t_{prod} = 40 years.

Table 3: Probabilistic McKelvey scheme model for the Liptov Basin (in MWt)

McKelvey scheme	Symbol	t_{prod} = 100 years	t_{prod} = 40 years
Total geothermal resources	RS_T	3,075	7,690
Total geothermal reserves	RE_T	218	498
Inferred (possible) reserves	R_{inf}	138	344
Total thermal potential (probabilistic)	$TTP_{(p)}$	66	164
Probable reserves	R_{pb}	49	122
Proven reserves	R_{pv}	32	
Recovery factor (interval / representative)	R0	0.021 – 0.125	

4. RESERVOIR SUSTAINABILITY AND PRODUCTION DEVELOPMENT

Recent shifting towards energy security, diversification in energy supply and stability projects in increasing interest in geothermal resources in Slovakia. While local legislation focuses on deliverability only, when applying permits, there is no control on reservoir energy capacity, nor its limits in renewability, recoverability, or sustainability (Fričovský et al., 2020a). Thus, with the ongoing upturn, a risk of reservoir depletion, whether thermal or hydraulic, rises.

National catalog of geothermal energy potential approaches the question of sustainability of geothermal energy production combining reservoir limits given by geothermal reservoir sustainable capacity / sustainable thermal potential – $P_{th(S)}$, and boundaries for further development defining a developable potential – $P_{th(D)}$.

4.1 Sustainable reservoir capacity model

To assess sustainable thermal potential of GWBs in Slovakia, the catalog adopts the reservoir capacity ratio approach (Bjarnadottir, 2010). Although presented procedure is rather based on energy-balance only, it is still available to provide information on a geothermal potential base clear for exploration and proving, where energy stored in reservoir when reached equals energy withdrawn. The procedure follows:

1) according to the reserve capacity ratio, the critical sustainable level of reservoir production equals 50 % of its reservoir capacity (10), recalling a lowest sustainable production (P_{th}) limit for r_{cap} = 0,5:

$$r_{cap} = \frac{TTP_{(p)} - P_{th}}{TTP_{(p)}} \rightarrow P_{th(S)} = 0.5\left(TTP_{(p)}\right) \tag{10}$$

2) after substitution of $TTP_{(p)}$ (Table 3) into (10), the sustainable thermal potential of the Liptov Basin is assumed $P_{th(S)}$ = 33 MWt for tprod = 100 years and $P_{th(S)}$ = 82 MWt for t_{prod} = 40 years, a common for both, the RES1 and RES2. Because of a catalog workflow, the model does not distinguish between respective reservoir units, hence destruction of energy balance in one will subsequently cause

depletion in the second. Limits for the rate of reservoir production sustainability according to different rates of reserve capacity ratio are listed in Table 4.

Table 4: Projection of sustainable production classification on geothermal conditions in the Liptov Basin. Modified after: Bjarnadottir (2010); Fričovský et al. (2020a)

reserve capacity ratio level	production classification	critical production limits for $t_{prod} = 100$ years	critical production limits for $t_{prod} = 40$ years
$r_{cap} < 0$	intense reservoir depletion	> 66 MWt	> 164 MWt
$r_{cap} = 0 – 0.5$	reservoir depletion	33 – 66 MWt	82 - 164 MWt
$r_{cap} = 0.51 – 0.75$	sustainable production	16 – 33 MWt	41 - 82 MWt
$r_{cap} > 0.75$	very sustainable production	< 16 MWt	< 41 MWt

4.2 Reservoir production in 2011 - 2022

A recent catalog proposal takes a period of PH = 2011 – 2022 as production history interval to address developable potential, as this is the longest period for which complete geothermal waters withdrawals began to be reported regularly towards the Slovak Hydrometeorological Institute, including pressure, temperature and head logs when applying for permission prolongations.

Most recently, there are several sites producing geothermal waters in the Liptov Basin. Four active geothermal wells produce geothermal waters for balneotherapeutical purposes at the Lúčky Spa, with the installed capacity of $P_{th,inst} = 3.8$ MWt (the thermal output at Q_{max} and $T_{ref} = 15$ °C), and a mean referenced thermal output (the thermal output at Q_{act} and $T_{ref} = 15$ °C) $P_{th,ref} = 0.47$ MWt during the PH. It is, however, necessary to accent that production of geothermal (healing) waters in spas is controlled by relatively strict spa legislation, i.e. Act No. 538/2005 Coll. (the Spa Act), and supervision to reservoir production and monitoring is provided by the Inspectorate of Spas and springs (ISS) by the Ministry of Health of the Slovak Republic, while permits and production of „normal“ geothermal waters reflect legislation given by Ministry of Environment of the Slovak Republic, i.e. Act No. 569/2007 Coll. (Act on Geology) and Act no. 364/2004 Coll. (Act on Water). The Thermal Park Bešeňová, as recreation resort, uses geothermal waters for space heating and recreation, previously supplying local greenhouses too, now operating 2 wells at $P_{th,inst} = 11.5$ MWt, tapping the RES2 complex, however, mean reference thermal output is still $P_{th,ref} = 6.8$ MWt, varying seasonally 3.7 to 10.9 MWt mostly due to heating demand (Figure 5). Geothermal waters at the Liptovský Trnovec site are produced for recreation, supplying local thermal park from a single well, with $P_{th,inst} = 5.5$ MWt and mean $P_{th,ref} = 1.8$ MWt, however, with continuous increase in production. The Rudolf geothermal well operates for Liptovský Ján wellness resort at constant $P_{th,ref} = 0.8$ MWt as of $P_{th,inst} = 1.21$ MWt.

4.3 Developable potential

According to definitions, the developable potential $P_{th(D)}$ represents part of energy available for future increase in production according to a normalized mean yearly production and a reference base, i.e. the sustainable potential $P_{th(S)}$. At recent level of catalog, the developable potential is assessed for the entire basin, working with cumulative $P_{th,ref}$ from all active wells. To note, the most recent in Liptovský Mikuláš has not been included, as no production data are available.

A model of developable potential in the catalog applies only if cumulative $P_{th,ref} > P_{th(S)}$ for the geothermal water body (case of layered, simple or connected conceptual models) or if the condition is met for the given reservoir complex in stratified conceptual models. Obviously, there is no developable potential, where actual production exceeds the $P_{th(S)}$. During the given production history, the $r_{cap} = 0.81$ to 0.89 for $t_{prod} = 100$ years, while $r_{cap} = 0.93$ to 0.95 for $t_{prod} = 40$ years, classifying the production of the geothermal energy in the Liptov Basin sustainable to very sustainable respectively. Derivation of $P_{th(D)}$ is as follows:

1) normalizing thermal output variation (10) according to a production curve (Figure 5), where the cumulative $P_{th,ref} = 6.7$ MWt and 13.6 MWt as a minimum and maximum value, to yield a representative output $P_{th,ref*} = 10$ MWt:

$$P_{th,ref*} = P_{th,ref(MIN)} + 0.5\left(P_{th,ref(MAX)} - P_{th,ref(MIN)}\right) \tag{10}$$

2) harmonizing the representative thermal output according to a production history (11) yields $P_{th(D)} = 20$ MWt for $t_{prod} = 100$ years while $P_{th(D)} = 69$ MWt for $t_{prod} = 40$ years.

$$P_{th(D)} = P_{th(S)} - P_{th,ref*} + 2\left\{Q1(P_{th,ref}) - 1.5\left[\left(Q3(P_{th,ref}) - Q1(P_{th,ref})\right)\right]\right\} \qquad (11).$$

Projection of $P_{th(D)}$ on $P_{th,ref}$ through the production history scores $r_{cap} = 0.49 – 0.59$, with $r_{cap} < 0.5$ only at 5 % of the time span. Since drops are related to the oscillation in reservoir production and rather relate to production maxima with a lap of 1 month, it is also assumed the reservoir would recover just after decline in thermal output, due to the cyclic production regime. However, as the $P_{th(D)}$ is function of $P_{th(S)}$, the reserve capacity ratio score yields $r_{cap} = 0.49 – 0.54$, with $r_{cap} < 0.5$ only at 7 %. This is due to an effect of increased sustainable thermal capacity and fit of $P_{th(D)}$ and $P_{th,ref}$.

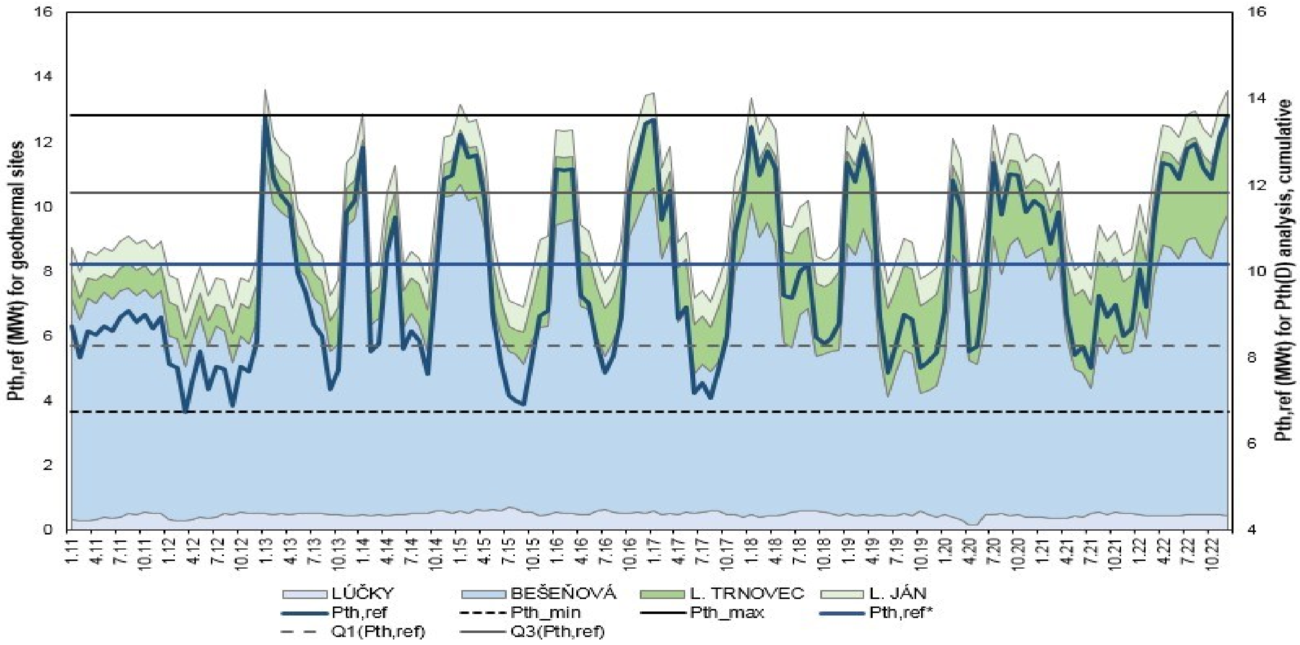

Figure 5: Liptov Basin – geothermal energy production data as of 2011 – 2022; projection on $P_{th,ref}$.

5. CONCLUSIONS

The geothermal resource in the Liptov Basin has already been proven by 23 wells since 70's, out of which 9 are operated recently at 5 sites – the Lúčky, Bešeňová, Liptovský Trnovec, Liptovský Ján and Liptovský Mikuláš, whether for space heating (individual), recreation,, balneotherapy or as a heat supply for industrial processes. However, considerably good knowledge of reservoir properties for the shallow reservoir in the Choč Nappe system, and its successful proving in the Krížna Nappe Mid Triassic carbonates makes the geothermal water body still a point of interest. In consequence, a risk of reservoir depletion rises with generally weak monitoring of geothermal resources in the country, supplied by missing controls on installations development in terms of sustainable reservoir capacity.

The geothermal potential catalog of Slovakia, now peer-reviewed, combined guided / conditioned probabilistic modeling in both, assessing the recovery factor and the geothermal energy potential according to geological and geothermic models of each geothermal water body, along with setting guides to carry or post-process simulations based on their conceptual models. The Liptov Basin has been identified as of hydrogeologically open reservoir environment for both, the RES1 and RES2 complexes, which are, classified as connected. This calls for a unique Monte Carlo simulation for the R0 and geothermal potential, assuming each change in a first complex will be of an impact onto another, so that the geothermal potential is not cumulative.

The geothermal reserves booking approach (Sanyal – Sarmiento, 2005) has been adopted in geothermal potential model construction (Table 3). Considering a sustainable period of production $t_{prod} = 100$ years (Axelsson et al., 2001), the probabilistic total thermal potential that corresponds to 50 % rate of success in proving or production, equals $TTP_{(p)} = 66$ MWt. Applying a reserve capacity ratio approach (Bjarnadottir, 2010) setting the critical rate of production to be sustainable as 50 % of the geothermal potential, the sustainable reservoir capacity may roughly reach $P_{th(S)} = 33$ MWt. A given production history as of 2011 – 2022 shows variation in a cumulative real thermal output of all active wells in $P_{th,ref} = 6.7$ MWt and 13.6 MWt, normalized to $P_{th,ref*} = 10.2$ MWt. After harmonization to compensate for local extremes, the sustainable thermal potential is assessed for $P_{th(D,100)} = 20$ MWt. This procedure allows to keep a sum of $P_{th(D)}$ and actual production $P_{th,ref}$ at $r_{cap} > 0.5$ for most of a time, thus limiting a risk of depletion, the more as the energy withdrawal is rather cyclic, so even short periods of $r_{cap} < 0.5$ during short periods of production-highs, are subsequently balanced by longer periods of moderate or low production, allowing the system to recover. Obviously, this means a possibility to almost double a recent production, likely when targeting the RES2 complex. Using the same procedure for $t_{prod} = 40$ years, the increase in energy capacity means $TTP_{(p)} = 164$ MWt and $P_{th(S)} = 82$ MWt. Hence $P_{th,ref}$ and $P_{th,ref*}$ are independent on balanced period of production, the $P_{th(D)} = 69$ MWt. A model dynamics allow it to update each year, and to adopt the estimate to an actual state.

Understanding many shortcomings of probabilistic modeling (e.g. Sanyal – Sarmiento, 2005` Garg – Combs, 2011, 2015; Grant, 2014; Ciriaco et al., 2020) somewhat limited through the guided approach, we rather recommend to use the $P_{th(S)}$ and $P_{th(D)}$ as a critical rate of geothermal energy production, definitely not to overproduce as long as use of complex reservoir monitoring would infer higher geothermal energy content.

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