NEW HARMONIZED METHOD FOR OUTLINING TRANSBOUNDARY GEOTHERMAL RESERVOIRS AND RESOURCE ASSESSMENT

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ABSTRACT

Geothermal reservoirs and geological structures are often cut cross by country borders, therefore sustainable and economically sound production of geothermal energy require harmonized policies and transnational resource management.

A novel methodology of outlining and characterizing large transboundary geothermal reservoirs based on harmonized geological, geothermal and hydrogeological data, maps and models from six project partner countries has been elaborated. The reservoirs were also characterized with regard to their lithology, main porosity types, temperatures and chemistry of the stored fluids. Furthermore, their geothermal resources have been estimated based on a probabilistic method.

Development of this harmonized methodology allows identifying transboundary geothermal reservoirs to serve as a basis for further estimations of the existing geothermal potentials and resources in a transnational scale, in order to distinguish between prosperous and non-prosperous regions and for sustainable management of geothermal resources.

1. INTRODUCTION (CHAPTER TITLE, BOLD CAPITALS, 3 PT SPACING BEFORE AND AFTER)

The Pannonian basin in Central Europe is one of the European areas with well-known positive geothermal anomaly. There is relatively detailed information available on their regional, cross-border extension at the western, whereas less data are known from the south-eastern regions. Large-scale geothermal reservoirs from these south-eastern parts have not been outlined and characterized yet in a uniform way considering aspects such as potential future uses, their depths, temperatures, chemistry of stored fluids, etc.

The main objective of the DARLINGe project is to enhance the sustainable and energy–efficient use of the still untapped deep geothermal energy resources in the central and south-eastern part of the Danube Region (HU, SLO, SRB, HR, BH, RO). In order to achieve the project objectives of increasing geothermal energy in the heating sector, a holistic approach of identifying and characterizing the main geothermal reservoirs of the project area was applied.

The investigated area covers a region with the extent of 99,372 km^2, encompassing southern Hungary (south-Transdanubia and southern part of the Great Plain), north-eastern Slovenia (Pomurje and Podravje), northern Croatia (Međimurje, Hrvatsko zagorje, Podravina, Posavina, Moslavina, Slavonia), western Republika Srpska and the central and northern parts of Bosnia-Herzegovina, northern Serbia (Vojvodina) and western Romania (Crisana and Banat) (Figure 1.).

Figure 1: The DARLINGe project area

2. METHODS FOR THE IDENTIFICATION OF GEOTHERMAL RESERVOIRS

Identifying geothermal reservoirs of the DARLINGe project region was based on available geological, hydrogeological and geothermal information. Both the content and the data format largely varied in the partner countries. In addition to these differences at national scales, the density of the available information and the level of knowledge of the geological and hydrothermal systems were significantly diverse in the different regions. Due to these large differences, it was not possible to harmonize the source data and create unified basic geological-hydrogeological-geothermal maps from scratch.

In the absence of a common geological model, the most important hydro-stratigraphic units (rock assemblages having the same hydrogeological behaviour) were identified as potential geothermal reservoirs applying some simplification. These units contain the most often exploited thermal water aquifers. Two main types of geothermal reservoirs were determined. The thermal aquifer layers of the Pannonian shelf front and shelf plain formations was called "basin fill reservoir (BF)" in this work, while potential thermal aquifers of the basement formations were called "basement reservoirs" (BM). The two main reservoir types represent different types of porosity.

Some potential geothermal reservoirs occur in the Quaternary formations as well, but they are out of the scope of our study, because of their relatively lower temperature (usually slightly exceeds 30˚C in the central parts of the basin) and principal importance of these aquifer layers in drinking water supply despite their slightly elevated temperature. There are only some exceptions for this, for example in the deepest part of the Drava sub-basin and the Makó Trough where temperature can exceed 50 °C in the Quaternary formations. However, it is worth to mention that the separation of Quaternary and the very similar Pliocene fluvial sediments sometimes is rather uncertain in these areas.

Considering utilization schemes, different temperature categories were distinguished within the main types of reservoirs (BF and BM). The subcategory of 30-50 ˚C can be important mainly for balneology. Reservoirs having temperature between 50 and 100 ˚C are primarily suitable for direct heat utilization. Within that the 75-100 ˚C subcategory represents the temperature range where thermal water can be applied for district heating systems. Reservoirs having temperature between 100 and 125 ˚C, 125-150 ˚C, or temperature exceeding 150 ˚C have the potential for combined heat and power generation (CHP) projects using binary technologies.

To provide the opportunity of resource estimation reservoirs were identified as closed 3D bodies. This result, that sometimes different formations serve as the basement of one reservoir. For similar reason the surface projection of the top and the basement of a reservoir can be different. The theoretical section of the identified geothermal reservoirs is shown on Figure 2, where the top surface and the bottom surface of the reservoirs were illustrated with separate lines.

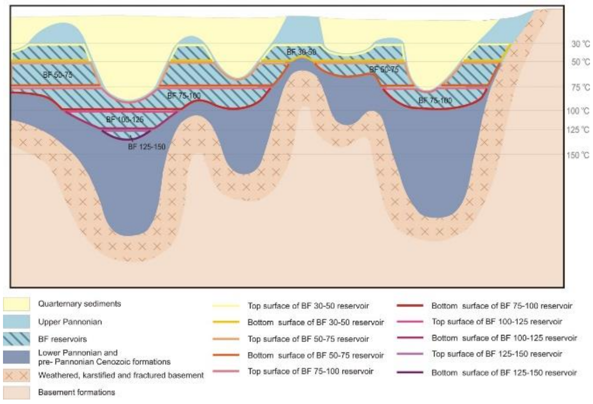

Figure 2: Schematic view of reservoir types

Characterization of the temperature distribution of the subsurface basin fill sediments was carried out by creating different isotherm surfaces.

Delineation of geothermal reservoirs was based on the combination of the new harmonized geological and isotherm maps and surfaces applying SURFER and ArcGIS software.

3. DETERMINING MAJOR GOTHERMAL RESERVOIR AQUIFERS

Several depth surfaces of various geological units were created for the subsequent modelling and calculations:

- the top surface of the shelf sediments forming the top of the basin fill reservoir (Figure 3),
- the shelf-edge of the Pannonian lake, representing a shale-sand lithological boundary, forming the BF-bottom (Figure 4),
- the top surface of the basement formations (the Pre-Cenozoic basement), which can represent the BM-top without the Senonian sediments. Latter

was not isolated from the Pre-Cenozoic formations (Figure 5).

BF reservoirs consist of porous formations of shelf front and shelf plain formations deposited in the Pannonian Lake. The sediment succession is built up of altering sand and sandy clay layers characterized by a strong anisotropy in hydraulic conductivity (Kh/Kv) often higher than 5000 (Tóth et al. 2016). Despite of the lower permeability of the clayey-marly strata, hydraulic connection exists between the sand layers, which make the entire Upper Pannonian sedimentary series one hydro-stratigraphic unit, characterized by an almost uniform hydrostatic pressure. The reservoir is built up from 30 to 100 m thick sand-prone units which can be tracked regionally. The sandy aquifer layers have got intergranular porosity of 20-30% and hydraulic conductivity of 4×10-6–5×10-5 m/s (Rotár-Szalkai et al. 2017).

Under the several kilometres thick Neogene sedimentary rocks the basement of the Pannonian basin is extremely diverse and shows a complex structure, built up of various metamorphic and non-metamorphic Palaeo- and Mesozoic crystalline and carbonates rocks that formation was associated with the Alpine-Carpathian orogene (Csontos and Vörös, 2004; Schmid et al., 2008; Haas and Budai, 2014). They are arranged into nappes along thrust sheets, dissected by strike-slip and normal faults, associated with the multi-phase tectonic development of the basin (Fodor et al., 1999; Horváth et al., 2006; Haas et al., 2012). BM reservoirs may contain different types of fractured and fissured formations consisting of crystalline metamorphic rocks, or carbonate complexes of different age. The fractured crystalline rocks may exhibit an enhanced permeability in the main tectonic zones, as well as in their upper weathered zones. The fractured, partially karstified carbonate rocks are characterized with enhanced porosity in their intensively karstified zones, most commonly in the upper part of the carbonate sequences. Some tectonic zones in the basement rocks, especially in the neo-tectonically active regions have got individual importance with high hydraulic conductivity and active hydraulic connections to other large aquifer systems.

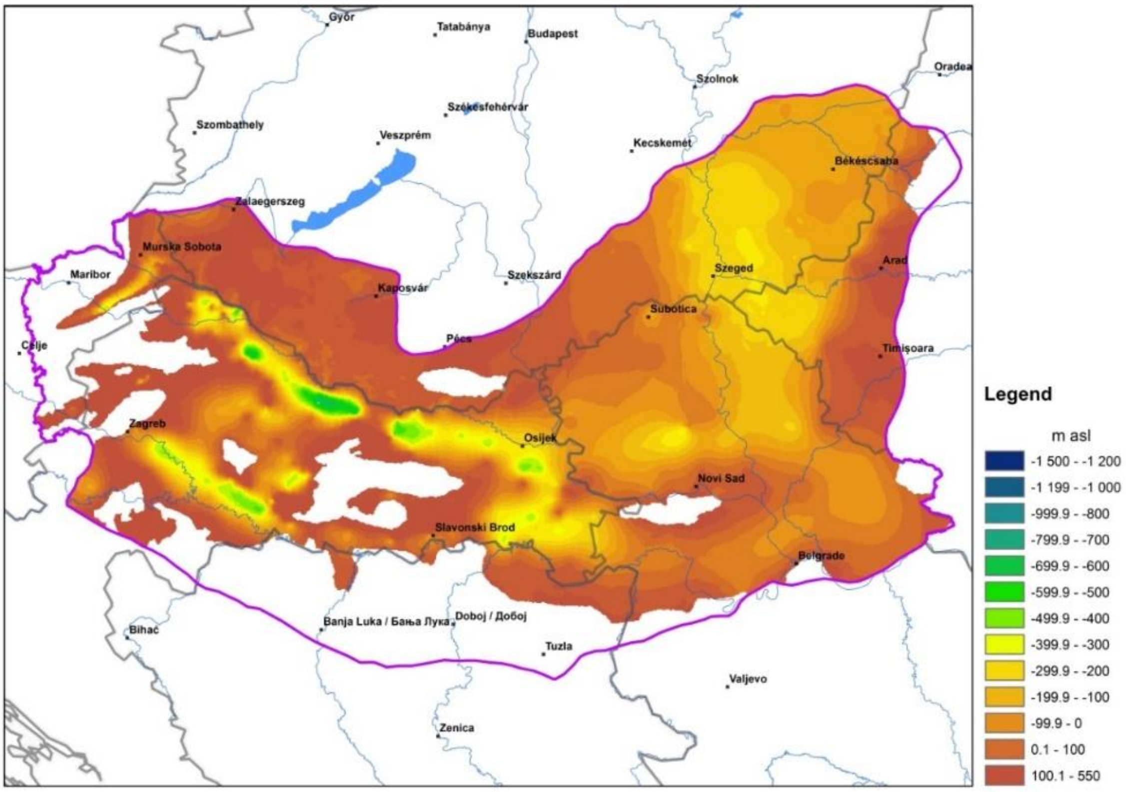

Figure 3: The depth horizon between the Pannonian lake deposits and Quaternary terrestrial sequences (BF top)

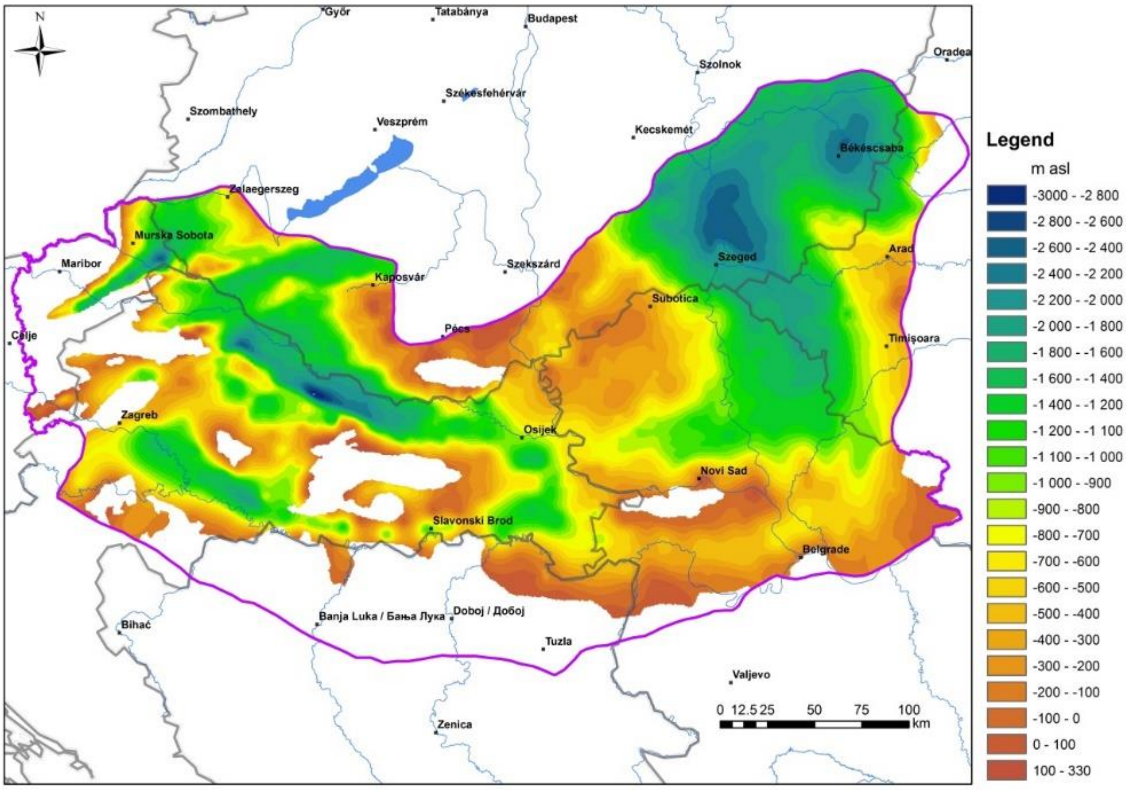

Figure 4: The depth horizon of the bottom of the nearshore sandy succession deposited in the Pannonian lake (BF bottom)

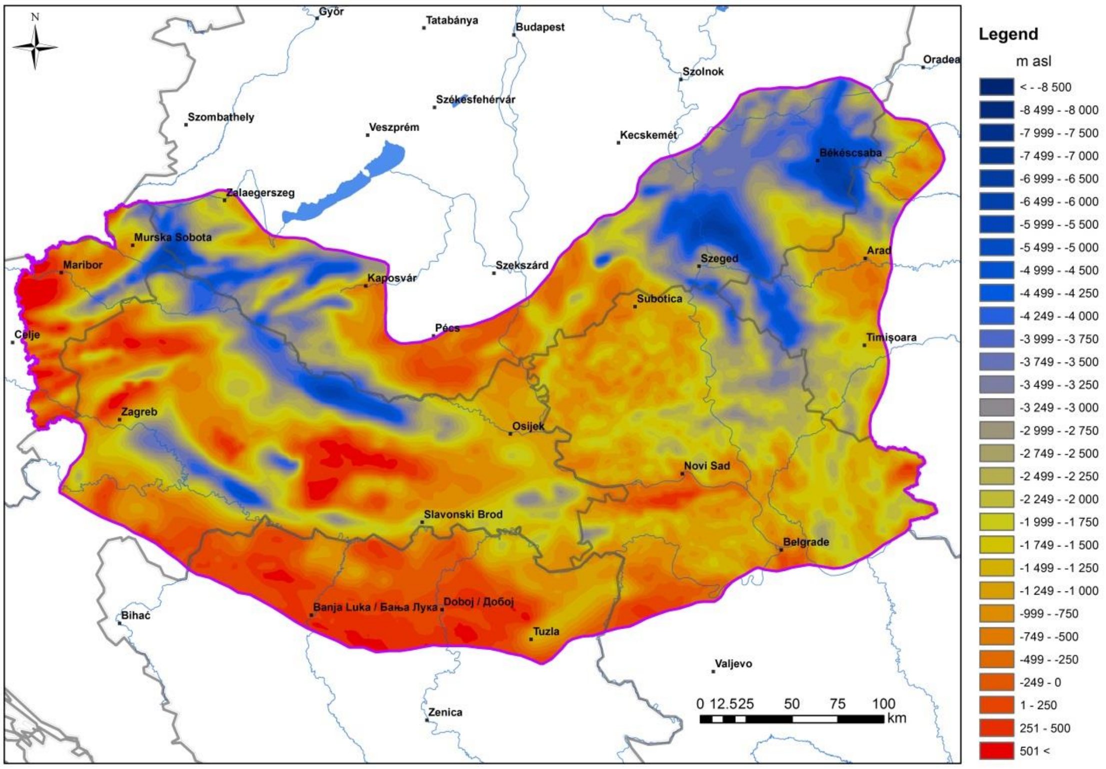

Figure 5: The depth horizon of the pre-Cenozoic basement formations (BM top)

4. CONSTRUCTION OF THE ISOTHERM SURFACES

Information about geothermal conditions derived from temperature measurements performed in thermal water wells, or in hydrocarbon boreholes. Since these measurements usually have a great uncertainty, thermal data (temperature, geothermal gradient, etc.) may show a big standard deviation even within a small region. To increase the reliability and eliminate the problem of unfavourable spatial distribution of temperature data is a simplified conductive geothermal model was applied.

The various subsurface isotherm surfaces were edited on the basis of a simplified conductive model (details discussed in Rotár-Szalkai et al 2018), which was established for the entire S-ern part of the Pannonian basin in the DARLINGe project. The basic hypotheses of the calculation method was that the higher heat-flow (higher values than world average) in the Pannonian basin is caused by the thinning of the lithosphere that resulted from lithosphere stretching coeval with the formation of the basin (Dövényi and Horváth 1988, Royden et al. 1983). The relief of the pre-Pannonian basement evolved parallel with the intensive inflow of sediments due to thermal subsidence, i.e. the depth of the basin is proportional to the degree of thinning of the crust. The spatial variation of heat-flow density therefore reflects the changes of the basin depth. So the actual temperature (and the depth of isotherm surfaces) in the basin fill sediments can be calculated with a function where the parameter of this function is the spatial variation of heat-flow density, which represents the changes of the basin depth (depth of the pre-Pannonian basement).

For the validation of the modelled temperature distribution, we compared them with the real temperature measurement data from wells. The comparison statistically showed very close connection, but locally some differences occurred. Differences are expected in the regions where convection (modifying effect of groundwater flow) has important role in spatial subsurface distribution of temperature or caused by uncertainty of temperature measurements

The same method cannot apply to the temperature of basement reservoirs. In most of the cases convection is the prior process in basement formations (especially in karst formations) and in the case of convection, calculated data by convection model can differ from the real values significantly. Nevertheless, the comparison of the calculated values of the conductive model to the measured temperature values in the basement formation is very important from geothermal potential point of view, because anomalies indicate the regions of intensive thermal convections. These regions are the most prosperous regions with high thermal potential.

5. DELINEATED RESERVOIRS

5.1. Basin fill reservoirs

BF reservoirs with all temperature categories (up to 150 °C) are located in the deep sub-basins of the Pannonian Basin (Makó Trough, Békés Basin, Drava Basin, Sava Basin). A significant decreasing in the reservoirs' extension can be observed parallel with increasing depth and temperature. The deepest reservoir is the BF125-150, which is restricted for a very small area within the Drava-Basin where temperatures are slightly above 125 °C. Series of different horizons were created containing the top and bottom surfaces of reservoirs with different temperature intervals.

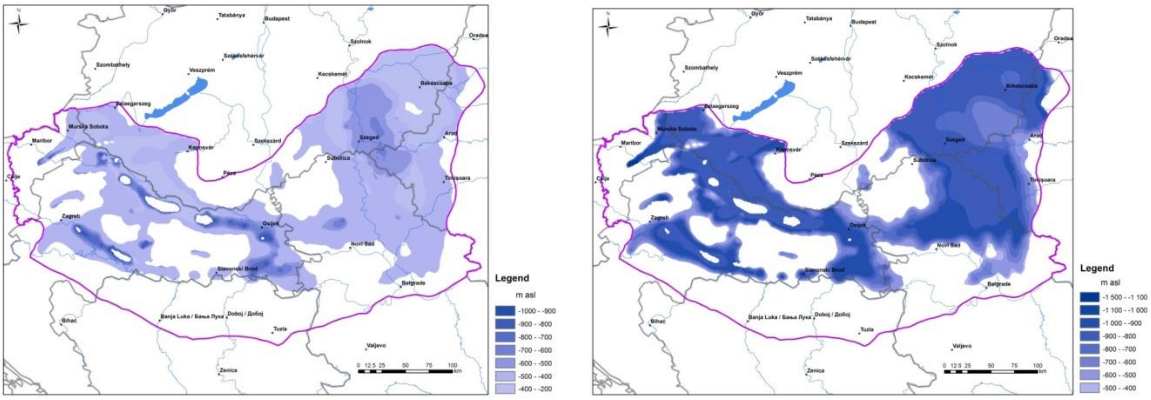

Figure 6: Top (left) and bottom (right) surface of the BF30-50 reservoir.

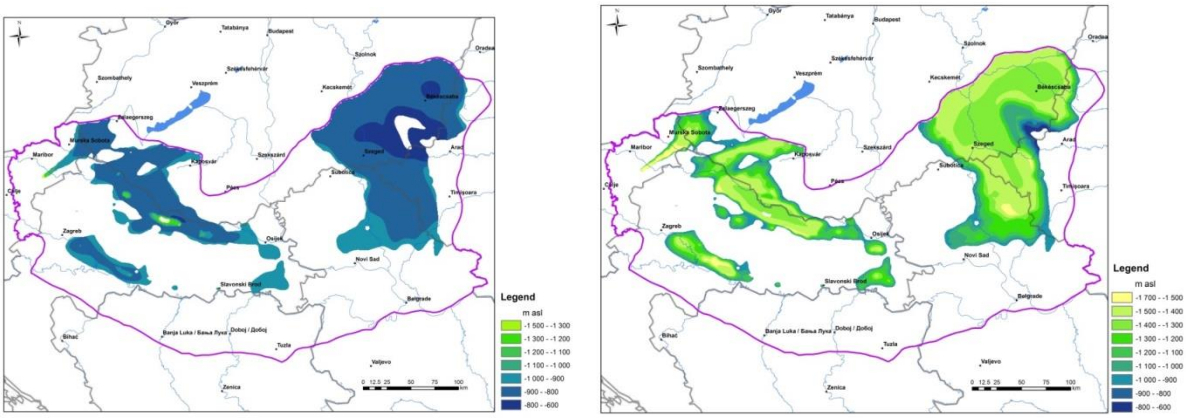

Figure 7: Top (left) and bottom (right) surface of the BF50-75 reservoir

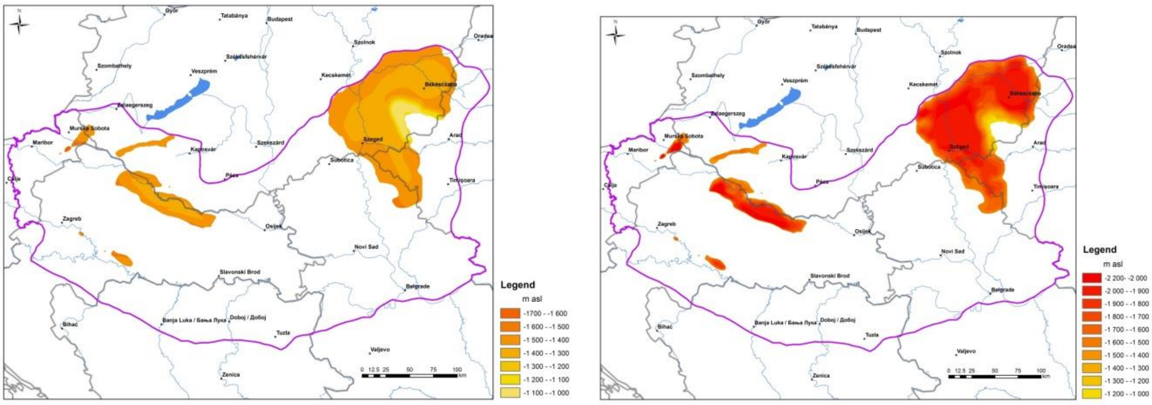

Figure 8: Top (left) and bottom (right) surface of the BF75-100 reservoir

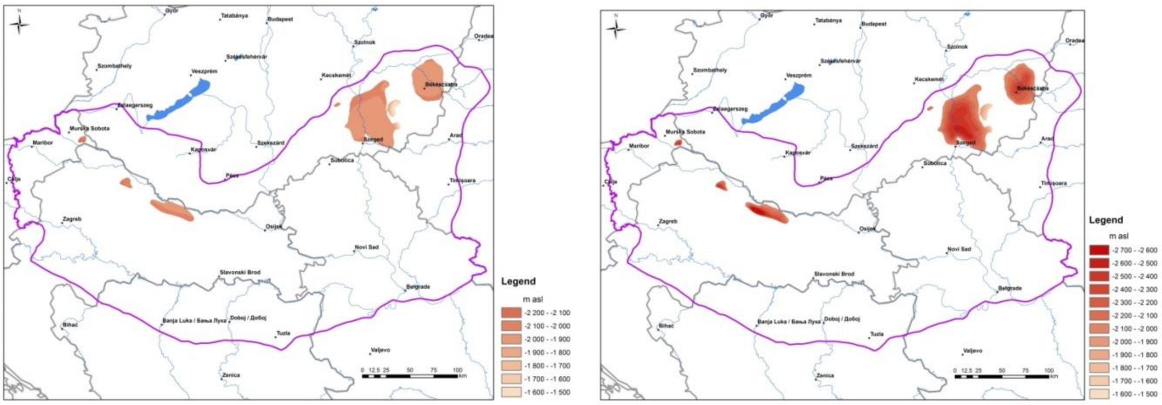

Figure 9: Top (left) and bottom (right) surface of the BF100-125 reservoir.

5.2. Basement reservoirs

During outlining of basement reservoirs, the relevant geological formations cannot be identified due to the scattered data in the complex geological environment. Additionally, due to the different hypothesis about tectonic evaluation of the project area and uneven geological data distribution, it was not possible to construct a common geological map showing the basement formations in the time-frame of the DARLINGe project. Therefore, we provide a general description of the potential basement reservoirs, followed by short descriptions about the basement reservoir regions of the different partner countries, based on current geological knowledge (Rotár-Szalkai et al 2018). Basement reservoirs in the Pannonian Basin are connected to those formations of pre-Cenosoic age, which are brittle and due to various processes, the secondary porosity of the rock frame could have been increased at such a level, that it is able to store a geothermal fluid suitable for economical exploitation. The brittle rocks in the basement are mostly carbonate (limestone, dolomite), crystalline (granite, granodiorite, gabbro, gneiss, mica-schist,) and subordinately volcanic (andesite, basalt) formations. Processes increasing porosity are weathering, karstification and tectonism.

6. RESOURCES ASSESSMENT

The most important element of characterization of geothermal reservoirs is determining geothermal potential to express in a quantitative way the amount of available geothermal energy. For geothermal resources it is possible to refer different potential categories like theoretical-, technical-, economic-, sustainable-, and developable potential (Rybach 2010). As the different potentials in this order are more and more realizable and require more and more detailed information, regional resource estimations are usually applying the first two categories. The theoretical potential describes the physically usable energy supply (the heat in place). Due to technical, structural and administrative limitations only small fractions of the theoretical potential can actually be used. Technical potential describes the fraction of the theoretical potential that can be used under existing technical restrictions (currently available technology) (Rybach 2015).

The first limit is presented in the maximum realizable drilling depth which is between 5-7 km (Muffler & Cataldi 1978). In addition to recovery factor (which means the ratio of heat recoverable versus heat in place) shows the degree of technically available part of available geothermal resources. According practical experiences its value is rather uncertain and varies in wide range. Depending the geology and permeability it is between 0.1-0.25 in porous systems while 0.08-0.2 in fractured systems (Nádor 2016).

Theoretical and technical potential of the geothermal reservoirs were calculated for selected sub-basins (Figure 70) with the more frequent applied volumetric method (Muffler &. Cataldi 1978). According to the basic concept the geothermal resource assessment is designed to establish the amount of heat that is available from a reservoir (Williams 2007).

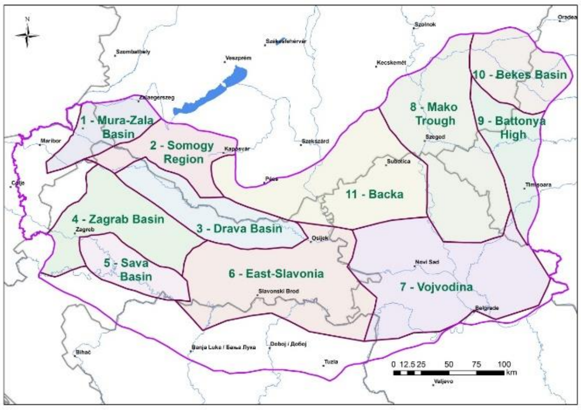

Figure 10: Regions of resources estimation.

Since most of the cases extracting heat from the rock is possible by production of geothermal fluid only the heat content of moveable fluid (fluid situated in the effective pore space) was considered in the calculation applying volumetric method.

The input parameters used for estimating the heat content of movable water in the reservoirs are: the area of the reservoirs (measured); depth (measured and interpolated); temperature (estimated); effective porosity (estimated). Considering uncertainty, a probabilistic approach was applied with the method of Monte Carlo simulation which is wide spread in geothermal resource assessment (Nádor and Zilahi 2016).

The area of the reservoirs is considered as static value and is determined as the surface projection of the top of the reservoirs.

The thickness of the reservoirs varies from place to place. These values are determined from the top and bottom horizons of the reservoirs represented in 500 × 500 m grid files.

Temperature was estimated by the conductive geothermal model (see chapter 7.3). Its value varies from place to place too and applied as average value calculated from the conductive model. It was determined for each grid cells related to the average depth of the reservoirs (as reference depth) for each temperature intervals.

Effective porosity was derived from total porosity. Its value is the function of actual basin depth and the function of the clay content. Lacking detailed geological model, sediments of the shelf plain and shelf front were not separated, therefore clay content in the model varies between a wide range of 20-60 % (based on expert estimation and literature of previous regional geological and hydrogeological modelling (Nádor & Zilahi 2016, Tóth et al. 2016)) and independent from basin depth, actual depth or coordinates. The average value is estimated as 40% which is related to the entire sequence.

The effective porosity is calculated with Monte Carlo simulation, where three independent variables are applied. The first random variable is represented by the specific depth (± 5%), the second one for the error of the estimated total porosity (± 10%) and the third one is for the estimated clay content (±20%).

Heat energy stored in the pores associated with high-, medium-, and low levels of confidence are based on P90, P50 and P10 of the resulting cumulative probability distribution respectively. Two types of estimation were done, calculating the total heat content of moveable fluids and calculation considering recovery factor with the conservative value of 0.1 (Table 1).

7. CONCLUSIONS

The above presented holistic approach and developed novel methodology provides basis for the transboundary and supra-regional thermal energy management on the south-eastern part of the Pannonian Basin and can serve as an example for other regions. Delineation of transboundary reservoirs can be done applying the above detailed simplifications and conceptional models. Resource estimation made by probabilistic approach can result calculations related to regions with only few information or uncertain data.

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Table 1: Estimated heat content of effective porosity considering recovery factor (0.1) in the BF reservoirs related toselected sub-basins, confidency levels at P10, P50, P90 [PJ].

Region (sub-basin) ID and name	30-50 °C			50-75 °C			75-100 °C			100-125 °C			125-150 °C		
	P90	P50	P10	P90	P50	P10	P90	P50	P10	P90	P50	P10	P90	P50	P10
	PJ	PJ	PJ	PJ	PJ	PJ	PJ	PJ	PJ	PJ	PJ	PJ	PJ	PJ	PJ
1. region Mura-Zala Basin	536.5	739.9	975.0	678.2	939.5	1232.9	87.4	120.1	157.9	10.3	14.3	18.9			
2. region Somogy region	830.8	1152.2	1516.9	1093.7	1515.4	2005.5	23.5	32.5	42.7						
3. region Drava Basin	950.0	1301.4	1722.8	2294.5	3204.1	4200.5	1026.5	1416.4	1879.8	193.3	269.1	353.1	9.0	12.5	16.4
4. region Zagreb Basin	311.9	431.7	566.7	89.2	122.7	162.8									
5. region Sava Basin	482.0	666.5	883.7	688.8	951.0	1254.5	37.2	51.3	68.0						
6. region East-Slavonia	487.0	674.5	890.0	215.9	297.9	393.3									
7. region Vojvodina	777.6	1068.3	1405.2	149.7	207.5	275.1									
8. region Mako Trough	2721.9	3760.7	4965.8	7823.4	10849.6	14350.2	4247.4	5915.3	7806.7	957.5	1327.8	1748.2			
9. region Battonya High	556.2	762.8	1007.7	649.9	892.4	1183.5	159.7	221.3	293.0						
10. region Bekes Basin	1005.7	1392.5	1839.1	2680.2	3726.7	4925.8	1725.5	2364.8	3121.3	350.9	483.2	641.0			
11. region Backa / Bačka	363.7	503.2	663.3	162.9	226.7	297.6									