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Strategy paper on sustainable cross-border geothermal utilization

Title	Strategy paper on sustainable cross-border geothermal utilization
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CONTENT

1. PREFACE

The immense heat of the Earth (whose main source is the decay of radioactive isotopes in the continental crust) is stored in the different rocks themselves, as well as in the fluids filling their pores and fractures. Apart from the Enhanced Geothermal Systems (EGS - extraction of heat energy by circulating water via production and re-injection wells through artificially created fractures in massive hot rock volumes in the deep subsurface, still not a commercial technology), and ground-source heat-pumps (exploitation of shallow geothermal energy, a significant proportion of the overall utilization of geothermal worldwide), ***major use of geothermal energy*** is based on the ***abstraction of thermal groundwaters with deep circulation (hydrogeothermal systems).*** The heat distribution of these large scale regional flow systems are governed by convection. Heating from the Earth interior causes thermal expansion of the subsurface fluids causing lower density, and therefore their rising along suitable pathways, like subsurface conduits and faults. Usually cold water from precipitation with higher density and higher hydraulic potential recharges the systems. Consequently, the ***utilization of hydrogeothermal systems*** has both ***water management (abstraction of thermal groundwater, as carrying medium of heat) and energy (exploitation of heat energy itself) aspects.***

The Pannonian Basin is well-known of its good geothermal potential due to the favorable geological setting and being rich in thermal water, which is widely used for recreational-balneological purposes as well as in the agriculture, and to a less extent in district heating. The intensive exploitation of the reservoirs, combined with the current insufficient re-injection practice (especially in intergranular environment that is still under the research) may threat the long-term productivity of the aquifers. Due to the geographical-geological setting, much of the large thermal water aquifers are determined by geological structures and are shared by neighboring countries. Therefore unfavorable effects of excessive exploitation (e.g. drop of temperature, yield) might be exposed in the adjacent regions, leading to undesirable changes in the natural environment and renewable energy resource that is shared by neighbouring countries.

The TRANSENERGY project - running in the frame of the Central Europe Programme between 2010 and 2013 - aimed ***to support a harmonized and integrated thermal groundwater and geothermal energy utilization management*** among Hungary, Slovenia, Austria and Slovakia, and as such, provides a good example for other regions in Europe sharing trans-boundary hydrogeothermal resources.

There is a growing number of different types of utilization (direct heat applications in district heating and agriculture, balneology) in the region, and a rapid growth is forecasted (especially related to combined heat and power schemes) in the coming years, so it is essential to get a profound knowledge on the available resources and reserves, ***impacts of abstraction-exploitation***, and a better understanding of the ***interactions of different utilization schemes*** in order to avoid potential conflicts and ***set up priorities***, if necessary.

The aim of this document is to ***summarize the most important results*** of TRANSENERGY project and provide tangible ***recommendations for a sustainable and efficient utilization of transboundary hydrogeothermal resources*** on regional level, respecting the natural boundaries of geothermal reservoirs that exceed national levels of evaluation. These recommendations are based on the main project outcomes: a complex assessment of the present production and wide-range utilization of thermal groundwater, as well as the results of integrated evaluation of geological, hydrogeological and geothermal models at various scales. These appraisals were carried out by more than 80 experts of the four national geological surveys of the partner counties, providing an impartial assessment and common understanding of the hydrogeothermal systems of the western part of the Pannonian Basin. The developed problem-oriented approach of TRANSENERGY focused on the needs of decision-makers and might be applied in other regions in Europe, thus helping the countries to reach their NREAP targets without threatening the environmental targets and/or interests of their neighboring regions.

In order to communicate precisely which goals, related to the management of hydrogeothermal resources in the western part of the Pannoninan Basin should be achieved in the future, and which concrete steps are necessary to realize them, first we give a short outline on the identification of ***selected stakeholders***, their ***needs*** and the elaborated ***working methods*** (i.e. "to whom, what and how" we accomplished).

The next main chapter of this report provides an overview on the current situation of utilization of thermal groundwaters and geothermal energy in the studied region ***(state-of-the-art).*** Many of the TRANSENERGY activities and results supported this assessment: to identify the hydrogeothermal reservoirs and understand the main processes operating in them, to get a clear picture on the existing utilization schemes, their merits and pitfalls, as well as non-technical issues, such as overview and comparison of the regulatory and financial framework in the project countries. Within this chapter a ***general overview*** is provided, where the first part is relevant for the entire project area (called supra-regional area), followed by a ***problem-oriented description*** of the studied ***five cross-border pilot areas***. Based on the careful analysis of the present situation gaps and future tasks are summarized in a ***SWOT*** analysis at the end of this chapter.

In the next chapter, a ***vision*** is set up, i.e. the desired future status of the hydrogeothermal systems is identified, taking into consideration the binding targets of related EU and national policies (e.g. achieving and maintaining the good status of aquifers by 2015 according to the Water Framework Directive, accomplishing the target numbers of geothermal energy defined in the National Renewable Action Plans by 2020, etc.). Based on a careful evaluation of the different needs and often contradicting interests of the key-players / main policies (including economic and environmental impacts, territorial inequalities), priorities are also defined.

Finally, in the last main chapter tangible ***recommendations*** are given to attain a real break-through and to achieve the identified goals, aims as versioned.

2. INTRODUCTION TO THE PROJECT AREA

The TRANSENERGY project encompasses the western part of the Pannonian Basin and parts of the Vienna Basin (Fig. 1). The project area has been delineated by considering the boundaries of the most important geological units and tectonic structures, the recharge areas supplying the thermal water systems, the rivers as main discharges and the groundwater divides. The outlined territory (47,700 km^2) is mainly a lowland area with some smaller hilly regions, surrounded by the Eastern Alps and Northern Calcareous Alps at the NW, the Carpathians on the N, the Transdanubian Central Range in Hungary in the SE, and the Kozjak, Pohorje and Haloze Mountains in Slovenia in the SW. The largest lowland area is the Danube Basin on the N-ern part of the project area, shared by Slovakia and Hungary, which is divided from the Vienna Basin by the Leitha Mountains and the Little Carpathians. The area of the Vienna Basin is divided between Austria and Slovakia. On the SW-ern part there are two important basins: the Styrian Basin shared by Slovenia and Austria, and the Mura-Zala Basin located in Slovenia and Hungary. Two capitals of the partner countries are located within the project area: Vienna and Bratislava, but there are several populated cities, too, such as Győr, Graz and Maribor.

Figure 1: The entire study area (red line) of TRANSENERGY encompasses the W-ern part of the Pannonian Basin and parts of the Vienna Basin (referred as "supra-regional" area). Detailed studies were performed on five selected cross-border pilot areas

In ***geological terms*** (Maros et al. 2012), the "supra-regional" project area can be divided into two main parts (Fig. 2). The Alpine-Carpathian orogene (1) shows a complicated geological structure. The outcropping mountain regions, as well as their subsided parts forming the basement of the large sedimentary basins are built up of metamorphic and non-metamorphic Palaeo- and Mesozoic crystalline and sedimentary sequences. They have a complex structural pattern, arranged into nappes along thrust sheets, dissected by strike-slip and normal faults. In the basement, these rocks represent fractured-karstified reservoirs at a depth of 2000 m, or below, often cross-cutting political borders.

The intramountain basins (2) compromise the Palaeogene basins that evolved as a consequence of the compressional stress-field of the Alpine collision (the Flysch basins, the Gosau basins and the Inner Carpathian Paleogene Basin) as well as the Neogene basins (Vienna Basin, Danube Basin, Styrian Basin, Mura-Zala Basin, Dráva basin) that formed during the Late Miocene-Pliocene („Pannonian Basin" system). These basins have a wide range of sedimentary infill sequence: deep water cyclic turbidites; rhythmic coarse sand, conglomerate and sand, fine grained aleurite with marl intercalations (flysch deposits); shallow marine carbonates and paralic coal-bearing layers, sandy-clayey lagoon sediments; deep water sandy-clay marl, delta-front sand bodies, delta plain-to alluvial plain sandy-clayey sequences. These large sedimentary successions, often several thousand meters thick, comprise significant intergranular aquifers, of which the most widespread are the Upper Miocene-Pliocene ("Upper Pannonian") ones which are shared by all TRANSENERGY countries (Fig. 2).

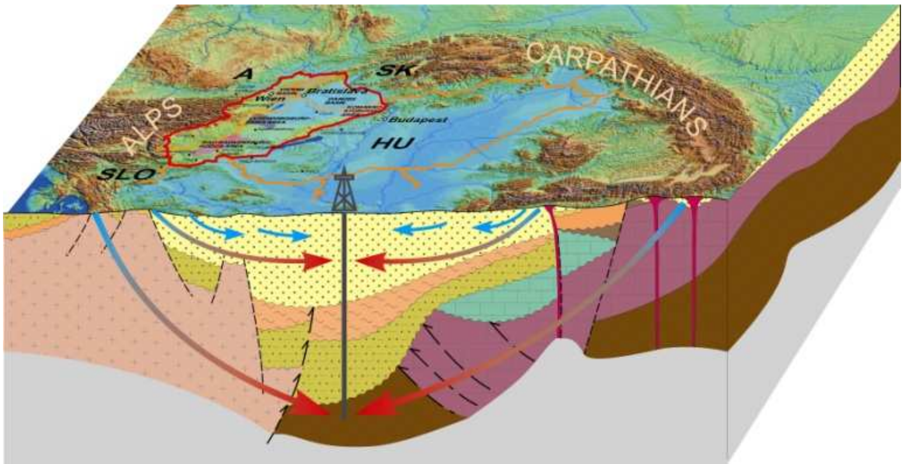


Figure 2: Sketch of the geological structure, main reservoir types and regional flow systems of the Pannonian Basin. TRANSENERGY area is contoured by red line.

The ***regional thermal groundwater flow system*** of the TRANSENERGY supra-regional area is linked to the geological structures, thus in many cases crosses country borders (Fig. 2). It is controlled by the considerable hydraulic potential differences between the recharge and discharge areas (i.e. surrounding mountain chains and low-lying basin), sufficient recharge (precipitation) and extensive deep-lying permeable formations outrcropping on large areas. The regional flow system has two sub-systems (Tóth et al. 2012). One is related to the deep-seated fractured-karstified basement rocks that are supplied from the mountainous recharge areas, where these rocks crop out. These flows might also feed the overlying porous sedimentary aquifers in the deep subsurface, otherwise they are separated. Some deep-seated, isolated basement reservoirs might also exist that do not have a direct hydraulic connection to the surface, containing stagnant thermal groundwater with higher temperature and salinity of a rather NaCl type (fossil waters in closed structures).

The other major sub-system operates in the porous sediments of the Neogene basins and is divided to an upper gravity-driven part and a deeper part, where stagnant fossil and confined groundwaters are found. The regional gravity-driven groundwater flow system of the intergranular aquifers collects heat from a large subsurface area and is mainly hosted by the delta-front and the delta-plain facies sandy units of the Upper Miocene-Pliocene sedimentary sequence at a depth range between 1000-2000 m. Under favourable conditions, the sandy aquifer units outcrop on the hilly areas with a higher hydraulic potential, therefore providing a fairly quick and direct recharge. This sedimentary succession is characterized by a frequent alternation of sand-silt-clay layers. Although the permeability of the clayey-marly strata is 1-2 magnitude lower than that of the sands, this is still enough to provide hydraulic connection between the sandy units, thus make the entire sedimentary succession one hydrostratigraphic unit.

Regarding the ***geothermal conditions*** of the TRANSENRGY project area, it does not comprise the hottest areas of the Pannonian Basin. Nevertheless, the overall geothermal potential is good in many parts (e.g. Mura-Zala and Styrian Basins in the SW, Vienna Basin, N-ern part of Danube Basin), where the heat-flow is up to 110-130 mW/m^2 and geothermal gradient can be as much as 45 °C/km. As a result, subsurface temperature distribution is favorable at many places (Goetzl et al. 2012), e.g. the depth of the 50 °C isotherm is found at 900-1200 m at most of the area, while to have 100 °C one has to drill 2000-2500 m deep in average (Fig. 3).

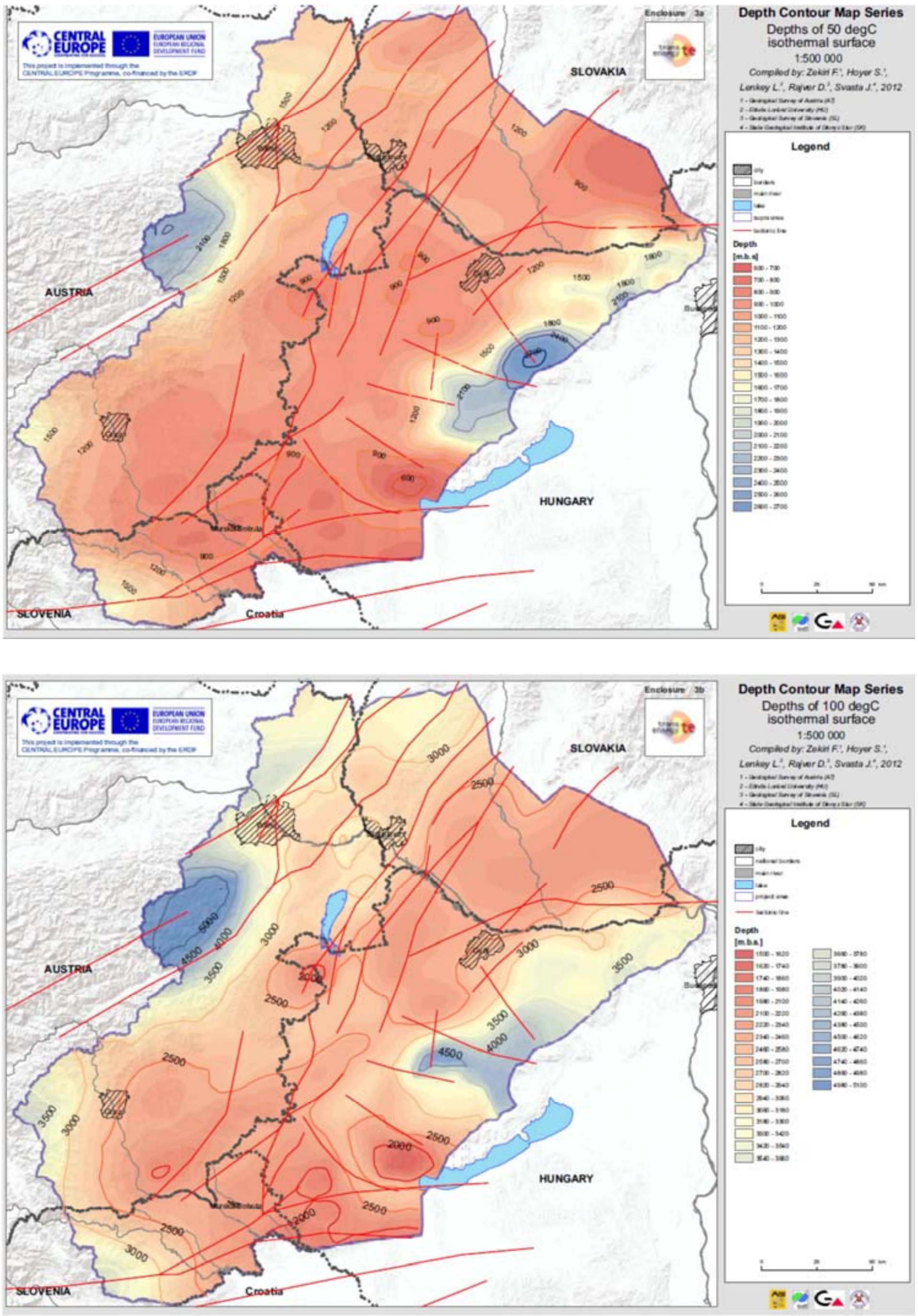


Figure 3: Depth of the 50 °C and 100 °C isotherms

3. TARGETED STAKEHOLDERS AND PROJECT WORKING METHODS TO ADDRESS THEIR NEEDS

Distinguish the targeted stakeholder groups, identify their needs, focus project work according to these recognized demands and finally communicate results “in the language” they speak; this is the right method to maximize impacts of any projects. Each potential target group has different interests and demands, which were overviewed and anaysed at the beginning of TRANSENERGY (Table 1). Although TRANSENERGY’s results contribute to some extent to almost all stakeholder groups, the project work has been conducted in a way from the very beginning that it should provide information to the ***decision makers and authorities, as primary target group***. The reasons were multi-folded. The project ***partners*** are experts of the ***national geological surveys*** of the four participating countries, and as such, their organizations’ mission is to provide the governments and decision makers comprehensive and ***impartial geoscientific information, support policy making*** related to the sustainable management of the environment and its resources. National geological surveys are responsible for the systematic acquisition, interpretation, management and dissemination of geoscientific data of their country’s landmass. They handle national geoscientific databases, too, so they are the best qualified organizations to provide scientifically based models and evaluations at national and macro-regional scales, independent of sectorial/users interest.

As authorities dealing with everyday management, licensing, etc. of thermal groundwater/geothermal energy were among the main targeted stakeholders, a special attention was paid to identify them. Based on a questionnaire survey, altogether 40 ***authorities’*** data (10-Austria, 15-Hungary, 7-Slovakia, 8-Slovenia; information on organization, contacts, role, etc.) were organized into a ***database*** (http://akvamarin.geo-zs.si/authorities) (Prestor et al. 2010).

The final project results also target the ***decision/policy makers at international level*** (Table 1), aiming to provide them scientifically based recommendations and evaluations supporting the performance of EU policies and elaboration of various strategies.

Stakeholder group	**Identified needs**
Decision makers (ministries, authorities, governmental bodies) *at national level*	-up-to-date information on the current utilization schemes and impacts, based on reliable datasets and impartial evaluations -concise thematic expert summaries supporting preparation of licences, policy documents (including on the national performance of binding targets from various EU directives)
Decision/policy makers at *supra-national/EU level* (bilateral water commissions, ICPDR, UNECE, Danube Strategy, DG Energy, DG Regio, etc.)	-bi/multilateral evaluations at a cross-border/supra-regional scale -recommendations for transnational management strategies -recommendations on long-term sectorial strategies
Companies developing geothermal projects	-information on the geothermal potential at a regional scale, including technical facilities -information on the current national regulatory and financial environment
Users (present and potential, including municipalities)	-information on the targeted reservoir properties and limits on their sustainable use -short and easy licensing procedures
Project investors, financing institutions	-financial supporting schemes -viability and risks management of the projects
Academia (universities, research organizations, scientific associations)	-up-to-date high-level scientific data -interpretations, models
Education (universities, high-school)	-training materials at various levels
Wider public	-increase awareness of geothermal

Table 1: Stakeholder groups and their needs in TRANSENERGY project with highlighting the primarily addressed decision/policy makers

Nevertheless, ***other stakeholder groups*** can also largely benefit from TRANSENERGY results. The outlined potential geothermal reservoirs (Rotár-Szalkai et al. 2012) provide an excellent overview for ***project developers*** on the prospective areas for further possible explorations, while feasibility studies (Kujbus 2012a, b, Vika et al. 2013) demonstrated for ***future investors*** that on the basis of project data and models tangible projects can be planned. The overview of current legislation (Lapanje et al. 2011) and financial incentives (Nádor et al. 2013) deliver useful information on the non-technical issues. The elaborated high quality geoscientific models (Rotár-Szalkai et al. 2013 a, b) can be also used in further ***academic research,*** while some results of pilot area models provide detailed information on reservoir properties for present and potential ***users***. Although education and raise of public awareness were not among the main project activities, an online game available at the project website (http://transenergy-eu.geologie.ac.at) was developed too, which offers basic information and education on geothermal energy for the ***wider public***.

After the identification of the main stakeholders and their needs, it was also important to ***transform the recognized general demands into tangible questions*** and ***elaborate a working method*** to be able to answer them. By setting up a questions and answers (Q&A) list (Table 2) it became clear that most of the questions can be answered on the basis of different geoscientific models based on a common understanding of the hydrogeothermal systems, therefore ***establishment of joint databases and modelling activity were defined as core activities of the project***.

Geoscientific models represent the simplified version of the existing hydrogeothermal systems (which are complex in reality) and by the interpretation and extrapolation of input data, they provide a continuous information in space (e.g. about the geological buildup, rock parameters, hydraulic heads that direct groundwater flow, temperature distributions in the subsurface, etc.) also for those areas, where measured data are not available. By quantifying the different parameters, models also simulate the relevant interactions of the real systems and may provide information about their future responses (Rotár-Szalkai et al. 2010).

The ***geological*** models outlined rock geometry, determined the main geological units with similar hydrogeological characteristics (i.e. hydrostratigraphical units), which were important input data for the hydrogeological and geothermal models. The ***hydrogeological-hydrogeochemical*** models described the thermal water flow system, while the ***geothermal*** models expressed the 3D temperature distribution in the subsurface.

Modelling activity was performed at two scales and in successive phases: first models (geological, hydrogeological and geothermal) were performed at 1:500 000 scale for the entire project area ("***supra-regional models***"). The aim of these models were to handle the project area in a uniform system approach, to determine the main geological structures and flow systems and the relation between them, to describe distant hydrogeological processes, to describe the geothermal potential and quantify the hydrogeothermal resources, and to provide boundary conditions for the pilot models. The ***models*** developed for ***pilot areas*** at a scale of 1.100 000 to 1: 200 000 focused on special transboundary problems which were different on each area. On the pilot areas both ***steady state*** (expected changes in the system under present utilization practice) and ***scenario*** models (responses of the system to different predicted/hypothetical utilization schemes in the fututure) were developed.

Some specific questions	Tool for answer
-Where and in which depth the main aquifers are?	*geological model* (3D distribution of the main hydrostratigraphic units)
-Which are the main flow systems and interactions among them? -How much thermal water can be abstracted which has natural recharge (i.e. quantify available free water resource)? -What is the current quantitative and qualitative status of the aquifers?	*hydrogeological model* (hydraulic parameters of the main hydrostratigraphic units, recharge and discharge zones, hydraulic potential fields and flow directions, groundwater budgets)
-Information on gases / dissolved content that might restrict utilization (scaling, corrosion, necessity of water treatment, utilization of associated gases, etc.) -Information on chemical composition (potentials for balneological utilization as medicinal waters)	*hydrogeochemical investigations* (chemical composition of thermal water)
-What is the temperature at certain depths? -How much heat is stored/available?	*geothermal model* (subsurface temperature distribution, estimation of geothermal resources and reserves)
-Where and how deep the potential reservoirs are? -What are the main reservoir properties (lithology, temperature, fluid composition)? -For which purpose the reservoir can be used? -What is the interaction between the different reservoirs? - What are the limits of abstraction, is re-injection necessary?	information on hydrogeothermal reservoirs (*combined interpretation* of geological, hydrogeological and geothermal model results)

Table 2: Q&A list: Most often addressed questions from authorities/decision-makers dealing with thermal groundwaters / geothermal energy resources in the TRANSENERGY region

4. STATE-OF-THE-ART

4.1. Geothermal conditions at supra-regional scale

The W-ern part of the Pannonian Basin has favorable geothermal conditions which were quantified by the supra-regional geothermal model (Goetzl et al. 2012). Within the model 16 regional maps were edited which show the surface heat-flow density (Fig. 4), temperature distributions at a depth of 1000, 2500, 5000 m and at the top of the pre-Tertiary basement (Fig. 5), the depths of different (50°C, 100°C and 150°C) isotherms (Fig. 3), as well as Heat in Place and Specific Identified Resource calculations for the Neogene sediments, the upper 50 m of the basement rocks and in 5 annd 7 km rock volume respectively.

The different temperature maps give an overview on the expectable rock temperatures in certain regions. The observed positive anomalies in 1000m below surface correspond to shallow hydrodynamic systems, whereas deeper subsurface temperature distributions are mainly influenced by large scale crustal structures. These maps indicated that in some parts of the supra-regional area positive geothermal anomalies occur in the subsurface. The SW-ern part of the project area covering the parts of the Styrian and Mura – Zala Basin is a region with favourable geothermal conditions (> 120mW/m^2). The increased HFD values (in the Mura – Zala Basin) are related to the convection zones in the pre-Tertiary basement rocks and to various geological conditions like e.g. reduced crustal thickness. Additionally several local to regional scale geothermal anomalies were depicted. The positive geothermal anomalies in the southern part of Vienna (“Oberlaaer High”) and between Bratislava and Vienna (Bad Deutsch-Altenburg) are likely to be related to naturally ascending thermal water (hydrodynamic systems). At the central part of the Danube basin in Slovakia high HFD values can be observed. This is a result of the thick sedimentary basin fillings. In the region of Komarno and Sturovo the depicted positive geothermal anomalies are also correlated with circulating groundwater systems.

The Specific Identified Resources maps imply that a huge amount of heat is stored in the subsurface. However, only the heat stored in porous, permeable rocks can be utilized economically by production of hot water or steam, and these rocks comprise only a small fraction of the total volume of rocks. These calculations were made more percisely for the selected hydrogeothermal reservoirs on the pilot areas (Chapter 4.9).

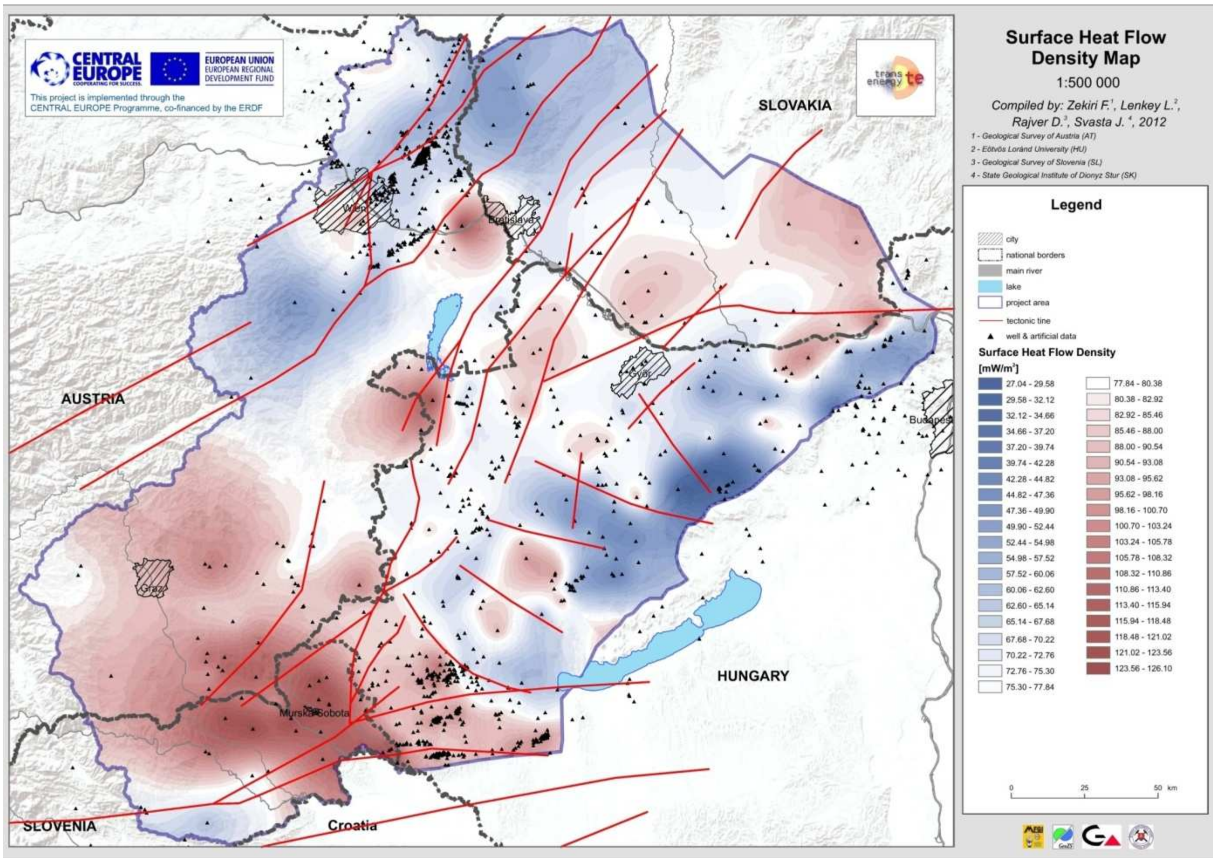


Figure 4: Surface heat flow density map of the supra-regional area

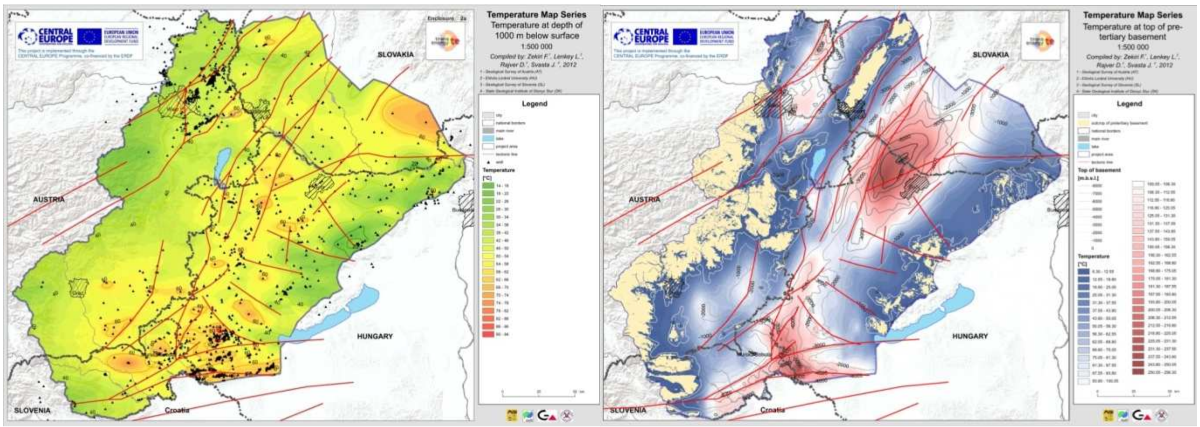
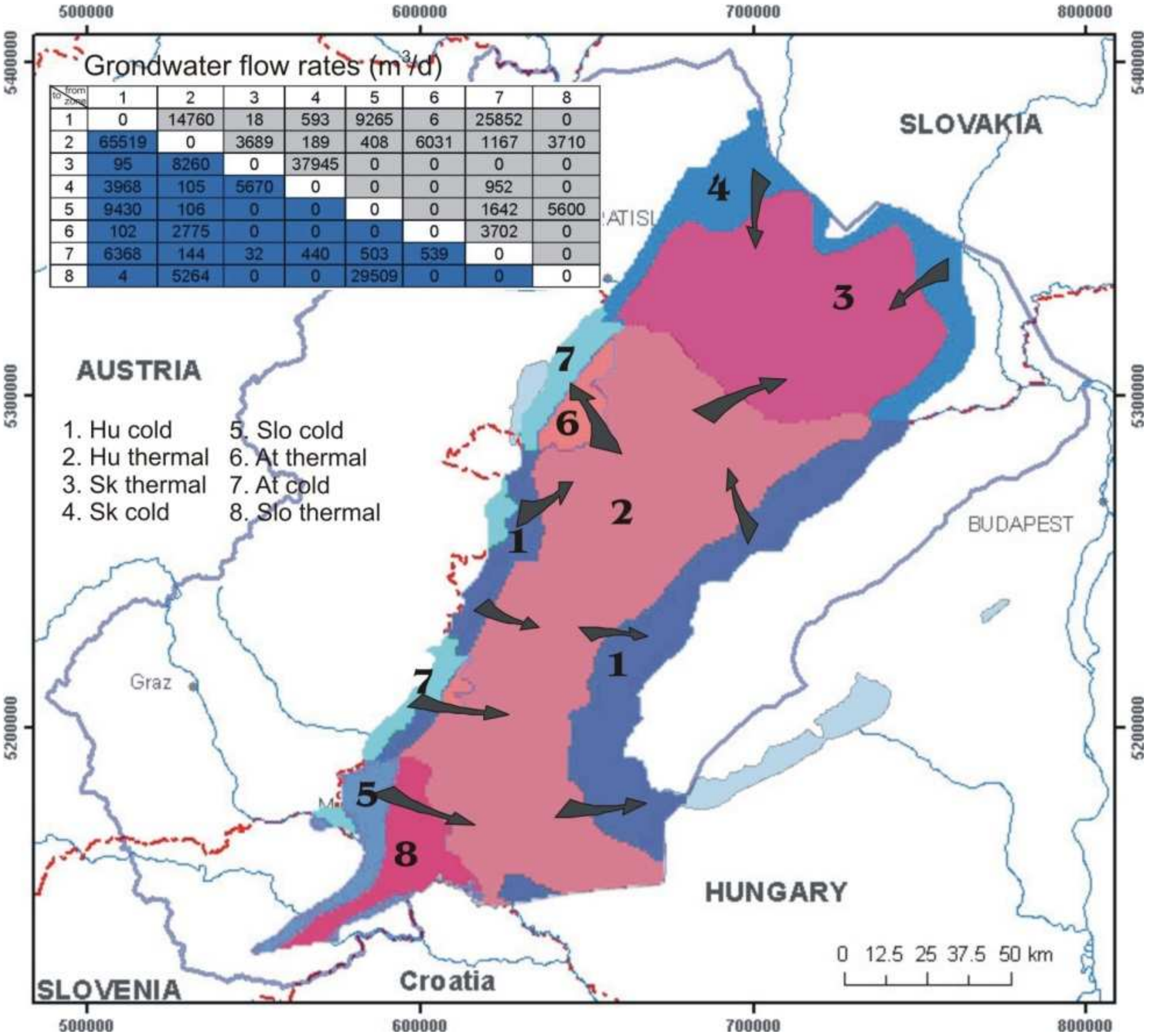


Figure 5: Temperature at a depth of 1000 m and on top of the pre-Tertiary basement

4.2. Transboundary thermal groundwater flow at supra-regional scale

The results of the supra-regional hydrogeological model (Tóth et al. 2012) provided firm evidences for significant thermal water flow across the political borders both in the Neogene intergranular and in the fractured-karstified basement aquifers. The model furthermore quantified the computed water budgets and the transboundary water transfers (Fig. 6) and also showed that the present productions in each country have significant transboundary effects (Fig. 7). These effects were further studied in more details at the pilot areas (Chapter 4.9.).



Grondwater flow rates (m^3/d)

to \ from zone	1	2	3	4	5	6	7	8
1	0	14760	18	593	9265	6	25852	0
2	65519	0	3689	189	408	6031	1167	3710
3	95	8260	0	37945	0	0	0	0
4	3968	105	5670	0	0	0	952	0
5	9430	106	0	0	0	0	1642	5600
6	102	2775	0	0	0	0	3702	0
7	6368	144	32	440	503	539	0	0
8	4	5264	0	0	29509	0	0	0

Figure 6: Computed water budgets and the transboundary water transfers on the supra-regional area

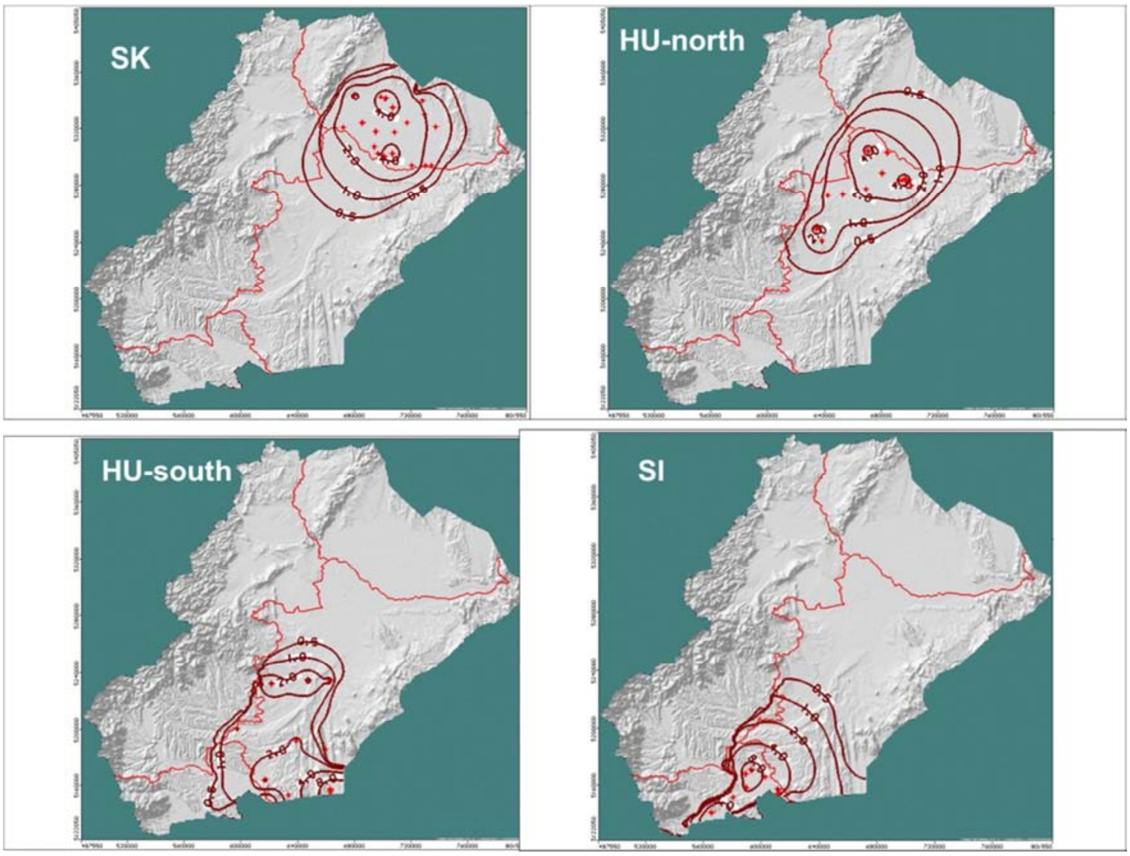


Figure 7: Computed drops in hydraulic heads in the Upper Pannonian intergranular aquifer due to present productions in Slovkia, Hungary and Slovenia, numbers on isolines refer to drop in meters

4.3. Current use of thermal groundwaters

One of the major results of TRANSENERGY was a detailed overview and analysis of the present thermal water utilization in the region. An extensive survey of the existing thermal water users, utilization parameters and exploited aquifers (Rman et al. 2011a, b) identified altogether ***175 users*** (23-SLO, 28-SK, 20-AT, 104-HU) out of which 144 were active, with current abstraction of thermal groundwater (outflow temperature > 20 °C) from ***308 boreholes*** (35-SLO, 39-SK, 50-AT, 184-HU). All data have been incorporated into a database, available at: http://akvamarin.geo-zs.si/users/.

If the number of organizations is compared to the country's project area, Hungary is the most densely exploited (6.3 users per 1000 km^2), Slovenia (5.8 users per 1000 km^2 becomes the second, followed by Slovakia (2.9 users per 1000 km^2) and Austria (1.1 user per 1000 km^2), however, the territorial distribution is uneven and some ***heavily exploited areas*** can be outlined, in some cases at transboundary regions (e.g. along the Danube, Mura-Zala Basin) (Fig. 8).

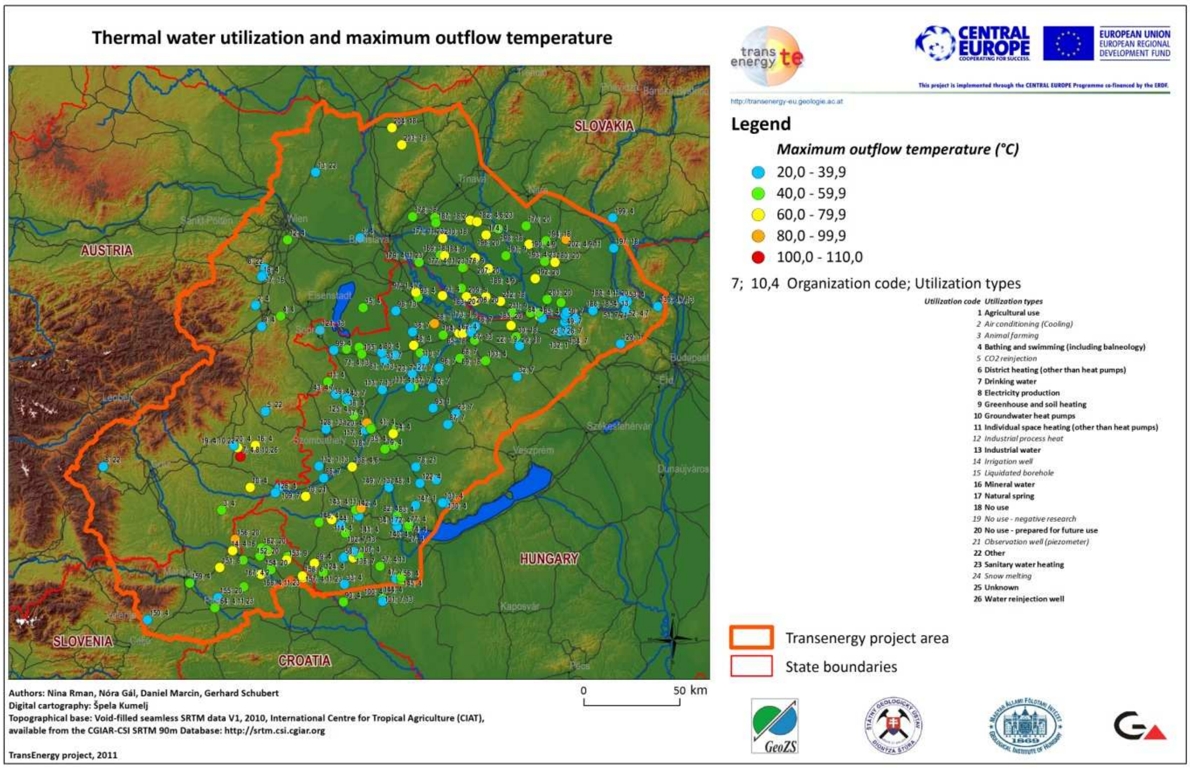


Figure 8: Thermal water utilization and max. outflow temperature

The overwhelming type (Fig. 9) of use is ***bathing and swimming including balneology***, followed by using as a ***drinking water***, however this is reported only for Hungary where thermal water is considered to have an outflow temperature of ≥ 30 °C. Individual space ***heating*** is at the third place and exists relatively at few places, mostly in the Danube Basin in Slovakia and in NE-Slovenia; geothermal district heating is even less (e.g. Lendava-Slovenia, Galanta-Slovakia, Vasvár-Hungary). Industrial water use is reported only from Hungary, and sanitary water use from Slovakia and Slovenia. The utilization of thermal water for heating of greenhouses applies only to a dozen of boreholes in Hungary, Slovakia and Slovenia. Power production exists only at one place (Bad Blumau, Austria) at a small pilot plant.

Although the outflow temperature is relatively low (majority is in the range of 20-60 °C in the area), and only a smaller number of the wells (mostly in the Slovakian part of the Danube Basin and in NE-Slovenia) produce thermal water above 60 °C (Fig. 2), the ***low percentage of energy utilization*** is still striking. Thermal water is mainly abstracted by pumping, and natural outflow prevails only in Slovakia.

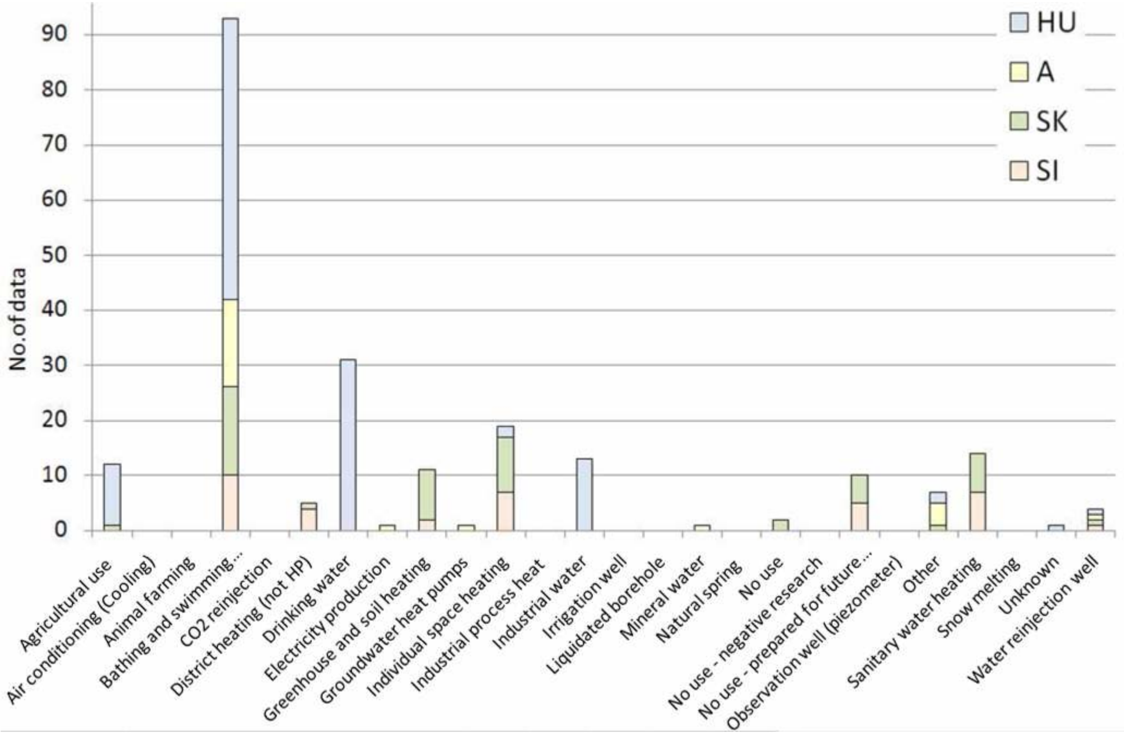


Figure 9: Thermal water use in the TRANSENERGY project countries (226 inputs for 175 organizations)

The main exploited geothermal aquifers are the Upper Pannonian sandstones (55%) and fractured-karstified Mesozoic basement rocks (limestones and dolomites) (27%), found at a depth between 500 and 2000 m on average. The Middle Miocene clastic (7%) and the Palaeozoic carbonate (4%) aquifers are also important. The ***total annual production*** from these aquifers was 31.3 million m^3 in 2009 in Hungary, Slovakia and Slovenia, whereas Austrian production data were confidential. If we estimate the Austrian production, the total annual thermal water abstraction can be approximated to be around ***35-40 million m^3/year*** in the project area**.** The large amount of produced thermal water, the overwhelming balneological use and the lack of re-injection at the few direct-heat application sites threaten the reservoirs to be ***overexploited***, as it was already demonstrated at several locations. In addition, our investigation revealed a granted or requested thermal water demand of at least double of the current production, which ***forecasts*** a hypothetical amount of thermal water abstraction of up to ***60 million m^3*** in the future (neglecting assumptions related to confidential production data in Austria).

The threat of overexploitation was further supported by the ***observed changes*** in operation, which was reported from many inspected boreholes. Only 1% of the boreholes targeting the Mesozoic carbonate aquifers indicated yield decrease, showing that they receive enough recharge. Contrary, 13% of the boreholes producing from the Upper Pannonian intergranular aquifers showed a decrease in the yield and water level, whereas temperature and water-level drop was reported from 21% of the boreholes producing from Middle Miocene clastic reservoirs. These unfavourable trends affected most seriously the Palaeozoic fractured metamorphic aquifers, where drop in yield/temperature was reported from 67% of the boreholes.

As analyses (Rman et al. 2011 a, b) showed, only ***four sites*** of geothermal energy applications ***have re-injection***, and only one (Bad Blumau, Austria, re-injection into Palaeozoic dolomite aquifer) operates continuously. Periodic re-injection happens at Podhajska (Slovakia) into the

Mesozoic carbonates and at Lendava (Slovenia), into the Upper Pannonian clastic reservoir, while at Mosonmagyaróvár (Hungary) the re-injection well is not in operation.

Due to the practical lack of re-injection, all users emit their used water to sewage systems or to the surface waters (creeks, rivers). Data / information on ***waste water treatment*** was very poor and showed that only 10% of users clean waste water at purifying plants (Austria, Slovenia). Waste water monitoring targeting quantity, chemistry and temperature, exists to some extent in all countries, however they do not provide sufficient data. ***Thermal pollution*** is a serious issue: more than ***94% of the active users*** emit waste water with average annual temperature ***above 20°C*** (17% between 20-25 °C, 60% between 25-30°C, and another 17% with temperature above 30°C). This implies that ***thermal efficiency is low***, and the extraction/utilization of heat energy is insufficient.

4.4. Delineataion of transboundary thermal water aquifers / hydrogeothermal reservoirs

The ***Water Framework Directive*** (WFD) (2000/60/EC) addressed for the first time in a comprehensive manner all the challenges faced by EU waters. It targets ***river basins***, i.e. natural hydrological, hydrogeological units irrespective of state borders. Furthermore the WFD recognized that the aquatic environments differ greatly across the EU and therefore did not propose any „one size fits all solution", i.e. provided ***only guidance on the execution*** of the achievement of its ultimate goals (good status of waters by 2027). This causes ***discrepancies*** among the countries, i.e. when TRANSENERGY prepared a systematic comparison of the national River Basin Management Plans (Prestor et al. 2012) it was demonstrated that ***the delineation of groundwater bodies*** (GWB-s as basic units of the RBMP-s) ***differ*** greatly in the participating countries, therefore ***does not allow a direct comparison of aquifers in the transboundary regions***.

In ***Slovenia,*** GWB-s are delineated only by surface boundaries and comprise a set of different vertical layers within the characteristic aquifer according to their different properties. The thermal water aquifers (T > 20°C) of the TRANSENERGY project area have been identified and characterised within the six groundwater bodies. Identified geothermal aquifer types in this region include the deeper Neogene sediments and the pre-Neogene carbonate or metamorphic basement rocks.

In ***Austria,*** GWB-s were distinguished based on the depth, i.e. shallow and deep ones. Among the deep GWB-s, the only thermal one was described in Upper Austria (the so called "Malm" aquifer situated in Upper Jurassic carbonates in the area between Bavaria and Upper Austria) and no groundwater body with thermal water was delineated within the Austrian area of TRANSENERGY.

In ***Hungary,*** GWB-s are classified according to lithology and temperature of the aquifer: intergranular and karstic types, and those producing water with outfllow temperature equal or higher than 30°C are considered thermal. The Hungarian part of the TRANSENERGY project encompasses two thermal intergranular and six thermal karstic groundwater bodies.

In ***Slovakia,*** three layers of groundwater bodies were delineated based on the depth (nevertheless with a different approach than in Austria, or Slovenia): upper layer (Quaternary GWB-s), basic layer (pre-Quaternary GWB-s) and deep layer (including thermal water aquifers, T >15 °C). The Slovak part of TRANSENERGY encompasses six geothermal groundwater bodies, which are situated in the Neogene sands, sandstones, conglomerates and the Triassic to Jurassic carbonates.

These discrepancies have several consequences:

- it is impossible to compare and assess in a comprehensive way the status, environmental objectives and measures of the hydrogeologically linked aquifers in the transboundary regions (as they belong to different groundwater bodies),
- it impedes the delineation of joint transboundary groundwater bodies for the same reasons.

To deliver a scientifically based and uniform context for the delineation of transboundary geothermal aquifers, ***potential hydrogeothermal reservoirs*** have been outlined on the basis of integrated interpretation of the results of the supra-regional geological, hydrogeological and geothermal models and hydrogeochemical data (Rotár-Szalkai et al. 2012).

Applying the definition of a geothermal reservoir ("a part of the geothermal field that is so hot and permeable that it can be economically exploited for the production of fluid or heat" by Grant and Bixley 2011) to the geological conditions of the TRANSENERGY area, the permeable rock volumes having a temperature higher than 50 °C were considered as potential geothermal reservoirs. To be able to provide a simple and transparent characterization for the decision-makers, ***three major reservoir categories*** were established based on the geological and hydrogeological properties of the rock units:

1) Upper Pannonian (i.e. Uppermost Miocene-Pliocene) porous reservoirs,
2) Miocene (i.e. Sarmatian, Karpatian, Badenian and Ottnangian) reservoirs (with 3 sub-types: porous, double-porosity, non-classified),
3) Basement fractured crystalline and carbonate (partly karstified) reservoirs.

The top surfaces of the reservoirs were constructed by combining the different geological horizons, isotherm surfaces, and hydrogeological characterization of the different geological formations.

The outlined ***Upper Pannonian porous reservoirs*** (Fig. 10) with a temperature range of 50-100 °C are the most widespread, ranging from the Danube Basin to the Mura-Zala Basin and cross-cut by political borders. These geothermal aquifers are widely utilized for balneological purposes as well as for direct heat (mostly greenhouses), therefore groundwater level, yield and temperature drops due to overexploitation are already existing problems at many locations. Usually the Upper Pannonian reservoirs get direct recharge via the overlying sediments, or from their outcropping sandy layers and / or Quaternary aquifers on the hilly areas with a higher hydraulic potential. This is reflected in the chemical composition of the stored thermal waters with relatively low salinity, and a total dissolved solid content increasing with depth. The deep regional thermal groundwater flow system developed in the Upper Pannonian sandy aquifers is generally characterized by an alkaline $NaHCO_3$ character. However, based on the differences in water chemistry, this large reservoir unit was subdivided into 4 sub-categories with the highest total dissolved content on its northern part and the most dilute waters on the south. These reservoirs can be potentially used for direct-heat purposes and balneology, but the high total dissolved content can be a restricting factor.

Due to lithological heterogenity and porous character, re-injection into these reservoirs has to be planned cautiously, as the necessary injection pressure can substantially increase within a relatively short time. The most common problem is the plugging of screens (perforation) in the well and pore throats of the reservoir formation. The precise mechanisms which determine injectivity are site specific, and processes are not entirely understood yet, therefore research and development is necessary before applications.

Upper Pannonian porous reservoirs above 100 °C occur in a much smaller region: the central part of the Danube Basin and in a small area in the Mura-Zala Basin in Slovenia, close to the Croatian border (Fig 10). As a consequence of the bigger depth, this reservoir is already partly separated from the regional gravitational flow system. The higher temperature makes it suitable also for combined heat and power applications, however restrictions of re-injection are similar as described above.

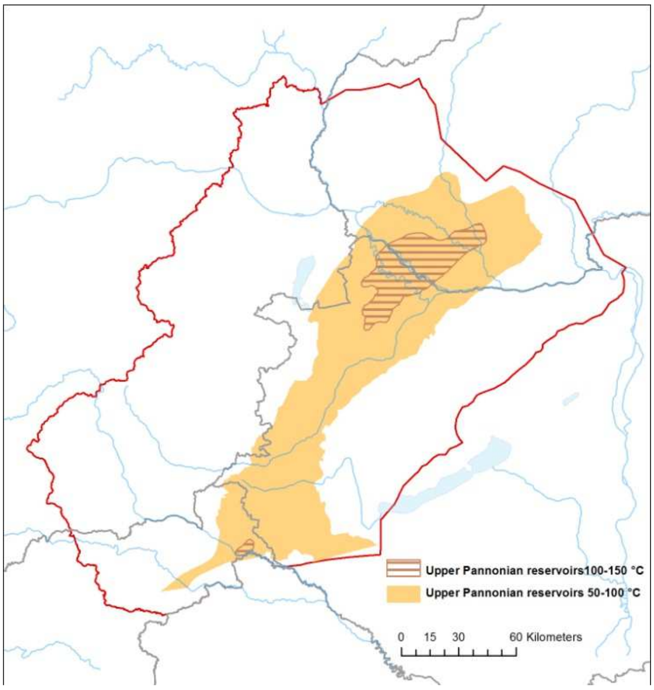


Figure 10: Upper Pannonian porous reservoirs

The identified ***Miocene reservoirs*** (Fig. 11) typically displayed a scatterd distribution occurring either on the marginal parts of the basins, or in elevated position on the basement highs. Based on the geological and hydrogeological properties of the Miocene formations, 3 sub-types were distinguished.

(1) Coarse grained sediments, conglomerates, sands, sandstones, deposited at several places in small (some tens of meters) thickness form porous thermal water aquifers, with usually direct hydraulic connection to the fractured basement reservoirs.

(2) The most important Miocene thermal water reservoirs are the widespread Badenian and the Sarmathian shallow-marine clastic carbonates with a few tens of meters thickness. They are considered as reservoirs with double porosity and also often have direct hydraulic connection to the fractured basement reservoirs.

(3) There are some known Miocene reservoirs (geothermal aquifers with operating wells), where the lithology of the screened interval cannot be identified due to missing geological information from well documentation, therefore these are displayed as "non-classified".

The depth of the different Miocene reservoirs shows a wide range depending on their local geological settings.

Depending on their position, the Miocene reservoirs are generally semi-open, or closed structures regarding their hydraulic connections. They store different types of groundwater depending on the burial depth. Where layers outcrop, the infiltrating Ca-Mg-HCO_3 water type is observed, while towards deeper parts the longer retention time, cation exchange, mixing, dissolved gas and other geochemical processes modify the composition, so Na-HCO_3 to Na-Cl types prevail and the reservoirs generally have high, sometimes extremely high TDS content, which may cause scaling problems during operations.

Despite the favorable porosity conditions, the high dissolved content and the relatively small thickness put a limit on the wide-range utilization of the Miocene reservoirs, furthermore re-injection can be also problematic. Nevertheless, balneological and direct-heat utilizations are feasible at certain locations with favorable settings, as well as combined heat and power in areas where temperature is above 100°C and reservoirs have a direct hydraulic connection to the fractured basement rocks.

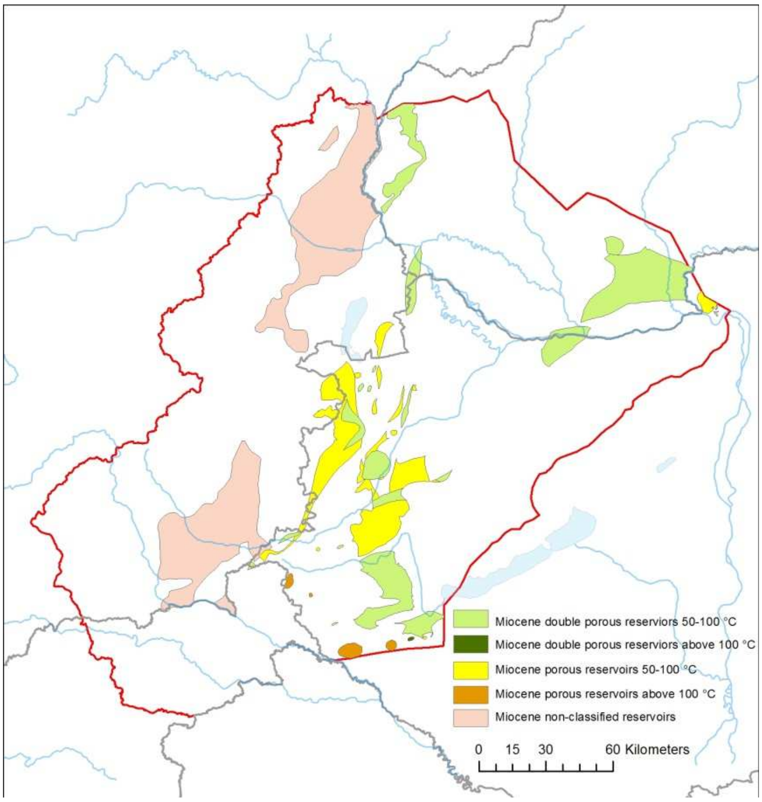


Figure 11: Miocene reservoirs

The ***fractured basement reservoirs*** were subdivided into two main sub-categories: crystalline (Fig. 12) and (partly karstified) carbonates (Fig. 13).

From hydrogeological point of view, the crystalline basement formations are considered to be aquicludes. Nevertheless, locally they can form fractured aquifer systems, especially the weathered upper 50 m of the basement. The locations of these aquifers are very uncertain, and can be further specified only by detailed geophysical methods. Considering this uncertainty, the entire crystalline basement with temperature higher than 50°C was outlined as a potential reservoir, which encompass most of the regions beneath the Neogene sub-basins and also includes siliciclastic rocks below the Vienna Basin. Regions where temperature exceeds 100 °C at the surface of the basement also have great extension in the central parts of the basins, while areas having temperature above 150 °C are restricted to the basin interiors (Fig. 12).

The fractured crystalline basement reservoirs are usually closed structures with restricted-, or limited connections to the regional flow systems, therefore the chemical composition of the geothermal fluids is expected to have high salinity and NaCl type (fossil waters). The reservoirs have a wide range of utilization potentials of direct-heat, combined heat and power and even power generation in parts where temperature may exceed 150 °C, however both production and re-injection is limited to larger fracture zones with increased hydraulic conductivity.

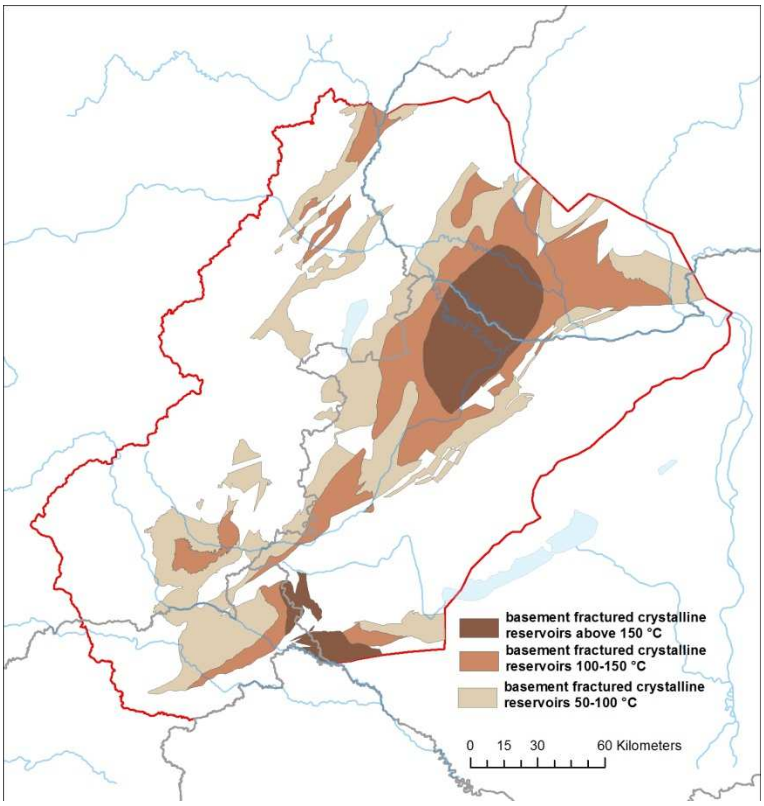


Figure 12: Basement fractured crystalline reservoirs

The non-metamorphic, Mesozoic formations and the carbonate units of the Graz Palaeozoic can be considered as potential fractured carbonate reservoirs, which occur in the basement of the Vienna and Styrian Basins and in the basement on the area of the Transdanubian Range (Fig. 13). They are fractured aquifers with different magnitude of permeability. Where the carbonate sequences could have been karstified during their geological evolution (especially the upper zone of the formations) permeability can be higher and form good to excellent reservoirs. Depending on the location, the temperature of these fractured carbonate basement rocks can be classified into 50-100 °C, >100 °C, >150 °C.

The chemical composition of the basement carbonate reservoirs depends on their hydraulic connections to the regional flow systems. The Mesozoic carbonates of the southern part of the Vienna Basin and the carbonate formations of the Transdanubian Range have low TDS content, because they have direct connection to the surface outcrops (direct recharge). The hydrogeochemical nature of these waters generally show a mixture of low salinity Ca-Mg-HCO_3 character related to the infiltrating cold karstwaters. In addition, Na-HCO_3 to Na-Cl types may also occur depending on the connection to other reservoirs, or their isolation from the regional groundwater flow system. The carbonate sequences at northern part of the Vienna Basin usually form closed reservoirs without recharge. Their chemical composition can be characterized with high TDS content.

Similarly to the crystalline reservoirs, the fractured carbonate reservoirs also have great utilization potentials for direct-heat, combined heat and power and power generation in parts where temperature may exceed 100-150 °C. Nevertheless, both production and re-injection is limited to larger fracture zones with increased hydraulic conductivity. The best opportunities are on those areas where the carbonates are highly karstified and fluids have low TDS content.

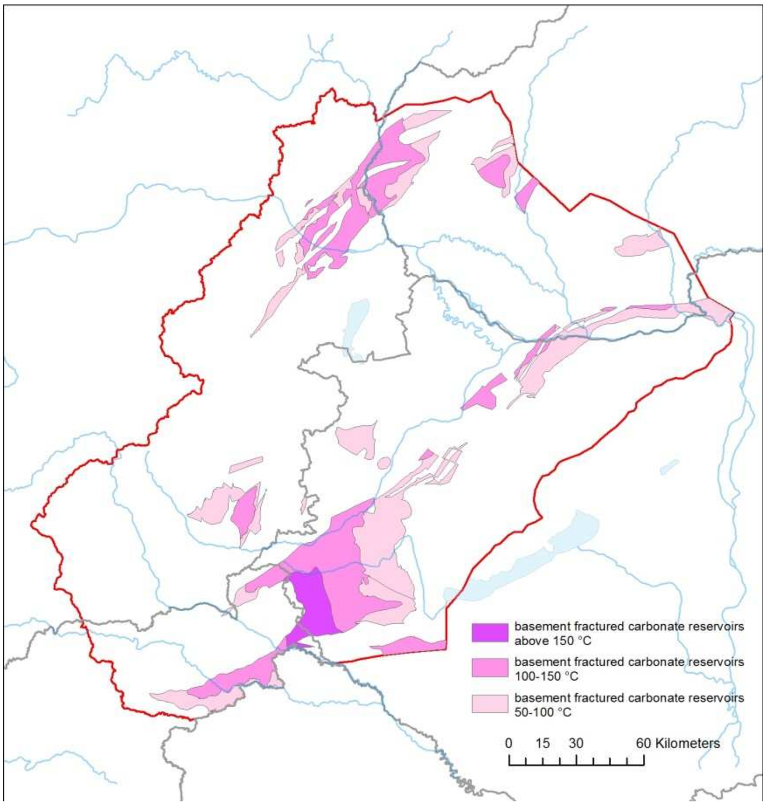


Figure 13: Basement fractured carbonate reservoirs

4.5. Monitoring

Monitoring, as integral part of management has been overviewed and analysed by several TRANSENERGY studies (Prestor et al. 2012, Rotár-Szalkai et al. 2013 c).

Monitoring of hydrogeothermal systems are ***two-folded***: on one hand they are strongly linked to the related questions of ***groundwater monitoring*** and management, and as such are rather focussing on the fulfilment of environmental targets (sustainable satisfaction of water demands without causing long-lasting qualitative and quantitative changes in the aquifers). On the other hand, measurements have to provide reliable data on ***energy contribution*** of geothermal installations, such as mass flow and temperature, which require different concepts and other types of parameters to be measured.

Monitoring associated with energy contribution are related to the measurement of physical changes in a geothermal reservoir, while environmental measurements have to provide information on the response of the natural system to the stress of abstraction and emission, as well as the efficiency of utilization. Both types of monitoring include the following measurements:

- Mass discharge history of production wells
- Enthalpy or temperature of fluid produced
- Wellhead pressure (water level) of production wells
- Chemical composition of water and steam produced
- Injection rate histories of re-injection wells

- Temperature of re-injected water
- Wellhead pressure (water level) of re-injection wells
- Reservoir pressure (water level) in observation wells
- Reservoir temperature through temperature logs in observation wells
- Well status through caliper logs, injectivity tests and other methods

In the frame of the implementation of the WFD-National River Basin Management Plans (being compulsory for all TRANSENERGY countries as Member States), groundwater monitoring wells have been selected from each country on which reporting towards the EU is a legal obligation (WFD-monitoring systems). Nevertheless, these representative monitoring stations for groundwater bodies, transboundary aquifers and protected areas have been selected in each country depending on the national conditions (hydrogeological situation, identified groundwater bodies, etc.) which vary a lot from country to country and in many cases do not characterize thermal aquifers. Furthermore, each country has its own rules on groundwater monitoring (including thermal water monitoring).

It was concluded that ***monitoring (quantitative and qualitative)*** in general is ***well regulated at national levels*** by different acts with detailed provisions on the parameters, frequency of measurements, reporting obligations, etc. It was also seen that the source of information (i.e. “sub-types” of monitoring) is fairly similar in the TRANSENERGY countries:

- at a national level the organizations being responsible for the coordination and implementation are typically governmental bodies (Slovak Hydrometeorological Institute-SHMI, Environmental Agency of Slovenia-ARSO, Regional Directorates for Environmental Protection and Water Management in Hungary),
- other monitoring sub-systems are operated by the individual municipals, local governments,
- periodical surveys are performed by government bodies, scientific institutes and other organizations,
- measurements are also performed by the users, water-license holders.

Nevertheless, there is a significant ***difference in the classification and terminology of the*** above listed ***“sub-systems”*** listed above in the TRANSENERGY countries, which led to different interpretations even among experts. For example in Hungary “areal monitoring” refers to monitoring at a national level that is under the auspices of the state, local governments or other state organizations. Its density and details of measurements are proportional to the rate of the public interest. The monitoring carried out by users is called „environmental impact monitoring”, while this is referred as „operational monitoring” in Slovenia. However under the EU WFD and Hungarian regulatory framework „operational monitoring” is defined as monitoring used to determine the status of water bodies identified as being at risk and following their changes as result of the programme of measures.

It was concluded that the ***monitoring of thermal water resources is insufficient*** in all TRANSENERGY countries. There are only a few (if at all any) observation wells being part of the “national” monitoring systems, which would provide reliable information on the actual static status of the reservoir. Monitoring of the active production wells by users is functioning; however the integrated evaluation of these data at a regional scale is missing in many cases.

To improve monitoring, tangible recommendations have been pharesed for monitoring wells at each pilot area based on the integrated evaluation and understanding of the targeted geothermal aquifers, these are discussed in details in chapter 4.9.

4.6. Reporting

Similarly to monitoring, the reporting on the utilization of geothermal resources is also two-folded: it has energy and environmental aspects.

Reporting of ***geothermal energy utilization*** has different levels. The ***compulsory reporting*** (including all TRANSENERGY countries, as Member States) is related to the performance of the National Renewable Energy Action Plans (NREAP). The yearly abstracted geothermal energy from the geothermal resources has to be reported to the Commission by 31 December 2011, and every two years thereafter. The sixth report, to be submitted by 31 December 2021, shall be the last report required. Nevertheless, these reports include only the total annual installed capacity (MW_e) and gross electricity generation (GW_e) in geothermal power production and total annual contribution in heating and cooling (ktoe) in direct use, so are too general for regional / local and sectorial assessments (e.g. geothermal energy used in the agriculture, district heating systems, etc.).

Nevertheless, there are several ***voluntary reporting methods***, which provide more detailed information. The internationally most accepted one is the so called »***Australian / Canadian Geothermal Code for Public Reporting***« (AGC 2009, CGCC 2010). The Codes aim to produce and maintain a methodology and provide a minimum, mandatory set of requirements for public reporting of exploration results to inform the existing and potential investors, their advisors, as well as governmental agencies. They give provisions on the entire life-cycle of a geothermal project, applicable also in other countries, therefore they became internationally accepted. The Codes provide a detailed list of parameters which have to be assessed including a set of pre-drilling exploration technical data, tenement, environmental and infrastructure data, subsurface and well-discharge data including reservoir properties, resource parameters, as well as additional factors. Although the Codes are well-known and accepted as a methodology in TRANSENERGY countries, reporting according to its requirements does not exist in everyday practice, partly due to its complexity and data confidentiality. Furthermore these data provide only local information related to a concrete project, therefore only summation of several reports would allow regional evaluations.

Nevertheless the Codes also lay down principles of categorization and assessment of geothermal resources and reserves, which were also used by TRANSENERGY while making potential evaluations for selected reservoirs at the pilot areas (see in Chapter 4.9).

Another voluntary reporting includes the ***IGA/EGEC templates***, which are required for the country update reports for the international geothermal congresses. The set of tables for deep geothermal include data on electric power generation (indirect use), as well as direct use (swimming, bathing and balneology, space heating including district heating, agriculture applications, aquaculture applications and industrial processes), where the installed capacity and annual energy use for each category is presented. Required data include: flow rate, inlet and outlet temperatures at maximum utilization and resulting capacity. All TRANSENERGY countries submitted these reports for the 2013 European Geothermal Congress, and so far these templates seem to be the most appropriate ones providing a comprehensive picture on the geothermal utilization of a country.

Reporting of ***environmental measures*** related to the Water Framework Directive in the frame of the national River Basin Management Plans are associated with the quantitative and qualitative status of groudwaters (Tables 3, 4). This is a well established and accepted methodology which delivers sufficient information on the environmental status of the targeted aquifers.

The level of groundwater in the groundwater body is such that the available groundwater resource is not exceeded by the long-term annual average rate of abstraction.	y/n/uncertain
Accordingly, the level of groundwater is not subject to anthropogenic alterations such as would result in: – failure to achieve the environmental objectives for associated surface waters,	y/n/uncertain
– any significant diminution in the status of such waters,	y/n/uncertain
– any significant damage to terrestrial ecosystems which depend directly on the groundwater body,	y/n/uncertain
Alterations to flow direction resulting from level changes may occur temporarily, or continuously in a spatially limited area, but such reversals do not cause saltwater or other intrusion, and do not indicate a sustained and clearly identified man induced trend in flow direction likely to result in such intrusions.	y/n/uncertain

Table 3: Reporting quantitative status of a groundwater body

The chemical composition of the groundwater body is such that:	
– does not exhibit the effects of saline or other intrusions or trends that could exhibit unstable conditions and uncertain prediction,	y/n/uncertain
– does not result in failure to achieve the environmental objectives for associated surface waters, nor any significant diminution of the ecological or chemical quality of such bodies, nor in any significant damage to terrestrial ecosystems which depend directly on the groundwater body.	y/n/uncertain

Table 4: Reporting chemical status of a groundwater body

4.7. Databases, data policy

Vast amount of different geological, hydrogeological and geothermal data were available at the partner national geological surveys in different formats, stored in various database structures. However, these inhomogeneous datasets did not make possible uniform evaluations in their original formats. Geoscientific models with consistent content for the entire project area established in TRANSENERGY required harmonized datasets from the four countries; therefore establishment of a ***joint, multi-lingual borehole database*** was one of the key-activities and core outputs of TRANSENERGY (Mikita et al. 2011). The expert database contains tens of thousands of data records from ***1686 boreholes*** (Fig. 14) in the four countries, organized into ***483 parameters*** and 11 major parameter groups (Fig. 15) including technical, geological, hydrogeological, geothermal and hydrogeochemical data. Databse of the active thermal wells used for the evaluation of current use (Chapter 4.3.) has a different structure and parameter content as required for specific evaluation. Nevertheless it is compliant to this borehole database.

In addition to provide experts by high-quality data, TRANSENERGY also aimed to make the main parameters of boreholes publicly available (considering confidentiality issues). Nearly 100 000 records regarding the key geological, hydrogeological, geothermal and hydrogeochemical properties from ***1041 boreholes*** (AT-115, SI-128, HU-742, SK-56) were made freely accessible at the project website (http://transenergy-eu.geologie.ac.at). This ***public database*** also significantly contributes to the work of authorities, decision-makers, as they can check on-line the most important parameters of boreholes in the targeted regions.

Nevertheless the strict Austrian data confidentiality policy was considered as a barrier during the project work.

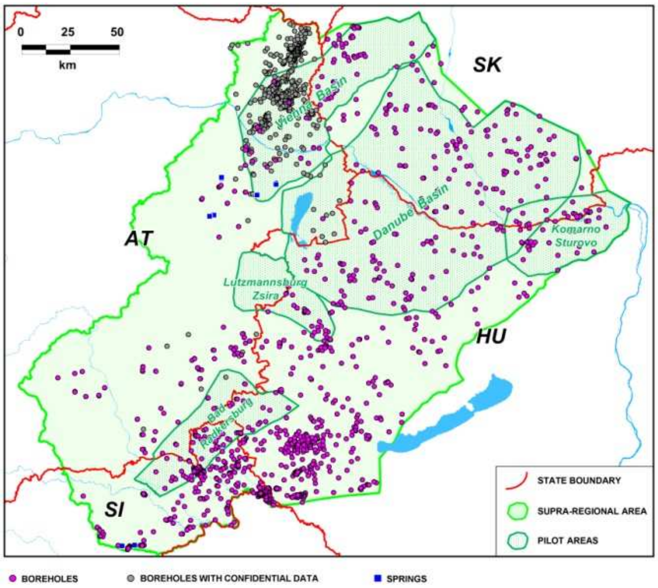
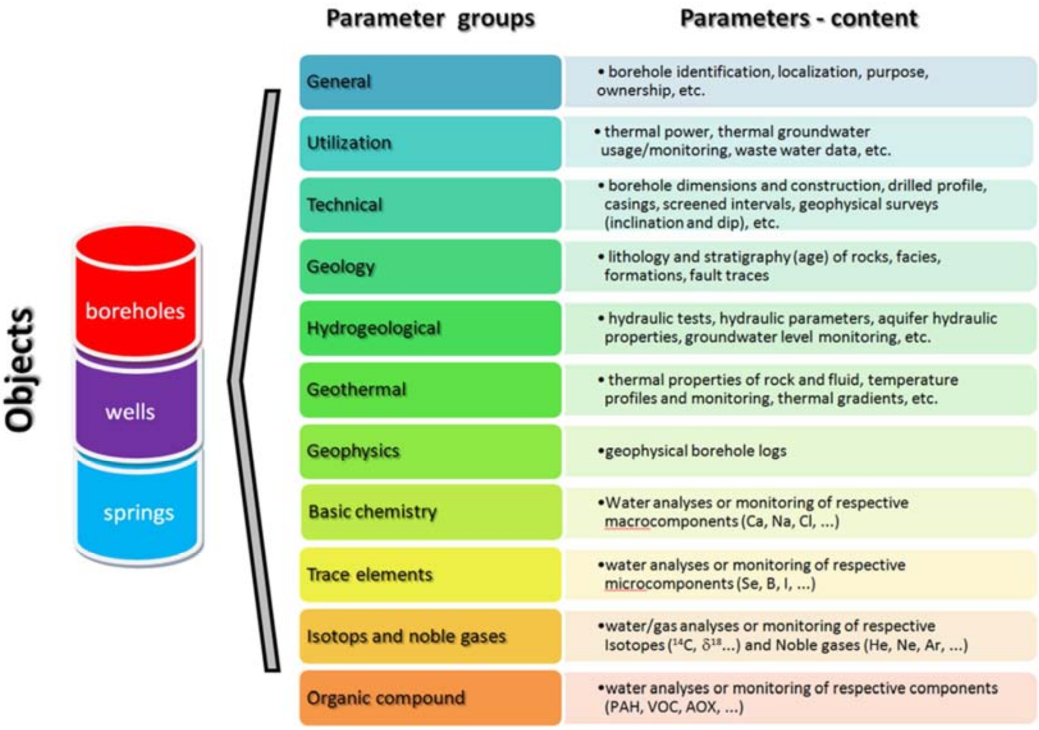


Figure 14: Distribution of boreholes of TRANSENERGY borehole database



Parameter groups	Parameters - content
General	• borehole identification, localization, purpose, ownership, etc.
Utilization	• thermal power, thermal groundwater usage/monitoring, waste water data, etc.
Technical	• borehole dimensions and construction, drilled profile, casings, screened intervals, geophysical surveys (inclination and dip), etc.
Geology	• lithology and stratigraphy (age) of rocks, facies, formations, fault traces
Hydrogeological	• hydraulic tests, hydraulic parameters, aquifer hydraulic properties, groundwater level monitoring, etc.
Geothermal	• thermal properties of rock and fluid, temperature profiles and monitoring, thermal gradients, etc.
Geophysics	•geophysical borehole logs
Basic chemistry	•Water analyses or monitoring of respective macrocomponents (Ca, Na, Cl, ...)
Trace elements	•water analyses or monitoring of respective microcomponents (Se, B, I, ...)
Isotops and noble gases	•water/gas analyses or monitoring of respective Isotopes (^{14}C, δ^{18}...) and Noble gases (He, Ne, Ar, ...)
Organic compound	•water analyses or monitoring of respective components (PAH, VOC, AOX, ...)

Figure 15: Parameters of the TRANSENERGY borehole database

4.8. Non-technical barriers

Although TRANSENERGY team experts are mostly geoscientists, they have been aware that for the development of the geothermal sectors in the region, favorable resource conditions are needed, however not yet enough; a reliable and transparent regulatory framework, as well as financial incentives is also essential. Therefore, a special emphasize was put on the evaluation of these non-technical barriers, too.

TRANSENRGY performed detailed analysis of international and national water management and energy policies and highlighted their ***competing interests***: ***water management policies*** are focusing on the ***protection of resources*** (in line with the provisions of the Water Framework Directive (2000/60/EC), i.e. achieving and maintaining the good status of waters by 2015, while (renewable) ***energy policy*** (2009/28/EC) puts the ***maximum utilization of resources*** in focus, in line with the target numbers of the National Renewable Energy Action Plans (NREAP). However not only the objectives, but measures, time-frames are different (Table 5).

	Water policy (2000/60/EC)	**Energy Policy (2009/28/EC)**
target	groundwater within aquifer, groundwater body	heat energy stored below the subsurface
objective	achieving and maintaining good (quality and quantity) status (constant level, no intrusions, etc.)	increase the proportion of RES/geothermal
framework	national River Basin Management Plans (groundwater body delineation and status assessment, monitoring)	National Renewable Energy Strategy and NREAP (programs of actions and incentives)
competence of governmental bodies	ministries of “environment”	ministries of “energy and economics”
time frame	2009 – **2015** – 2021 –	2010 – **2020** – 2030

Table 5: Comparison of European water management and energy policies

In addition, some main ***regulatory gaps*** at national levels of legislations were identified, too (Lapanje et al. 2011):

-geothermal resources are owned by the state, except for Austria where they belong to the land-owner

- in all 4 countries the geothermal resource management has a dual character, shared by ministries of “environment/rural development” dealing with abstraction of thermal groundwater, and ministries of “energy /industry /economics” looking at geothermal energy utilization without water production or dealing just with the heat extraction of thermal waters. The most permissive regulatory framework exists in Austria, where even the energy content of the thermal water is not acknowledged in the legislation, while the most integrated approach exists in Slovakia by having a Geological Act.

-abstraction of thermal water is based everywhere on a water license (water concession in Slovenia), however geothermal concession for deep geothermal (below -2500 m) exists only in Hungary

-re-injection of the abstracted thermal water for energy use is compulsory in Slovakia, Slovenia and Austria, however its ways are defined in individual water permits. Due to a recent change (2013) in legislation in Hungary, the used water “can” be re-injected, also defined in a case-by-case process. Temperature and chemical thresholds for emitting used thermal water into the surface are strictly regulated everywhere.

-monitoring exists everywhere, however there is a great variety in the different national systems, measured parameters and their frequency, types of organizations performing observations and in reporting

-data confidentiality is a major restricting factor in Austria, in the other countries various governmental organizations are responsible for collecting data related to thermal water production and geothermal energy utilization, however uniform national registers do not exits

-the system of licensing for exploration and exploitation of geothermal resources is not efficiently regulated, i.e. complicated and time-consuming, thus it does not help to develop the national geothermal sector

Despite of the favourable geological conditions, relatively a small number of geothermal projects have been realized in the TRANSENERGY countries due to the lack sufficient ***financial incentives***, which are required for the accomplishment and achievement of demanded profitability. The overview of financial supporting schemes (Nádor et al. 2013) showed that ***direct subsidies, funds and loans*** with capital from World Bank, European Investment Bank, international banks, sometimes from state budget are available to some extent, mostly supporting drilling for exploration wells, establishment and running of district-heating facilities. ***Tax incentives*** are not available in TRANSENERGY countries, except for Slovakia, where electricity is subject to a consumption tax except it is produced from renewable energy. Geothermal energy in theory would benefit from this exemption, however at the moment there is no geothermal-based electricity production in the country. Due to the lack of geothermal-based power generation in the TRANSENRGY countries (except for Austria) existing ***feed-in tariff/feed-in premium*** systems for RES are not relevant for geothermal. Nevertheless the Hungarian and Slovakian NREAP-s foresee geothermal-based electricity by 2020 (Slovenia does not), so feed-in-tariffs will become relevant in the future. The current Austrian feed-in-tariff for geothermal is too low to promote any further investment. ***Off-take and support schemes for green-heat*** are not available in any of the TRANSENERGY countries; however the geothermal conditions are mostly suitable for direct heat utilizations (district heating). ***Indirect support schemes*** were mostly realized through different “renewable energy-related” operative programs in Hungary, Slovakia and Slovenia financed by the Structural and Cohesion Funds, being the most efficient and major supporting scheme for geothermal projects in these countries with a rate of co-financing up to 85% and a total support for the geothermal sector in the range of 100 million €. The beneficiaries were typically SME-s, larger companies, non-profit organizations, private companies, municipalities. ***Risk insurance*** as one of the most important supporting instrument for geothermal is not available in any of the TRANSENERGY countries.

4.9. Pilot areas

Within the “supra-regional” project area five cross-border pilot areas (Fig. 1) have been selected for more detailed studies. Pilot areas are representative „hot spot” regions along the borders (thermal karst of Komarno-Sturovo area (HU-SK), Pannonian Central Depression of the Danube Basin (A-SK-HU), Lutzmannsburg – Zsira area (A-HU), Vienna Basin (SK-A) and Bad Radkersburg- Hodoš area (A-SLO-HU). These regions were selected because of their extrem sensitivity for any further intervention by different management policies in the neighboring countries.

To be able to phrase tangible recommendations for a sustainable management of transboundary hydrogeothermal resources of these pilot areas, first the current utilizations of thermal groundwaters in the araes are summarized. The hydrogeology and geothermal conditions are introduced on the basis of coupled groundwater flow and heat transport models, which were developed based on detailed 3D geological models, also taking into consideration the experiences and results of the supra-regional models, which provided boundary conditions for these more detailed models (Rotár-Szalkai et al. 2013a). ***Steady-state models*** described the regional thermal water flow systems in 3D, quantified the major thermal water budgets, and provided heat base calculations for the pilot regions. The results ***characterized the present state of the geothermal reservoirs*** (groundwater heads, velocities and major path lines, thermal and cold water budgets, water exchange at state borders, subsurface temperature distributions, etc.). In the next step, ***simulations for different heat and thermal water extraction scenarios*** and effects of different possible utilization shemes in the future were examined at each pilot area. ***Scenario modelling*** provided information about the possible limitations in thermal water utility, the need of protection, and described the geothermal exploitation capacity of the regions with indications on priorities in thermal water use (Rotár-Szalkai et al. 2013b). The results also mirror the rate of renewing of geothermal (in terms of water quantity, heat, hydraulic pressures, etc.) and the required time period.

Furthermore, harmonized ***assessment of geothermal resources*** was carried out at each pilot area (Goetzl, 2013c). The well accepted categories of geothermal plays, resources and reserves (c.f. “CanGea- Canadian Geothermal Code for Public Reporting”) were adapted to the TRANSENERGY area (Table 6, Fig. 16). Although it does not include all levels of resource assessment of CanGea, the chosen selection covers all aspects of TRANSENERGY goals.

Potential	Resource	Reserve	Definition used in TRANSENERGY
Heat in Place			*Heat stored in a subsurface volume. This term delimits the theoretically available geothermal potential, which could only be utilized by cooling down the entire rock volume of the specific Hydrogeothermal Play. In practice it won't be possible to extract the entire amount of heat stored by technical measures.*
	Inferred Resources		*Technically extractable amount of Heat in Place at a low level of confidence. The assessment of Inferred Resources is mainly based on modelling results and simplified assumptions at a regional scale.*
		Probable Reserves*	*Share of Inferred Resources, which can be developed in an economic way (e.g. considering maximum drilling depths or maximum distances to areas of settlement).*
	Measured Resources		*Technically extractable amount of Heat in Place at a high level of confidence by relying on direct measurements at wells.*
		Installed Capacities	*Already installed hydrogeothermal power.*

Table 6: Overview of the different levels of hydrogeothermal assessment considered in TRANSENERGY. Probable Reserves have been calculated in an experimental way only for the Vienna Basin pilot area.

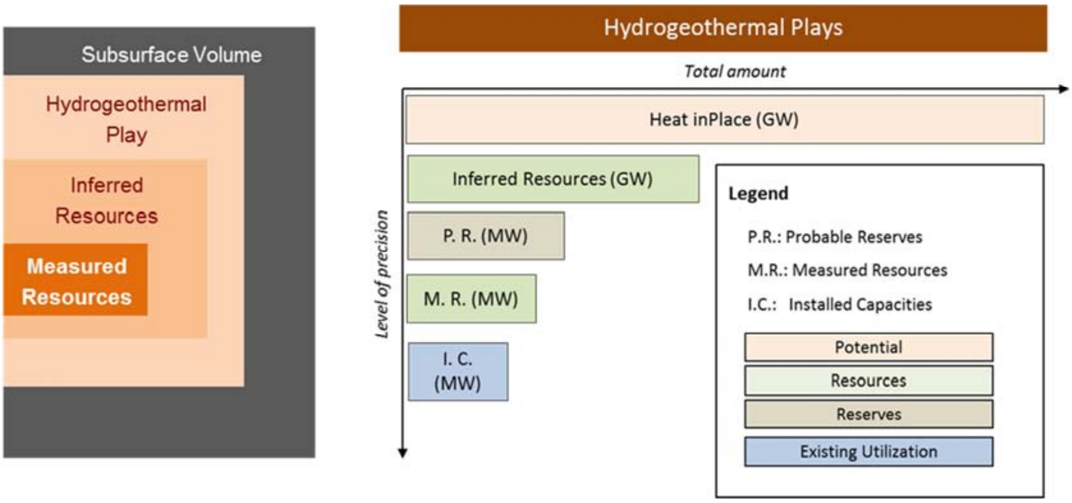


Figure 16. General scheme of the resource assessment applied in TRANSENERGY

At TRANSENERGY project ***the assessment of geothermal potential has been performed for relevant Hydrogeothermal Plays at the pilot areas*** assuming an operational lifetime of chosen technical utilizations (Table 7) as 50 years of full annual load. The main criteria for the selection of Hydrogeothermal Plays were:

- Coverage of at least one aquifer
- Relevance for present or future hydrogeothermal use
- Minimum average temperature level above 30°C

All calculations were based on the data acquired and models developed during the project. The assessment is limited to a regional scale (maximum resolution 1:100.000).

ID	Title	Required minimum temperature	Reference temperature (discharge, re-injection)	Type of scheme	Constraints
		°C	°C	-	-
1	**Balneology** (energy use of water for local heating)	30	10[*]	Single Well	None
2	**Heat Supply** (district heating as well as individual heating)	40	25	Doublet (2 wells)	Maximum flow rate 100 l/s or max. drawdown of 100 meters[**]
3	**Electric Power Generation** (combined with heat supply)	105	55	Doublet (2 wells)	Maximum flow rate 200 l/s or max. drawdown of 200 meters[**]

Table 7: Overview of the utilization schemes selected for hydrogeothermal resource assessment

In the ***five pilot areas altogether nine Hydrogeothermal Plays were identified*** (Table 8). Three of them are located in Miocene and Pliocene basin fillings (Vienna Basin and Danube Basin). They are mainly intergranular aquifers belonging to a single stratigraphic horizon. The remaining six Hydrogeothermal Plays are located at the pre-Miocene basement of the basins and are represented by fractured carbonate reservoirs, which comprise several different tectonic and stratigraphic structures (Table 8).

The geometrical attributes of the investigated Hydrogeothermal Plays have been derived from the steady-state 3D geological modelling, while the estimated range of reservoir temperatures came from the steady-state thermal models covering the pilot areas. The hydraulic transmissivity controlling the maximum yield of an individual geothermal doublet was calculated by combining the modelled thickness of a Hydrogeothermal Play with an averaged hydraulic conductivity, assuming isotropic and homogeneous conditions at the Play. The rock parameters such as Heat Capacity, Density and Porosity have been generalized based on measurements done by, or available at the involved geological surveys. Due to the lack of data, simple isotropic and homogeneous reservoirs had to be assumed. Data characterizing each studied Hydrogeothermal Play are presented at the description of the relevant pilot area.

ID	Name	Pilot Area	Description
VB1	*Aderklaa Conglomerate*	Vienna Basin	Conglomerates of the Miocene basin fillings (Lower Badenian)
VB2	*Deltafront Sediments (Eggenburgian - Ottnangian)*	Vienna Basin	Sandstones and sands of the Miocene basin fillings
VB3	*Tirolic Nappe System*	Vienna Basin	Dolomites and limestones of the Triassic basement of the Vienna Basin (Norian - Anisian)
VB4	*Juvavic Nappe System*	Vienna Basin	Dolomites and limestones of the Triassic basement of the Vienna Basin (Ladinian - Anisian)
VB5	*Central Alpine & Tatric Carbonates*	Vienna Basin	Dolomites and limestones of the Triassic basement of the Vienna Basin (Ladinian - Anisian)
TWB1	*Upper Triassic carbonates*	Komarno - Sturovo Area	Limestones and dolomites of the Upper Triassic basement
LZ1	*Devonian dolomite*	Lutzmannsburg - Zsira Area	Limestones and dolomites of the Paleozoic basement
DB1	*Upper Pannonian formations*	Danube Basin	Interchange of clays, marls and sands/sanstones of the Miocene basin fillings
BRH1	*Raba fault zone*	Bad Radkersburg - Hodoš Area	Carbonates and metamorphic rocks of the Pre-Tertiary basement (Triassic & Paleozoic)

Table 8: Overview on the Hydrogeothermal Plays selected for the hydrogeothermal assessment

The assessment of geothermal potentials, resources and reserves follows a workflow developed in the frame of TRANSENERGY. The entire Hydrogeothermal Play was covered with a 1 km x 1 km raster putting on individual geothermal doublet (1 production well + 1 re-injection well) at each cell in order to consider utilization schemes 2 (heat supply) and 3 (electric power generation) (Table 7). Considering scheme 1 (balneological use) only 1 single well was put at each cell. The preparation of input data and details of calculation methods of Heat in Place, Inferred- and Measured Resources, as well as Probable Reserves are summarized in Goetzl (2013c). The calculated numbers for each Hydrogeotheraml Play are shown at the description of the relevant pilot area.

Finally a ***"benchmarking"*** evaluation (indicators of sustainable management of thermal groundwater) is provided for each pilot area (except for the Vienna Basin, where no hydrogeothermal utilization exists at present). This methodology originally elaborated for the better management of the region of Lake Léman was further modified and applied for the TRANSENERGY pilot areas. As a transparent and objective set of indicators, it was considered as the best methodology to assess transboundary (thermal) aquifers and utilizations, which also makes possible to draw conclusions for future management strategies (see also in Chapter 3: Recommendations).

Association for the protection of Lake Léman (L'association pour la sauvegarde du Léman - ASL) initiated a wide research in 2002 to achieve and maintain a good water status of the Lac

Léman river basin (Lachavanne, J-B., Juge, R., 2009). The aim of the research was to offer a tool to the region to evaluate and support decision making that would allow to manage the water resources respecting the principles of sustainable development.

What has Lac Léman in common with transboundary thermal aquifers in the W-ern part of the Pannonian Basin? Lemano region is belonging to two countries (France and Switzerland), three regions and 600 communities. TRANSENERGY transboundary thermal aquifers are extending across state and other administrative borders. Although similar energy objectives and environmental goals exist in TRANSENERGY countries, these transboundary areas are situated in rather different economic and social environments and also natural conditions. Therefore it is very important to reveal the strong and weak points of the actual management practices and take resolved steps for their improvement.

Based on our studies of transboundary thermal aquifers and considering the "Lemano" idea and methods, we identified ***10 crucial indicators*** that should be observed to reveal the actual status and use of these reservoirs, which also enables to follow and compare the existing management practices:

1) Monitoring status.
2) Best available technology.
3) Energy efficiency.
4) Utilization efficiency.
5) Bathing efficiency.
6) Re-injection rate.
7) Status of water balance assessment.
8) Over-abstraction.
9) Quality of discharged waste thermal water.
10) Public awareness.

All indicators are based on an objective calculation method as described below. The results are marked in five descriptive categories: very bad, bad, moderate, good and very good, which allows a transparent comparison.

Data for evaluation of these indicators were partly collected through the obligations from the Water Framework Directive, the Directive on the Promotion of the Use of Energy from Renewable Sources, national obligations related to monitoring, and also following the EGEC recommendations for geothermal resources management. More detailed data were not freely accessible, especially for individual wells and users, but were gained by field inspections and interviews with the thermal water users in the frame of TRANSENERGY.

Monitoring status

The first and most important key indicator is a mandatory, unified and integrated active monitoring, carried out by water producers. This should be implemented by the user and should consist of continuous recording of groundwater level or wellhead pressure, water temperature, yield and chemical composition or conductivity (Axelsson and Gunnlaugsson 2000). Chemical sampling and interpretation of trends should follow the Groundwater Daughter Directive (European Union 2006). Where re-injection takes place, the required measurements should also be performed at the re-injection well. Monitoring results should be interpreted annually by users. These data should be combined with results derived from the passive monitoring of deep geothermal aquifers performed by governmental organizations. Only combined interpretation of the active and passive monitoring data would allow us to follow systematically the changes in aquifers, and make regional evaluations of the available thermal water resources that is necessary for leasing new water permits.

Monitoring status	**Points**
Sporadic observations	0
Active monitoring carried out by water producers: Continuous measurements of discharge (abstracted water), piezometric level, temperature and regular chemical water analysis of abstraction/operational well	5
Yearly report of active monitoring results submitted by concessionaire/licenser and approved by granting authority	3
Passive monitoring in non-exploited observation well: Regular measurements of piezometric level	1
Passive monitoring in non-exploited observation wells: Temporarily sampling of groundwater for chemical / isotopic analysis to identify global changes	1

The requirements are interdependent! If active monitoring exists (5 points), the points for additional passive monitoring and submission of the reports have to be added and summed.

$$I_{MON} = \frac{\sum_{i=1}^{n} P_i}{N_{tot}}$$

Where:
I_{MON} = monitoring indicator
P_i = points of abstraction well i) at a site
N_{tot} = total number of all abstraction wells

I_{MON}	Results	
	Descriptive	Points [%]
> 8	Very good	100
6 - 8	Good	75
4 - 6	Medium	50
2 - 4	Weak	25
< 2	Bad	0

Best available technology use

Encouragement of the use of best available technology (BAT) is proposed, as this will have a direct impact on decreasing the need for additional thermal water, thus increasing usage efficiency, mitigating potential system failures, as well as diminishing environmental pollutions. Application of cascade systems (utilization in series, where each sequential utilization type uses the heat or the waste thermal water from the preceding utilization type) is recommended. Re-injection wells are not evaluated here.

BAT use	Response	Points
Well-maintained wellheads which are isolated and protected from unfavourable weather conditions and unauthorised persons	Yes	0
	No	1
Materials installed in and above the well are inert for aggressive water/gas mixtures and higher temperatures. Calcite scaling problems are mitigated by injecting inhibitors	Yes	0
	No	1
Installation avoids areas of gas or water leaks and include the placement of a water release valve before the degassing unit at the wellhead.	Yes	0
	No	1
Abstracted water is precisely and continuously following the water demand. If pumping is required computer-managed frequency pumps are used	Yes	0
	No	1
The thermal water is used based on the principles of a cascade system, with both computerised and individual phases controlled as much as possible.	Yes	0
	No	1
Supporting technical, lithological, hydrogeological and chemical documentation is well-kept and regularly updated.	Yes	0
	No	1
Specific yield of wells is not decreasing	Yes	0
	No	1

The requirements are independent.

(Be aware that BAT is applied if as little points are collected as possible)

$$\bar{I}_{BAT} = \frac{\sum_{i=1}^{n} I_i * Q_i}{\sum_{i=1}^{n} Q_i}$$

Where:
$\bar{I}_{BAT}$ = indicator of BAT use
I_i = indicator I for the production well i)
Q_i = annual abstraction rate of the production well i) (m^3/a)

$\bar{I}_{BAT}$ [points]	Result	
	Descriptive	Points [%]
0	Very good	100
0-1	Good	75
1-2	Medium	50
2-3	Weak	25
> 3	Bad	0

Thermal efficiency

Though only a few users cool thermal water near to the mean annual air temperature (12 °C), this should be followed by others. Higher thermal efficiency should lead to a reduction in the total amount of abstracted thermal water, as well as lower thermal and chemical pollution of surface streams into which waste water is emitted. To indicate good thermal efficiency, a value of at least 70% use of available energy should be reached. This would mean that if wellhead thermal water temperature is 60 °C, waste water should have a maximum temperature of 26.4 °C before being emitted to the environment, while if wellhead water temperature is 40 °C, emitted wastewater temperature should be below 20.4 °C. Thermal efficiency should be increased step by step.

Thermal efficiency (η_i) is the ratio between used and available annual heat energy:

$$\eta_i = E_{used\ i} : E_{available\ i} \qquad (1),$$

Used annual heat energy ($E_{used\ i}$) Eq. 2:

$$E_{used\ i} = V_{aa} \cdot 4.18 \frac{kJ}{kgK} \left(T_{wellhead} - T_{outlet} \right) \qquad (2),$$

V_{aa} - average annual quantity of abstracted thermal water,

($T_{wellhead} - T_{\mathrm{outlet}}$) - temperature difference between abstraction (wellhead) and outlet (discharge).

Available annual heat energy ($E_{available\ i}$) Eq. 3:

$$E_{available\ i} = V_{aa} \cdot 4.18 \frac{kJ}{kgK} \left(T_{wellhead} - T_{location} \right) \qquad (3),$$

($T_{wellhead} - T_{\mathrm{location}}$) - temperature difference between abstraction (wellhead) and yearly average air temperature of the location, e.g. 12° C.

If the volumes of abstracted and waste water are the same ($V_{\mathrm{aa}} = V_{ww}$) then the thermal efficiency is calculated by Eq. 4:

$$\eta_i = \frac{T_{wellhead} - T_{outlet}}{T_{wellhead} - T_{location}} \qquad (4),$$

where $T_{wellhead}$ and T_{outlet} correspond to the aforementioned parameters.

If the abstracted thermal water is partly reinjected, then thermal efficiency is calculated by Eq. 5:

$$\eta = \frac{V_{aa}(T_{wellhead} - T_{outlet})}{V_{aa}(T_{wellhead} - T_{outlet}) + V_{ww}(T_{outlet} - T_{location})} \qquad (5),$$

If all abstracted thermal water is re-injected then the thermal efficiency $\eta = 1$ is 100 %.

$$TE_{\square} = \frac{\sum_{i=1}^{n} \eta_i * Q_i}{\sum_{i=1}^{n} Q_i}$$

Where:

TE = indicator of thermal efficiency on the respective user site

η_i = thermal efficiency for abstraction point i)

Q_i = annual abstraction rate of abstraction point i) (m^3/a)

TE [%]	Result	
	Descriptive	Points [%]
> 70	Very good	100
60 - 70	Good	75
40 - 60	Medium	50
30 - 40	Weak	25
< 30	Bad	0

Utilization efficiency

Utilization efficiency is the ratio between the average annual water abstraction and the maximum quantity that could be produced, i.e. the higher proportion of the available resource is utilized, better the utilization efficiency is.

Installed capacity is a technical parameter and represents the maximum possible abstraction rate of a well and it is normally designed for the potential peak water demand. Nevertheless, the potential peak water demand often forms the basis of the licensed maximum water quantity defined in water permits.

Within this research we collected information based yields and conditions stated in water permit and took these values as the potential maximum abstraction yields. We did not take into account the naturally discharged thermal waters (from springs), which are utilised by the ecosystems.

$$F_u = \frac{\sum_{i=1}^{n} Q_{a\,i}}{\sum_{i=1}^{n} Q_{cap\,i}} * 100\ [\%]$$

Where:
F_u = utilization efficiency indicator [%]
$Q_{a\,i}$ = average annual abstraction of a production well i) [m^3/s]
$Q_{cap\,i}$ = installed capacity of a production well (potential peak water demand ≈ maximum potential abstraction quantity defined in water permit) i) [m^3/s]

F_u [%]	Results	
	Descriptive	Points [%]
> 30	Very good	100
25 - 30	Good	75
20 - 25	Medium	50
15 - 20	Weak	25
< 15	Bad	0

Bathing efficiency

The indicator of bathing efficiency can be calculated on the basis of reported water use, i.e. the volume of pure thermal water used to fill swimming pools. A value of 10 m^3 per bather per day is considered as a reference value, above which pool water does not need to be disinfected.

Further development of this indicator is planned, in order to be able to include not just the amount of used water, but also its medical effect.

Re-injection rate

Where a closed thermal water exploitation system is used, all water (not considering technical barriers, i.e. re-injection into clastic aquifers) can be returned into the aquifer - although probably more than one re-injection well will be required. In open systems only non-treated and not polluted thermal water can be returned into the aquifer and as a consequence of less water amount, fewer re-injection wells might be necessary. Re-injection wells represent a large investment cost, which – without suitable financial support – are not feasible for most of the users. Even though re-injection is a legal requirement for energy use of thermal water, it currently takes place at a few sites (see also Chapter 4.3.).

Within this survey we checked only whether re-injection is applied or not. In the future it will be necessary to differentiate between re-injection into the aquifer from where the water is being abstracted, and re-injection into other aquifers. This latter case is mostly applied in practice, which is against the guidelines of the Water Framework Directive. This question is especially important when a groundwater with high organic and/or trace element content is reinjected into a shallower aquifer with a completely different chemical composition.

The re-injection indicator expresses the ratio between the reiinjected and abstracted annual volume of thermal water used for energy utilization purposes.

$$\overline{RI}_Q = \sum_{1}^{n} \frac{Q_{th_{reinj}}{}^{i}}{Q_{th_{abs}}{}^{i}} \ \textbf{[\%]}$$

$\overline{RI}_Q$ = indicator of ratio between reinjected and abstracted annual volume of thermal water for for heat abstraction [%]
Q_{abs} = abstracted volume of thermal water for energy utilization [m^3/a]
Q_{reinj} = reinjected volume of thermal water for energy utilization [m^3/a]

$\overline{RI}_Q$ [%]	Result	
	Descriptive	Points [%]
$\overline{RI}_Q > 60$	Very good	100
$40 < \overline{RI}_Q \leq 60$	Good	75
$20 < \overline{RI}_Q \leq 40$	Medium	50
$0 < \overline{RI}_Q \leq 20$	Weak	25
$\overline{RI}_Q = 0$	Bad	0

Status of water balance assessment

This indicator describes the depth knowledge which is available on the quantity status of the aquifer, and the reliability of data on which these assessments are based on. The need for re-injection is partly depending on the natural recharge of the thermal aquifers. Estimation of the latter is heavily depending on the quality and availability of regional hydrogeological data. More accurate estimates can be obtained when a national passive monitoring programme is implemented by the competent authorities, which should be combined and interpreted with data from users' active monitoring (see also indicator 1 Monoitoring status).

Annual data for water balance assessments and regional hydrogeological evaluations should be analysed every 3-6 years, since in this period the quantity and quality of aquifer trends become more evident (Goldbrunner et al. 2007). Until a regional numerical model of the appropriate aquifer is established, this monitoring scheme and analysis should represent a sufficient tool for granting new licences and supervising existing ones.

This indicator should be developed in the following successive cumulative levels:

Status of water balance assessment	**Points**
Not assessed	0
Critical level point is defined (not based upon measurements on the location but from other available data / locations)	0.25
Critical level point is defined (based upon average yearly minimum level value from previous years on the location)	0.5
Critical level point is defined. Renewable and available volume of water is assessed. Critical point of abstraction is defined. Study is made on the base of old / regional data and knowledge	0.75
Renewable and available volume of water is assessed. Critical point of abstraction and critical level point are both defined. Study is made and updated on the basis of actual measurements.	1

One well can have maximum one point, only one statement has to be selected and valued as a point for the indicator calculation.

$$I_{\mathbf{wba}} = \frac{points}{E_{tot}} * \mathbf{100\ [\%]}$$

Where:
I_{wba} = indicator of water balance assessment status
points = sum of points regarding the status water balance assessment
E_{tot} = total number of abstraction wells on the basin level (all users)

I_{wba} [%]	Results	
	Descriptive	Points [%]
> 95	Very good	100
75 - 95	Good	75
50 - 75	Medium	50
25 - 50	Weak	25
< 25	Bad	0

Over-abstraction (status of the aquifer based on the impact of the thermal water abstractions)

This indicator – in strong connection with re-injection rate and water balance assessment – provides information on the quantity status of the aquifer.

Status of the aquifer based on the impact of the abstractions	Response	Points
Significant decreasing of piezometric level is showing that new equilibrium could not be reached	Yes	1
	No	0
Decreasing water quality or temperature caused by the abstraction	Yes	1
	No	0
Decreasing of groundwater availability (lower yield, pump lowering)	Yes	1
	No	0
Impact on dependent ecosystems is significant	Yes	1
	No	0
Strata subsidence caused by the abstraction	Yes	1
	No	0

$$\bar{I}_{OE} = \frac{\sum_{i=1}^{n} I_i \bullet Q_i}{\sum_{i=1}^{n} Q_i}$$

Where:
$\bar{I}_{OE}$ = indicator of over-abstraction status on the respective site
I_i = sum points for source i
Q_i = annual abstraction rate of source i (m^3/a)

$\bar{I}_{OE}$ [points]	Result	
	Descriptive	Points [%]
0	Very good	100
0-1	Good	75
1-2	Medium	50
2-3	Weak	25
> 3	Bad	0

Quality of discharged waste thermal water

All countries have legislation in which the monitoring procedures and standards for the emitted waste (thermal) water are regulated, concerning direct emissions into the environment, or indirect through the sewage purifying plants. With this parameter we intended to investigate how many of these samples (wells) actually do fulfil the legislative standards for waste water emissions and therefore do not cause microbiological, chemical or thermal pollution of surface waters and other environment.

Because this type of information on waste water was not collected during the survey of current utilizations, we could not test the applicability of this indicator in practice.

$$I_{Qual_{disc}} = \frac{Smp_{positive}}{Smp_{tot}} * 100\ [\%]$$

Where:
I_{Qual_disc} = indicator - share of positive samples which meet the requirements for emitted waste water quality [%]
$Smp_{positive}$ = total number of positive samples per year
Smp_{tot} = total number of samples per year

$$\bar{I}_{Qual_{disc}} = \frac{\sum_{i=1}^{n} I_{Qual_{disc_i}} * Q_i}{\sum_{i=1}^{n} Q_i}\ [\%]$$

Where:
$\bar{I}_{Qual_{disc}}$ = indicator of suitability of discharged water [%]
Q_i = annual discharge of waste thermal water of source i (m^3/a)

I_{Qual_disc} [%]	Result	
	Descriptive	Points [%]
> 95	Very good	100
90 - 95	Good	75
80 - 90	Medium	50
70 - 80	Weak	25
< 70	Bad	0

Public awareness - accessibility of reliable information

For this indicator we inspected companies' websites and media material, where we searched for (even very short) descriptions of geothermal energy, or information on thermal water use. We inspected whether these materials contained information (in the national language mostly) on monitoring, cascade use, efficiency, geothermal energy, thermal water, pollution, chemical analysis of thermal water, waste water management, re-injection, water level decline, aquifer, etc.

Information about	**Points**
Monitoring	1
BAT use	1
Quantitative status (overexploitation)	3
Qualitative status of waste water	3
Energy efficiency	2

$$I_{inf} = \frac{\sum_{i=1}^{n} P_i}{N_{tot}}$$

Where:
I_{inf} = information indicator
P_i = number of points of abstraction site i
N_{tot} = total number of abstraction sites

I_{inf}	Results	
	Descriptive	Points [%]
> 8	Very good	100
6 - 8	Good	75
4 - 6	Medium	50
2 - 4	Weak	25
< 2	Bad	0

We did not incorporate into the benchmarking evaluations the naturally discharging thermal waters (from springs) which are utilised by the ecosystems.

4.9.1. Komárno-Štúrovo (Komárom-Párkány) Pilot Area

4.9.1.1. Introduction

The Komárno-Štúrovo (Komárom-Párkány) pilot area is situated in the NE-ern part of the Transdanubian Range in Hungary and its basinal part in Slovakia (Fig. 17). The 84 % of the total area (4447 km^2) belongs to Hungary, 16 % to Slovakia. Altogether around 530 000 inhabitans live in the area, mainly in smaller towns and villages. More than 190 000 people live in 7 larger towns in Hungary and Slovakia.

The land use is dominated by agriculture, while in the economical structure tourism is also important. The main tourist areas are Tata, Esztergom, Patince and Štúrovo. In the 1900's the coal mining (Tatabánya, Dorog, Mány, Dorog, Fenyőfő, Bakonyszentlászló) played an important role in the industry of the Hungarian part of the area.

Groundwater bodies of the area are divided by national boundaries and karstic aquifers were delineated by the International Commission for the Protection of the Danube River (ICPDR) as aggregated groundwater bodies. Our hydrogeological evaluation also focused on these karstic reservoirs, however some of intergranular aquifers were also taken into account during evaluation.

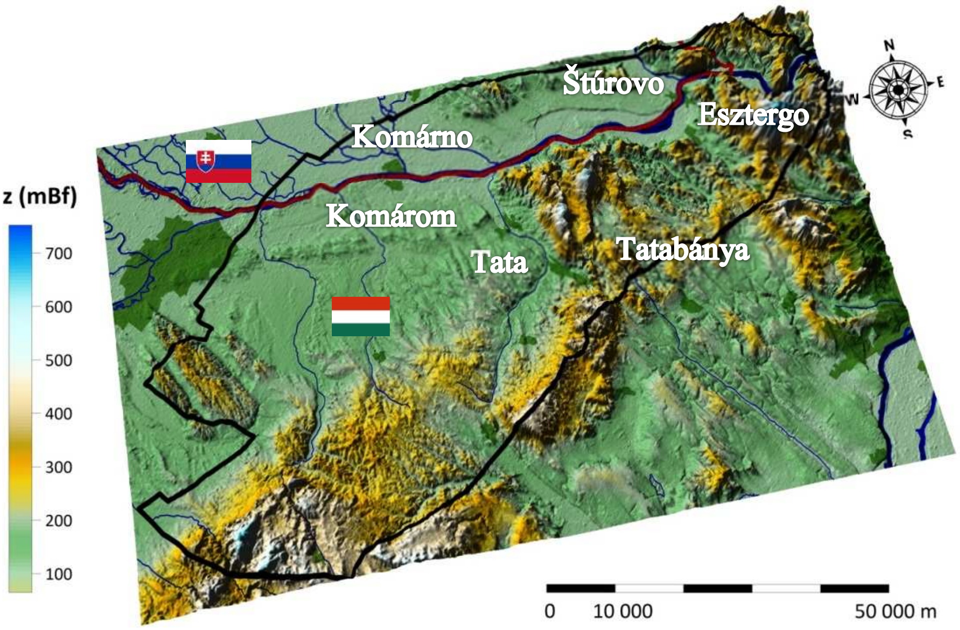


Figure 17: Geographical setting of the Komárom - Stúrovo pilot area and the main settlements

4.9.1.2. Geology, hydrogeology and geothermal conditions

The Komárno –Štúrovo pilot area belongs to the Komárno block (in Slovakia we consider in this evaluation Komárno high block) comprising a subsided N-ern blocks of the Gerecse and Pilis Mts. (Hungary). The surface of the pre-Tertiary basement extends towards the north from a depth of approximately 100 m near the Danube to as deep as 3000 m near the Hurbanovo fault. The pre-Tertiary basement of the Komárno block consists largely of Triassie dolomites and limestones up to 1000 m in thickness. These are underlain by very thick Lower Triassic shales.

The main and most important aquifers (as well as hydrogeothermal reservoirs) are the Upper Triassic platform limestones and dolomites (Dachstein Limestone and Main Dolomite) which are known from an area of about 1050 km^2. During the geological evolution of the area, a long-lasting subaerial exposure period caused a strong karstification of the upper part of the more than 1500 meters thick Triassic carbonate sequence after the Mesozoic, which thus got a higher permeability. These well karstified conduits and fractures along the main tectonic elements determine the groundwater (karst-water) flow.

The outcropping Upper Triassic rocks (North-Bakony, Vértes, Gerecse, Pilis mountains) form the main recharge areas, from where the precipitated groundwater flows towards the deeper regions to northwest and west in the buries karstic rocks. From the NW-ern edge of the aquifer the groundwater turns towards north-noth-east and in the Slovakian parts towards east (Fig. 18).

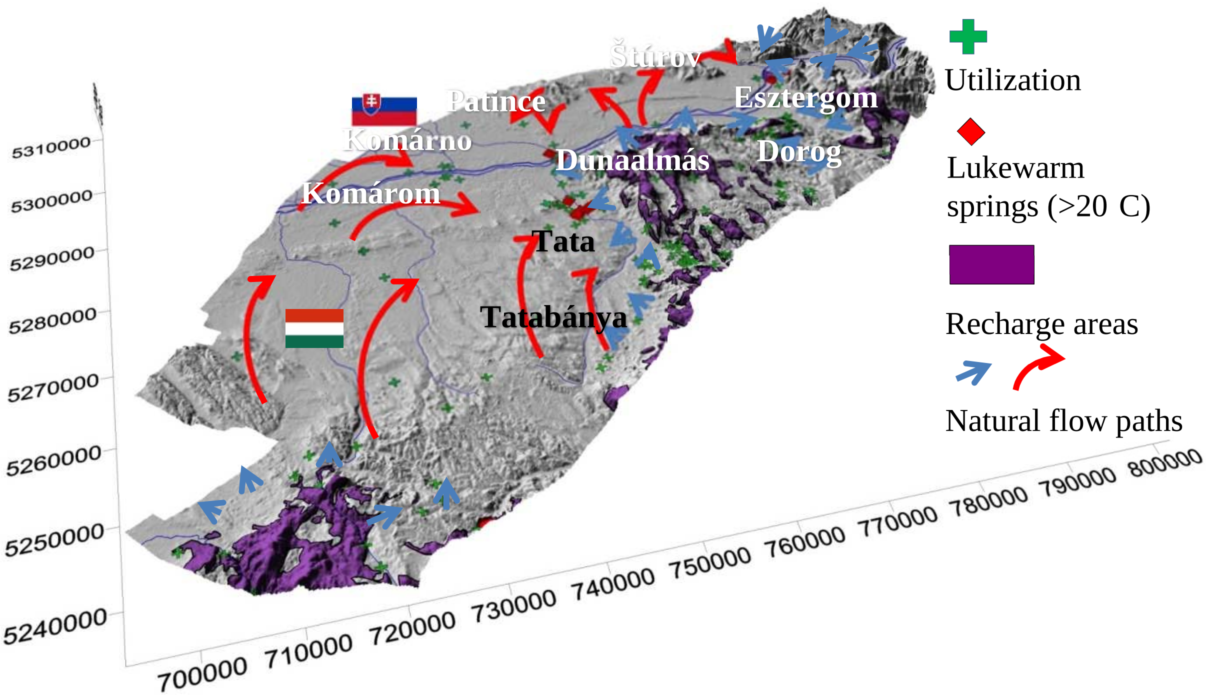


Figure 18: Sketch of the groundwater flow directions, main utilizations in the last 75 years and the lukewarm springs in the pilot area

The geothermal activity of the Komárno block has been known for a long time because lukewarm springs discharge at the margins of the karstic mountain blocks at Štúrovo and Patince with temperatures of 39 and 26°C respectively. Thermal springs have been also known on the Hungarian side of the pilot area even utilized in historical times, practically opposite to the above mentioned ones, at Esztergom and at Dunaalmás with temperatures of 26-27°C and 23-24°C. The investigated geological structure has a fast water circulation which causes a significant negative geothermal anomaly (i.e. much colder groundwater temperatures than it would be expected at certain depths): 20-22°C at 600-800 m bsl, 24.5-26.5°C at 1100-1300 m bsl, and around 40°C at 3000 m bsl. The Komárno block contains Ca-Mg-HCO_3 and Na-Ca-HCO_3-Cl chemical types of thermal water.

The marginal (W, NW, N) and deeper part (<-1600 m asl) of the Upper Triassic carbonate aquifer is characterized by higher temperatures which forms part of the deep karstwater flow system: these thermal (40-60 °C) karst water are abstracted by deep wells in the NW and N-ern part of the area (near Bábolna, Ács, Komárom, Komárno), which makes heating utilizations in the agriculture and/or domestic sector possible. However this represents only a smaller proportion of the stored groundwater compared to the lukewarm springs. In the NW-ern part characterized by higher temperatures, only a few wells exist and the deepest part of the aquifer is not properly known. However, in the future this area is potential for geothermal doublet(s) and/or cascade use targeting the Upper Triassic aquifer (Fig. 19).

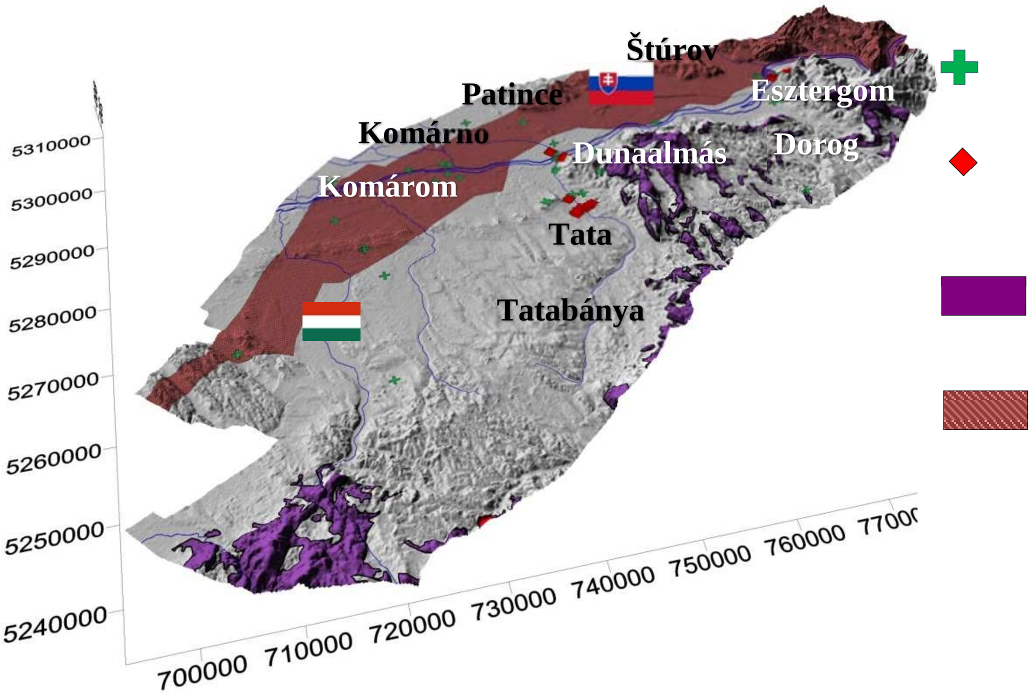


Figure 19: Distribution of the potential Upper Triassic hydrogeothermal reservoir (T>30°C) and its recharge area

The general characteristics and estimated geothermal potential of the Upper Triassic hydrogeothermal reservoir in the Komárno-Šturovo pilot area are shown in Table 9. The description and methods of geothermal potential assessment are summarized in at the beginning of Chapter 4.9.

General attributes	Gross volume (km^3)	164
	Aquifer volume (km^3)	2
	Average thickness (m)	200
Estimated reservoir temperature (°C)	Min	20
	Max	152
	Average	86
Estimated transmissivity 10^{-3} (m^2/s)	Min	n.a.
	Max	n.a.
	Estimated	3.2
Rock parameters	Bulk Heat Capacity (J/(m^{3x}K)	914
	Bulk Density (kg/m^3)	2650
	Porosity (%)	3
Heat In Place (MW$_{th)}$	Balneology (single well)	235
	Heat Supply (doublet)	15731
	Electricity (doublet)	3896
Inferred Resources (MW$_{th}$)	Balneology (single well)	51
	Heat Supply (doublet)	5327
	Electricity (doublet)	1319
Measured Resources (MW$_{th}$)	Balneology (single well)	0.2
	Heat Supply (doublet)	17.2
	Electricity (doublet)	0
Installed Capacities (MW$_{th}$)	Balneology (single well)	12.8
	Heat Supply (doublet)	2.5
	Electricity (doublet)	0

Table 9: Characteristics and estimated geothermal potential of the Upper Triassic hydrogeothermal reservoir in the Komarno-Sturovo pilot area

4.9.1.3. Current utilization of thermal waters

The main users are the baths in both countries in the NE-ern part of the area (Esztergom, Štúrovo) (Table 10). In Patince and Dunaalmás (historical) balneological and drinking water utilizations exist. Near Komárom and Komárno balneological and agricultural utilizations take place. Most of the users abstract the lukewarm or thermal water of the Triassic karstic aquifer, but some Miocene and Cretaceous local aquifers near Komárom and Komárno are also exploited.

Site	Number of wells	Aquifer	Usage	Actual production* (m^3/year) (2009)
Ács (HU)	1	Lower Pannonian Upper Miocene?	agriculture drinking water	77 916
Almásneszmély (HU)	3	Upper Triassic, Lower Jurassic	drinking water, agriculture, balneology	223 580
Bábolna (HU)	3	Upper-Lower Pannonian, Upper Triassic	balneology, agriculture	out of operation
Bakonyszombathely (HU)	1	Lower Jurassic, Upper Triassic	agriculture	388
Dunaalmás (HU)	2	Upper Pannonian, Jurassic	drinking water, agriculture, balneology	1050
Esztergom (HU)	6	Upper Triassic	balneology, drinking water	1 776 309
Komárom (HU)	2	Upper Eocene	balneology	548 623
Pannonhalma (HU)	2	Upper Pannonian		No data
Szomód (HU)	1	Upper Triassic	agriculture	1825
Szomor (HU)	1	Upper Triassic	agriculture	13 589
Tata (HU)	9	Upper Triassic, Middle Cretaceous	balneology, drinking water, industrial	63 343
Visegrád (HU)	1	Upper Triassic	balneology	142 112
Komárno (SK)	1	Lower Pannonian	balneology	10 274
Nová Stráz	1	Upper Pannonian	agriculture	out of operation
Patince (SK)	2	Upper Triassic	balneology, industrial	202 570
Stúrovo (SK)	3	Upper Triassic	balneology	440 059
Zlatná na Ostrove (SK)	2	Upper Pannonian	agriculture	105 290

*Allowed amount for production in the water permits is much higher in several cases than the actual annual production

Table 10: Current users of thermal water

4.9.1.4. Existing and potential future conflicts

Due to the intensive water abstraction during the long-term coal mining in the Transdanubian Range, the whole cold- and thermal karst system was affected by a regional depression which caused the drying out of most of the lukewarm springs. After the mining was terminated, the water level has been rising since the beginning of the 1990's. In this dynamically changing system it is hard to estimate the actual drop in karst water level, but in the S and SW-ern part of the area it is about 30 m, which decreases towards the north. Along the Danube between Komárom-Komárno and Esztergom-Štúrovo the actual drop in the karst water level is about 10 m. The still existing abstractions for drinking water supply in the area are much smaller than the mining abstractions in the past, so probably they will not risk the yield of the recovering main lukewarm springs.

Although the rising karstwater level definitely has positive effects on the revitalizing of lukewarm springs and groundwater dependent ecosystems in the area of Tata, it also results in seepages on the surface and thus risks the existing surface installations (buildings, garages, etc.). Therefore sufficient solutions have to be elaborated to utilize and/or drain the (surplus) seepage waters. Furthermore in this area there is a competition between the water demand of balneological utilizations, drinking water abstractions and the water demand of the groundwater dependent ecosystems, the latter having high priority in the Water Framewok Directive. Therefore the ranking of different needs and an integrated assessment of their impacts is vital important.

Current utilizations have two major environmental impacts: thermal pollution and overproduction. In the area of the natural discharges (Tata, Esztergom (HU), Patince (SK)) the thermal pollution of the surface waters is minimal and nature has been adapted to lukewarm karst waters.

4.9.1.5. Towards a sustainable management

Steady state modelling (Gáspár and Tóth 2013a) focusing on the karst aquifer in the NE-ern part of the Transdanubian regional karst flow system confirmed the close connection between the water and heat flow, where water flow affects the heat (convective) transport in the area. In the karstified dolomites and limestones the water can flow deep down from the surface without any barriers: the recharged precipitation cools down the system even at big depths. Due to the intensive flow system, this cooling effect can be observed also far from the recharge areas and elevated temperatures (80-100 °C) can be observed only at the N-ern and partly in the NW-ern, deep buried part of the Upper Triassic aquifers (Fig. 20).

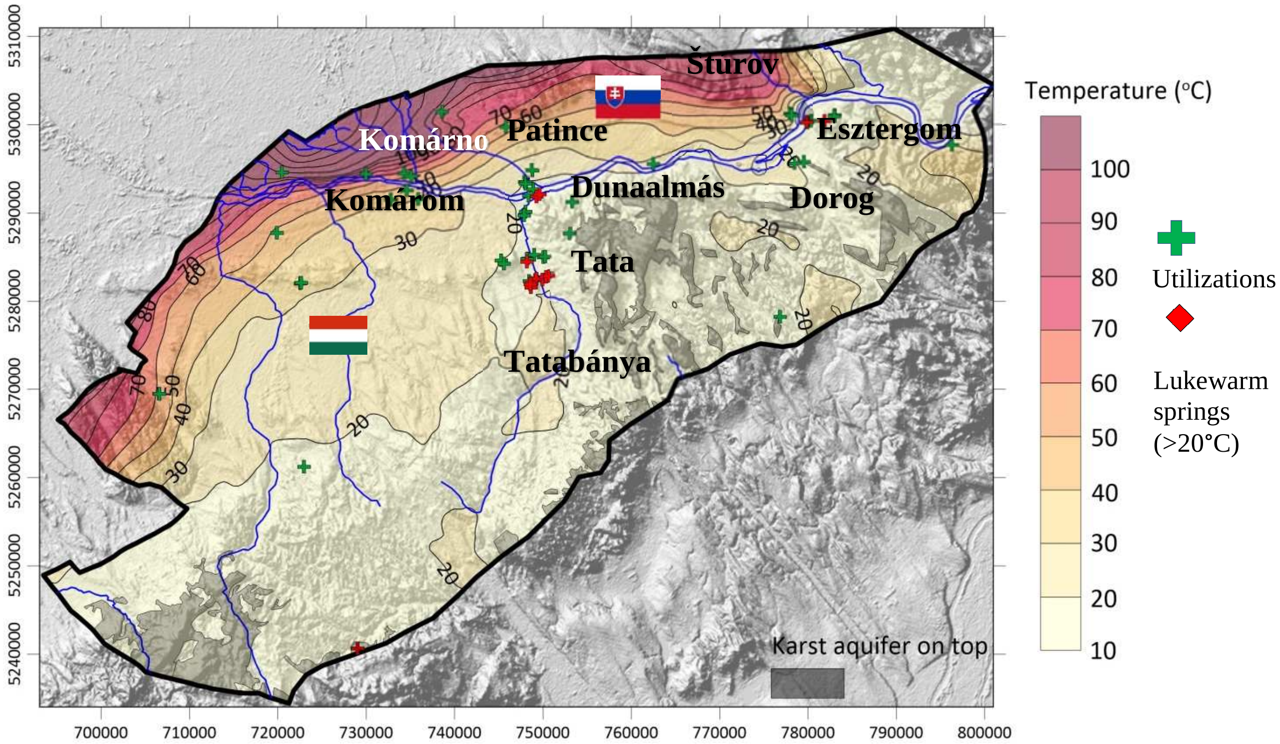


Figure 20: Modelled temperature distribution on the top of pre-Tertiary basement

Scenario modelling (Gáspár and Tóth 2013b) helped to quantify the connection between the cold karst water abstractions and the response of the lukewarm part of the karst flow system during and after the bauxite and coal mining. Scenario modelling of the intensive water production (Scenario1: Mine water abstraction with the yield in the late 1980's) showed regional depression in the whole region: the largest, 60-70 m drawdowns existed in the area of the water abstractions in the SE-ern part of the pilot area (near Tatabánya). The depression was observed also in the Slovakian part of the pilot area, especially around Komárno, where it could be as much as 30 m (Fig. 21). The most adverse and best seen effect of the intense water abstractions was the disappearance of the lukewarm springs in the Tata area.

From the end of the 1980's/the beginning of the 1990's the mine closures started in the Dorog and Tatabánya region and the karst system started to slowly regenerate (Scenario 2: Reduced water abstraction with the yield in the early 2000's). As a result the depression in the area of Tatabánya decreased from the former 60-70 m to 30-40 m, however the relatively increasing water level was still not high enough that the springs at Tata would work again. Transboundary effects were still demonstrated, although to a less extent, in the area of Komárom-Komárno the water level was "only" 20-25 m lower than in the natural state.

The scenario of the drinking water abstractions after the mine closures (Scenario 3) with main production sites near Tatabánya and Esztergom showed lower depressuration in the karst system (20-30 m water level drop in the local environments, 10-20 m depression in the whole region). Nevertheless, the relatively increasing water level was demonstrated to be high enough that the springs in Dunaalmás and Tata regenerated and started to work again. Yet, transboundary effects of drinking water abstractions could be still proven: in the area of Komárom-Komárno app. 15-20 m lower water levels were showed than at the natural state.

In summary: the scenarios studying the effects of various karst water abstractions (mining and/or drinking water-related) clearly quantified the thresholds at which lukewarm springs disappear/start to operate. These scenario model results provide good limit value estimates of (thermal) karst water abstractions without re-injection in the future at which environmental targets (groundwater dependent ecosystems) are not threatened.

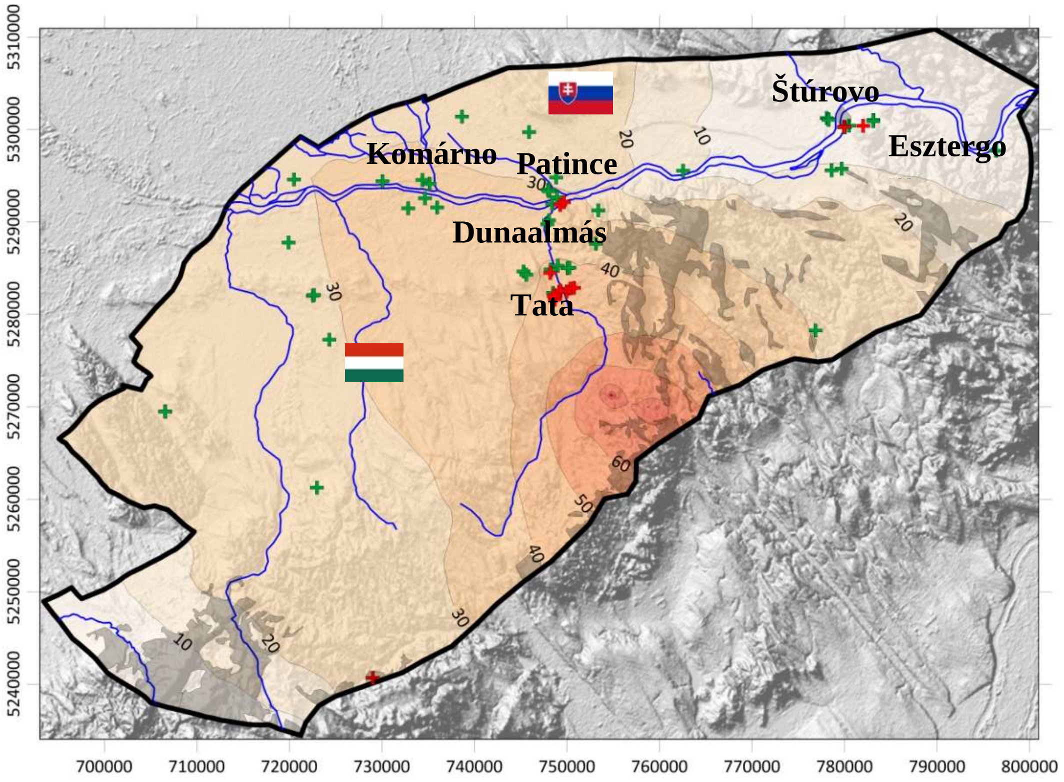


Figure 21: Modelled depressions in the Mezozoic karst aquifer (Scenario 1: Mine water abstraction with the yield in the late 1980's) (green crosses – geothermal utilizations, red crosses – lukewarm springs)

Scenario modelling (Gáspár and Tóth 2013b) also demonstrated the potentials and possible transboundary effects of deep geothermal utilizations in the area of Komárom-Komárno and raised awareness on the importance of re-injection. The evaluated hydrogeological structure (Mesozoic carbonates of the Komarno block basement reservoir) is not part of the regional flow system, but it is hydrauliccaly connected to it. To investigate the possible impacts of a future geothermal utilization close to the national border, 6 different utilization scenarios were studied with and without re-injection well(s) in one or both countries assuming infinite operation time (Fig. 22). The importance of the re-injection was confirmed by the simulations: the utilizations without re-injection had considerable transboundary impacts: the simulated depressions on the hydraulic potential were 6 - 12 m around the pumping wells. When re-injection took place, the modelled depressuration rates were reduced to 1.5 - 2.5 m around the abstraction wells, whereas a pressure increase around the re-injection wells was in the same range. In these scenarios (with re-injection) the operation of the geothermal system had no transboundary impacts. The scale and spatial extent of the impacts – in the case of theoretical doublets existing in both countries – were depending on the location of the injection wells.

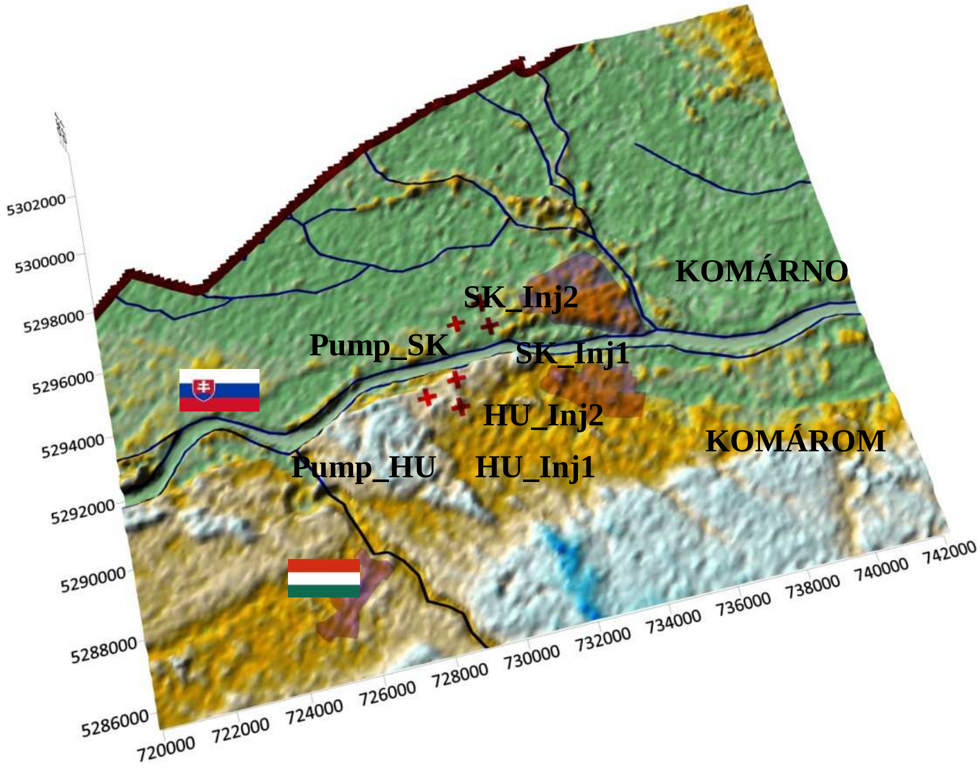


Figure 22: Theoretical well doublets in the area of Komárom – Komárno (red crosses – theoretical wells)

A detailed study on the joint (SK-HU) exploitation of transboundary geothermal energy resources in the Komarno block was performed by Svasta et al. (2013b) too, which also confirmed the suitability of this geological structure for energetic utilization. The scenario analysed common use of geothermal energy right at the state border by two geothermal doublets, organized in a tight 2 by 2 diagonal cluster assuming re-injection at a temperature of 15°C. The two doublets were designed in a way that in each country there is one separate system (Fig. 23). The main goal of this study, performed by transient coupled flow and heat simulations, was to test the proposed wells configuration and estimate operating life-time of the system by prediction of thermal breakthrough.

The results of this modelling showed that while using the projected system, the cooled water does not reach the production well from the injection area. This result is identical for all simulated amount of pumped and injected water. The injected water will begin impacting the temperature of the production well after more than 100 years of use.

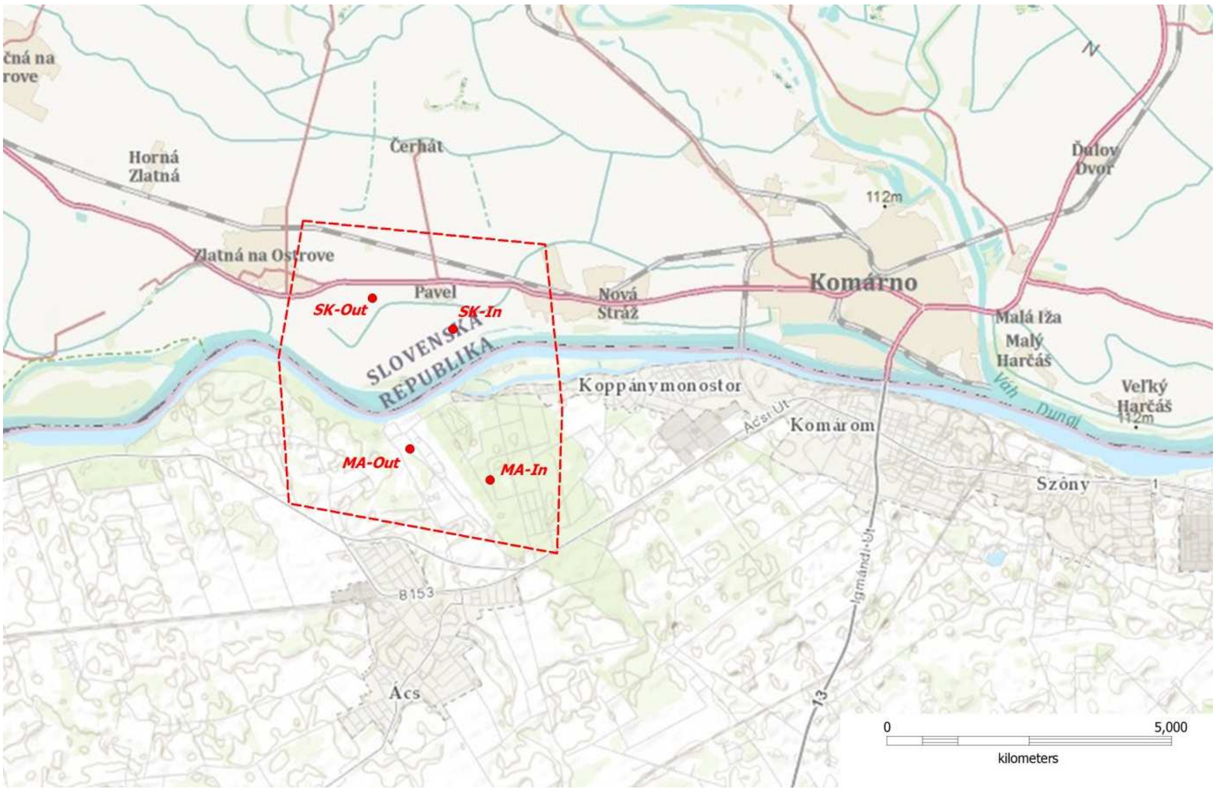


Figure23: Model area and allocation concept of the doublet cluster

4.9.1.6. Benchmark evaluation

The assessment of the management sustainability is based on an overview of 34 geothermal wells, 8 on the Slovakian side and 26 on Hungarian side. For the purpose of assessment the reported values for utilization on the Slovak side were from 2009, and for the Hungarian side from 2011 in this study. The results are summarized in Table 11 and Fig. 24.

No	Benchmarking parameter	Hungary			Slovakia		
		Value	Points	Evaluation	Value	Points	Evaluation
1	**Monitoring status**	5.87	50	Medium	4.0	50	Medium
2	**Best available technology**	0.94	25	Weak	1	50	Medium
3	**Thermal efficiency**	18%	0	Bad	73%	100	Very good
4	**Utilization efficiency**	109*%	100	Very good	23%	50	Medium
5	**Bathing efficiency**	100%	100	Very good	100%	100	Very good
6	**Re-injection rate**	0%	0	Bad	0%	0	Bad
7	**Status of water balance assessment**	0%	0	Bad	38%	25	Weak
8	**Overabstraction**	0.02	75	Good	0	100	Very good
9	**Quality of discharged waste thermal water**	no information			no information		
10	**Public awareness**	0	0	Bad	0	0	Bad

*– The water permit was modified at one of the wells in 2012, while the survey was carried out based on the average annual abstracted water and the licenced amount valid for 2011.

Table 11. Calculated values of benchmarking indicators for the Mesozoic carbonate thermal aquifer of the Komarno-Sturovo pilot area.

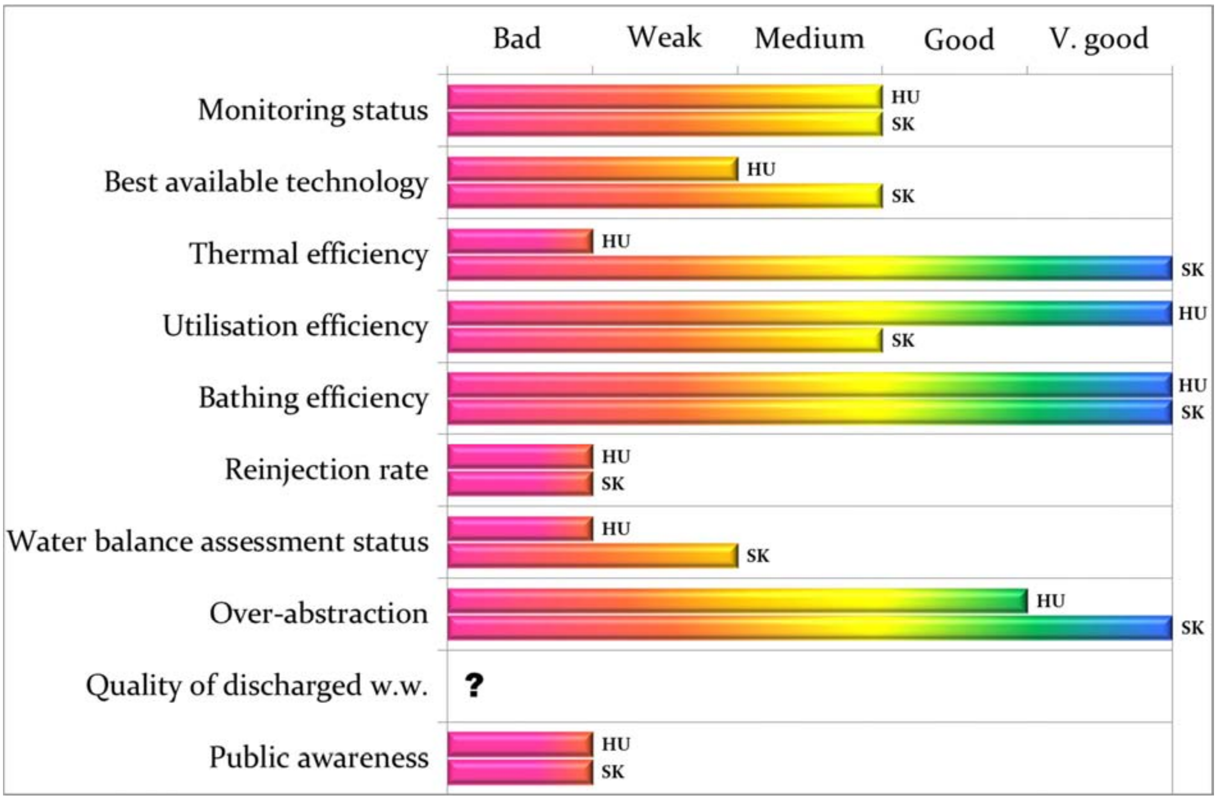


Figure 24: Overview of thermal groundwater management sustainability for the Mesozoic carbonate thermal aquifer of the Komarno-Sturovo pilot area, based on ten benchmarking parameters.

The benchmarking comparison shows that the general management of the geothermal aquifer has to be improved in both countries. The results and the main priorities for improvement are:

1) The monitoring evaluation of benchmarking is based only on active wells and shows a medium category in both countreis. It is based on reported abstraction (yield and temperature) on an annual basis with monthly reported values in both countries. Independent (passive) monitoring (through monitoring wells constructed exclusively for this purpose) is unsatisfactory, especially in Slovakia and should be established by the relevant authorities/ministries. Continuous karst water level monitoring wells, as part of the "areal monitoring" can be found only in Hungary at Tata and Esztergom.

2) Thermal efficiency shows very bad status in Hungary, but this is due to the methodology applied, which was developed for higher groundwater temperatures, therefore this indicator does not reflect correctly the thermal efficiency of a well at low wellhead temperatures (which is characteristic for the evaluated Hungarian wells).

3) Bathing efficiency is very good in both countries, reflecting its long-lasting traditions. However it focused only on the amount of the water that is available for recreation and does not reflect its effect on healing effects as stated in literature (and in Slovakia Act 538/2005).

4) No re-injection wells have been drilled or commissioned, shown by the very bad re-injection indicator. Nevertheless the aquifers are not over-exploited yet, shown by the good indicators of over abstraction. Recharge of geothermal water has been evaluated in a number of studies in Slovakia, studying the regional conditions for thermal water circulation and water regime along with calculations of water sources and reserves. Studies on drinking water protection area have been carried out on the Hungarian side. Unfortunately they lack periodic updates based on monitored data in the geothermal aquifer. These are reflected in the bad to weak indicator of water balance assessment status. However the water levels are rising on both sides of the pilot area and the previously dry springs re-appered again due to the abondoning of the mining activities in the region. In this sense the prognose for the future is that the water balance is expected to improve. Joint studies performed by the national geological institutes (surveys) and monitoring of the whole geothermal reservoir is advised.

5) There was no information collected on the quality of discharged thermal waste water within this research, and therefore we were not able to evaluate this parameter.

6) Information about the reported yield (geothermal water consumption), chemical composition and temperature of geothermal water is partly available on websites, but mainly in institutions responsible for data storage. Data on monitoring, BAT, quantity status of the aquifers, quality of waste water or energy efficiency of thermal water exploitation are not yet available to general public and sometimes they are possibly not even monitored.

4.9.2. Lutzmannsburg-Zsira Pilot Area

4.9.2.1. Introduction

The Lutzmannsburg-Zsira pilot area is situated in the transboundary zone of Austria and Hungary. The Sopron-Ödenburger Mountains, Rosalia Mountains, Bucklige Welt and the Kőszeg-Rehnitz Mountains mountains surround the Oberpullendorf Basin representing the western part of the pilot area, which is gradually lowering eastward into the southern part of the Little Hungarian Plain (Kisalföld). The elevation of the mountains varies between 400-900 m and on the lowland area the lowest point is 119 m asl.

This rural area holds mainly villages and small cities with 60 000 inhabitants. Balneology and balneologic tourism are important parts of the regional economy. There are famous spas operating both sides of the national border, such as Sárvár, Bük and Lutzmannsburg (Figs 25, 26). In addition to the well-known spas, there are several smaller users, like hotels, or baths in the region and further demands for new balneological utilizations exist. Due to the favourable geothermal conditions the energy utilization of geothermal resources – which does currently not exist yet – is a potential for the area. Locally, especially in the smaller cities the energy demand can meet the untapped resources.

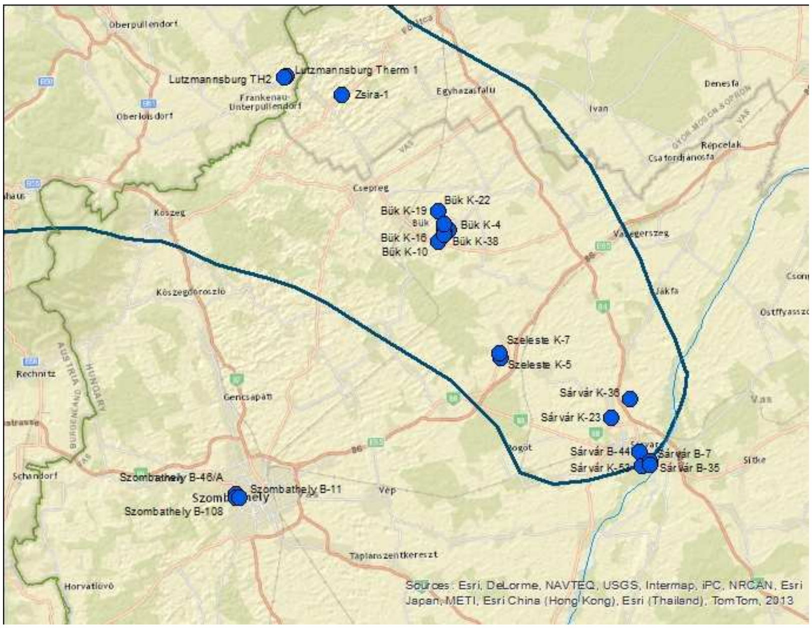


Figure 25: Thermal wells at the Lutzmannsburg-Zsira pilot area

Figure 26: Thermal spa at Bükfürdő

4.9.2.2. Geology, hydrogeology and geothermal conditions

The Lutzmannsburg – Zsira pilot area has no natural geological borders. The basement consists mainly of metamorphosed crystalline rocks of the Austroalpine and the Penninic units outcropping in the western margin of the area. These units form different nappe systems thrusted on each other. In addition to the metamorphic crystallines, the Devonian Bük Dolomite Formation is an important unit of the basement, as it stores most of the thermal water in the region. The basement is covered with Neogene sediments which deposited in morphological depressions on the tectonically preformed surface of the basement. The basement is locally overlain by older Miocene sandy limestone or calcareous sand layers which form potential hydrogeothremal reservoirs. The Upper Miocene-Pliocene (Pannonian) porous sediment series has growing thickness toward E-SE. The maximum thickness is 2000 m at the eastern part of the region. The sedimentary succession is built up of varying layers of sand, silt and clay (Fig. 27).

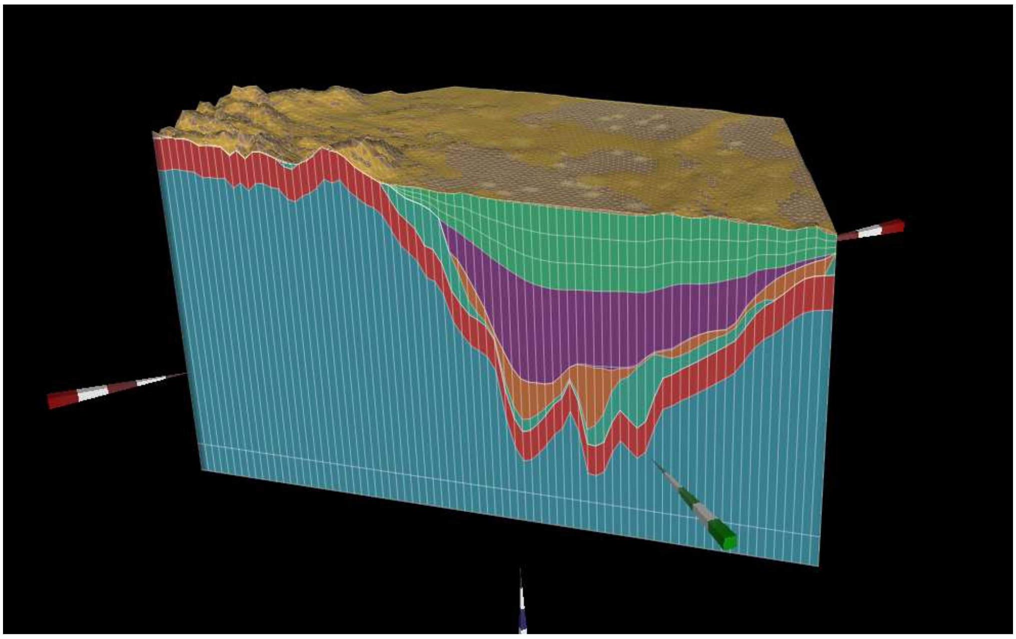


Figure 27: Geological block diagram of the Lutzmannsburg-Zsira pilot area

The main recharge of thermal groundwater is from precipitation in the high elevated mountain regions, mainly situated in Austria. Part of the infiltrated precipitation is flowing towards the deeper layers and feeds the regional flow systems. At higher depths the groundwater warms up, and changes its chemical character due to water-rock interactions. In some places where the basement is hydraulically connected to the porous Neogene basin fill sediments, the basement aquifers may pass water to the overlying intergranular aquifers, otherwise the two flow system are separated. The direction of groundwater flow in the intergranular Pannonian aquifers is from west towards the northeast, east and southeast, following a semi-radial pattern. The main groundwater discharge areas (rivers and alluvial valleys especially the Marcal river) are out of the studied area. In natural conditions several wetlands, especially the Hanság had an important role in groundwater discharge.

The chemical composition of the groundwater varies from mostly $CaMgHCO_3$ and $NaCaHCO_3$ type waters stored in the Upper Miocene aquifers to NaCl type waters characteristic to Lower Miocene aquifers. NaCl and $NaCaHCO_3$, $NaHCO_3$ chemical type waters characterize the Devonian aquifers, depending on their position within the reservoir.

The subsurface temperature is increasing eastward parallel with the increasing basement depth. It starts to decrease at the SE-ern margin of the area, where the basement is rising again towards the outcropping Transdanubian Range. The highest temperature occurs in the Szombathely-Sárvár zone, where the temperature of the basement varies between 80-110 °C at a depth of 2500 m bsl. The deepest temperature measurements were done in the crystalline basement at Egyházasrádóc (Rád-1) at a depth of 3401.5 m, where the temperature reached 115.8 °C. The Rád-2 borehole discovered 112°C in 2950 m depth.

Three different types of transboundary geothermal reservoirs have been identified in the pilot area: Upper Pannonian porous reservoirs, Miocene porous reservoirs locally with double porosity, and basement fractured carbonate reservoirs (Bük Dolomite).

The Upper Pannonian porous reservoirs are composed mainly of sandstones characterized by intergranular permeability and confined groundwater levels. This type of reservoir has good hydraulic connection both in vertical and horizontal direction which ensures continuous recharge and low total dissolved content (below 2000 mg/l) of the stored thermal water. It is used in Bük, Sárvár and Szeleste. The maximum temperature reached is 53.5°C at the region of Sárvár. Upper Pannonian reservoirs are also important as cold drinking water supply.

Older Miocene geothermal reservoirs may be composed of clastic sediments (conglomerate, sand, sandstone), with often direct hydraulic connection to the basement reservoirs. The Lutzmannsburg spa uses this type of aquifer at the depth 450-900 m. The other type of Miocene thermal water aquifers with double porosity are the Badenian and Sarmathian shallow-marine clastic carbonates with a few tens of metres thickness.

Fractured-karstified basement reservoirs, which were in the focus of studies in this pilot area are represented by the Bük Dolomite, situated in three separated blocks on the area at more than 1000 m depth. These blocks have different hydraulic connections with their surroundings, which results in different hydrochemical characters. The block at the Bük region has restricted recharge, with lower (4000-14000 mg/l) total dissolved content. The other two blocks near Sárvár form closed structures without any significant recharge, therefore characterized by high total dissolved content. The high permeability originates from multiple tectonic stresses, the reactivation of structural elements, and possible karstification during subaerial exposure periods during the geological evolution of the area.

The general characteristics and estimated geothermal potential of the Devonian Bük Dolomite hydrogeothermal reservoir in the Lutzmannsburg – Zsira pilot area are shown in Table 12. The description and methods of geothermal potential assessment are summarized at the beginning of Chapter 4.9.

General attributes	Gross volume (km^3)	120
	Aquifer volume (km^3)	6
	Average thickness (m)	600
Estimated reservoir temperature (°C)	Min	60
	Max	110
	Average	80
Estimated transmissivity 10^{-3} (m^2/s)	Min	n.a.
	Max	n.a.
	Estimated	0.48
Rock parameters	Bulk Heat Capacity (J/(m^{3x}K)	n.a.
	Bulk Density (kg/m^3)	n.a.
	Porosity (%)	3
Heat In Place (MW$_{th)}$	Balneology (single well)	412
	Heat Supply (doublet)	7014
	Electricity (doublet)	3603
Inferred Resources (MW$_{th}$)	Balneology (single well)	22
	Heat Supply (doublet)	1809
	Electricity (doublet)	919
Measured Resources (MW$_{th}$)	Balneology (single well)	22
	Heat Supply (doublet)	434
	Electricity (doublet)	39
Installed Capacities (MW$_{th}$)	Balneology (single well)	4
	Heat Supply (doublet)	0
	Electricity (doublet)	0

Table 12: Characteristics and estimated geothermal potential of the Devonian hydrogeothermal reservoir in the Lutzmannsburg – Zsira pilot area

4.9.2.3. Current utilization of thermal waters

Extensive groundwater abstractions have been existing in the region for several decades. The majority (53%) of groundwater extractions happens from the Upper Pannonian aquifer, 9% from the Quaternay aquifers, while 3.5% is abstracted from the Sarmathian (Miocene) reservoirs. Production from the Devonian basement aquifers is 1.5% of the total rates.

Thermal waters are used exclusively for balneological purposes. Famous spas (Lutzmannsburg – Austria), Bük and Sárvár (Hungary) are situated within a relatively short distance from each other. The main reservoir of Bük Spa is the Devonian Dolomite (but Upper Pannonian aquifer layers are also used (together 1695 m^3/d). There are some Upper Pannonian thermal water utilization in the pilot area at Szeleste (273 m^3/d), Szombathely and Sárvár (500 m^3/d) (Table 13).

Name	Depth [m]	Formation	Water temp. [°C]	Water use	Monitoring
Lutzmannsburg Th-1	960	Karpatian Sand	32.6	balneology	half year
Lutzmannsburg Th-2	813	Karpatian Sand	33	balneology	half year
Bük K-4	1282	Bük Dolomite Formation	58	balneology	yearly
Bük K-10	1100	Bük Dolomite Formation	58	balneology	yearly
Bük K-16	782	Újfalu Sandstone Formation	42	balneology	yearly
Bük K-19	630	Somló and Tihany Formation	39	balneology	no monitoring
Bük K-22	718	Újfalu Sandstone Formation	38.5	balneology	yearly
Bük K-38	900	Somló and Tihany Formation	44.5	balneology	yearly
Szeleste K-7	800	Újfalu Sandstone Formation	36	balneology	
Szeleste K-5	1258	Újfalu Sandstone Formation	49.5	balneology	
Szombathely B-108	639	Somló and Tihany Formation	34.2	balneology	yearly
Szombathely B-46/A	700	Somló and Tihany Formation	37	balneology	yearly

Name	Depth [m]	Formation	Water temp. [°C]	Water use	Monitoring
Sárvár B-35	1293	Zagyva Formation	44	balneology	yearly
Sárvár B-44	1300	Újfalu Sandstone Formation	48	balneology	no monitoring
Sárvár B-7	998,5	Újfalu Sandstone Formation	44	belneology	yearly
Sárvár K-53	1050	Újfalu Sandstone Formation	46	balneology	yearly

Table 13: Current users of thermal water

4.9.2.4. Existing and potential future conflicts

The effects of thermal water withdrawals on hydraulic heads have been observed in both countries, furthermore observed alterations in groundwater chemistry also suggested man-induced changes in the thermal water flow system. The effects of groundwater extraction, the relation and possible interactions between the three identified reservoirs (Upper Pannonian, Miocene, and basement reservoirs) as well as the recharge and thermal conditions of these reservoirs however were not clear and required further clarification, which were the main addressed questions at this pilot area.

4.9.2.5. Towards a sustainable management

The coupled groundwater flow and heat transport ***steady state*** model provided three-dimensional information on hydraulic head and temperature distributions as well as on groundwater fluxes (Kovács and Rotár-Szalkai, 2013a). Model simulations indicated that regional groundwater table drawdown varies between 1-15 metres in response to production from all aquifers. The depressurisation of the pre-Neogene aquifers generally varies between 2-12 metres. The largest pressure drop exists around the Bük boreholes.

The modelled temperature distribution indicated little vertical variations of temperature within the Upper Pannonian sediments, and gradually increasing temperatures within older sediments and the fractured basement (Fig. 28).

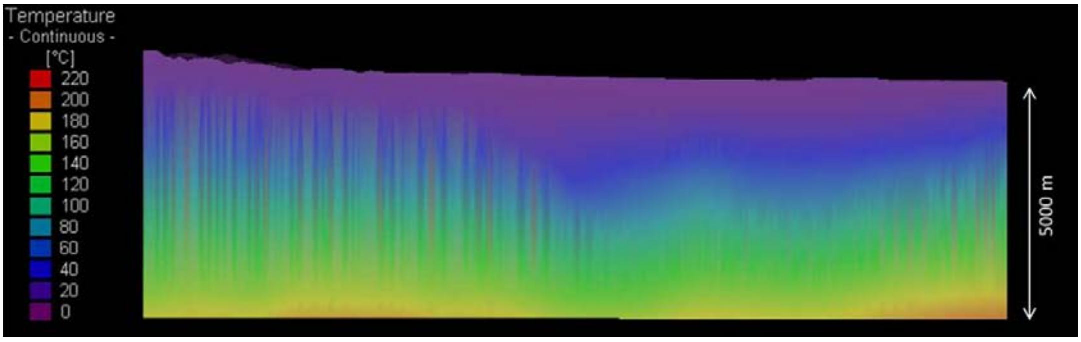


Figure 28: Simulated NW-SE temperature profile

In ***scenario modelling*** (Kovács and Rotár-Szalkai 2013b) the Lutzmannsburg-Zsira local system was studied in details, which comprises the following components (Fig. 29):

- Two extraction wells at Bük: Bük K-4 and Bük K-10 abstract groundwater from the Devonian Bük dolomite at a total rate of 1500 m^3/day. Production of thermal groundwater started in 1962 at a rate of 200 m^3/day and gradually increased over the following years to the current extraction rate. The temperature of the outflowing water is 58 °C.
- Two production boreholes at Lutzmannsburg: Thermal- 1 and Thermal -2 started operation in 1994 at an abstraction rate of 430 m^3/day. These wells are screened within the Karpatian sediments, and are operated alternately.
- An observation borehole at Zsira: Zst-1 is screened within the Karpatian sediments, and is located in between the Zsira and the Lutzmannsburg abstraction wells, thus providing information on the combined effects of these productions.

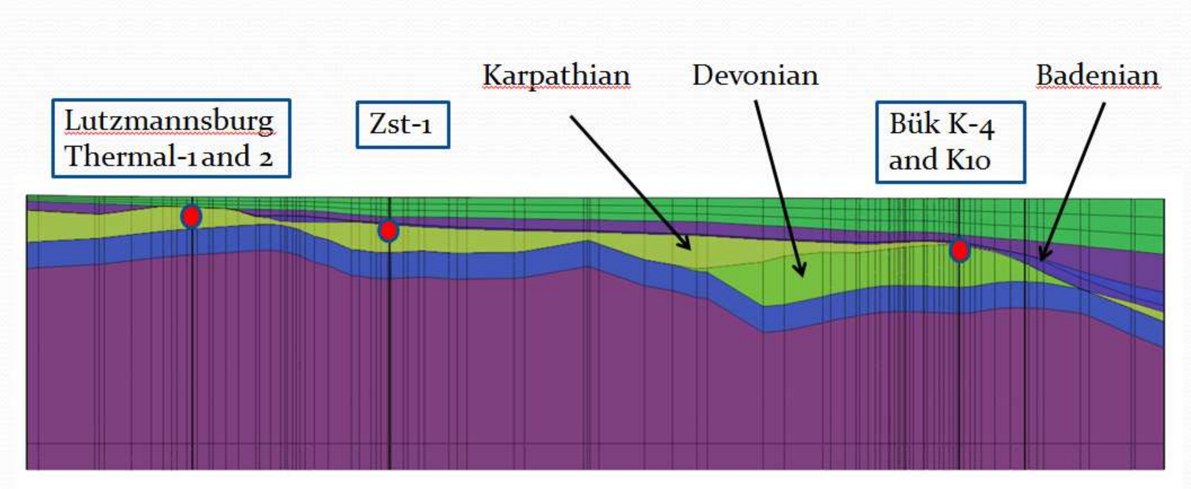


Figure 29: Local hydrostratigraphy of the Lutzmannsburg-Zsira local system (NW-SE cross section)

Since the beginning of groundwater abstraction at the above locations, the following changes were observed:

- A gradual increase in the concentration of main water components including Na, K, HCO_3, Cl and SO_4 in Bük K-4 and K-10;
- A gradual pressure drop up to 15 metres in Zsira Zst-1.

It was suspected, that the pressure drop observed in Zst-1 was caused by the depressurisation of the Bük thermal water production boreholes and that the increasing salinity was the result of saline water leakage from underlying or overlying reservoirs. However the exact source of saline groundwater has not been identified before. The detailed analysis of the modelled flow vectors indicated the reversal of natural flow directions at the Bük and Lutzmannsburg boreholes. While the natural recharge of the Bük Dolomite is through the overlying Karpatian sediments from the west, the depressurisation due to production casuses the reversal of natural flow. As a consequence, groundwater leaks into the Devonian reservoir not only from the Karpatian but also from the overlying Badenian sediments located in the west and from the low-permeability basement rocks underlying the Bük Dolomite (Fig. 30). The analysis of water chemistry of the main reservoirs around the Bük Dolomite block indicated that

Badenian reservoirs contain high-salinity waters which might alter groundwater composition of the Bük Dolomite through mixing processes.

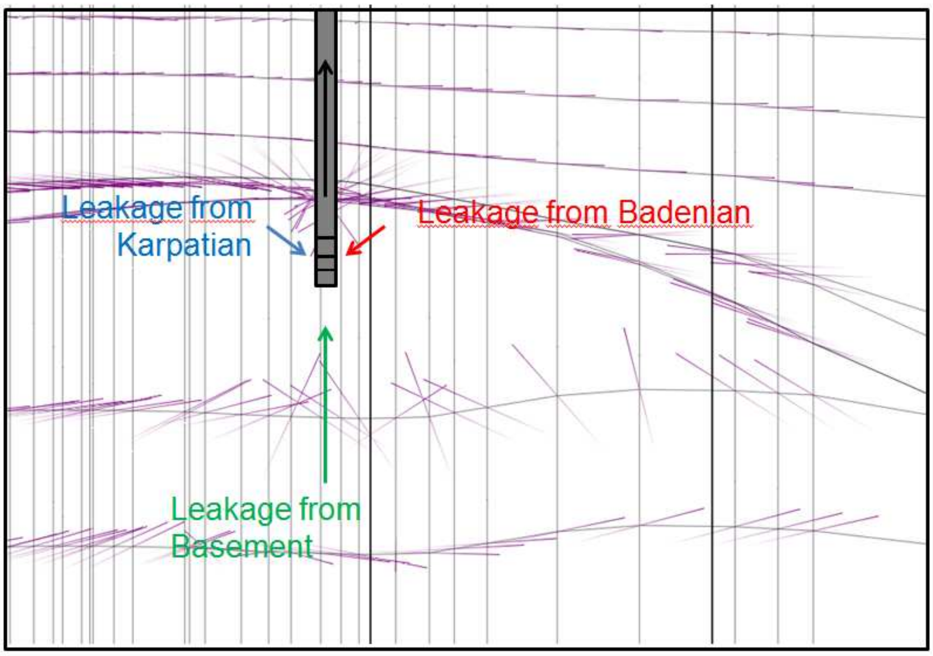


Figure 30: Groundwater leakage in response to production from the Bük Dolomite block

In order to separate the hydraulic influence of different water extractions and to determine the sources of depressurisation observed in the Zsira Zst-1 bore, a production state model was applied. By »switching off« user groups, certain areas, different scenarios could be investigated and the hydraulic impact of abstraction wells could be evaluated. The simulated scenarios included the following:

1. No groundwater extractions at Bük;
2. No groundwater extractions at Lutzmannsburg;
3. No groundwater extractions at Bük or Lutzmannsburg;
4. No groundwater extractions in the Upper Pannonian aquifer;
5. No groundwater extractions in the Hungarian part of the pilot area;
6. No groundwater extractions in the Austrian part of the pilot area;

The simulated drawdown rates are shown in Table 14.

Borehole	Simulated depressurisation (m)						
	current production	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Zsira Zst-1	15.3	10.6	14.1	9.6	9.7	5.1	11.2
Lutzmsb Th-1	32.3	30.7	11.4	10.1	21.5	25.7	27.3
Bük K-4	59.9	9.4	59.0	9.1	51.5	3.1	56.8
Bük K-10	49.8	9.3	49.3	8.9	41.8	3.0	47.1

Table 14: Simulated depressurisations according to different scenarios

The conclusions of the different drawdown scenarios are the following:

- Both the Bük and Lutzmannsburg productions contribute to the drawdown observed in Zst-1;
- The Upper Pannonian abstractions also contribute to the depressurisation observed in Zst-1. When the Bük and Lutzmannsburg boreholes are switched off, an approximate 10 m depressurisation remains in the border zone area. This suggests, that the
- Lower Pannonian aquitard is not an effective hydraulic barrier in the long term;
- The contribution of the Upper Pannonian and Quaternary productions located in Hungary is comparable to that of the Bük and Lutzmannsburg abstractions. Both production groups contribute to the depressurisation along the border zone equally;
- Both Austrian and Hungarian productions contribute to the depressurisation in Zst-1; the contribution of the Hungarian wells is slightly larger.

The above observations clearly indicate that a harmonised cross-boundary groundwater management is essential for the successful optimisation of groundwater and thermal water utilisation and is only possible on the base of a joint evaluation / numerical modelling of the system.

In order to investigate the potential consequences of the future stress on the geothermal and groundwater systems of the pilot area, a twofold increase in production rates has been simulated ***(Scenario 7)***. This included the increase of existing productions (no additional production boreholes were introduced) and the simulation of equilibrium potentials. The results clearly indicated that the increase of production rates would put a significant stress on the groundwater system: the water table drawdown would be as much as 26-28 metres, compared to the 10-12 metres at current production levels (with having a value of 16 metres in the border zone).

In order to investigate the effects of re-injection of thermal water, a hypothetical geothermal doublet has been simulated, too ***(Scenario 8)*** in the eastern Devonian dolomite block. This reservoir is similar to the dolomite reservoir exploited by the Bük abstraction boreholes, but is hydraulically independent and thus not affected by artificial activities. Similarly to the Bük production wells, 1500 m^3/day abstraction rate has been applied, and the same amount was assumed to be reinjected in a borehole located approximately 500 metres apart.

According to the simulation results, the re-injection borehole had a thermal influence in a circle of 4 km radius around the well. The cooling effect did not extend far beyond the boundaries of the eastern dolomite block (Fig. 31). The steady-state drawdown rates around the virtual borehole doublet showed that the abstraction borehole had a steady state depressurisation of up to 60 metres without re-injection, while if re-injection is applied, it dropped to 13 metres. At the same time, a pressure increase of 7 m developed around the re-injection borehole (Fig. 32).

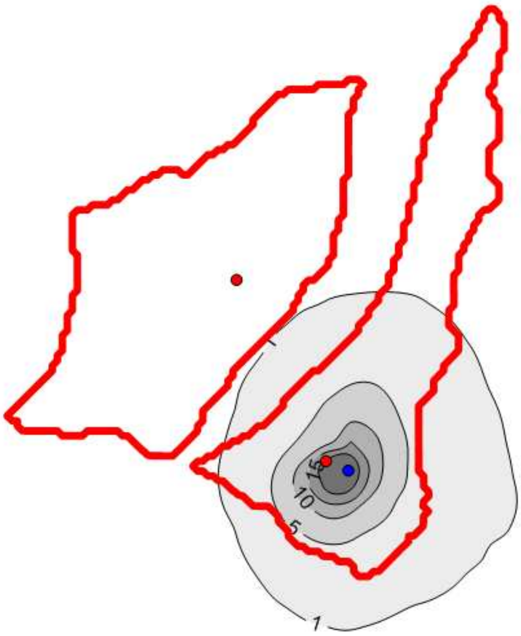


Figure 31: Steady-state temperature drop around the re-injection borehole of a virtual borehole doublet installed in the Eastern Bük Dolomite block (blue dot refers to re-injection, red dot to productions well). Simulated extraction rate is 1500 m^3/day, re-injection temperature is 20 °C. Red dot towards the NW represents existing Bük production well at the W-ern dolomite block. Red lines show the areal distribution of the Bük Dolomite (W-ern and E-ern blocks)

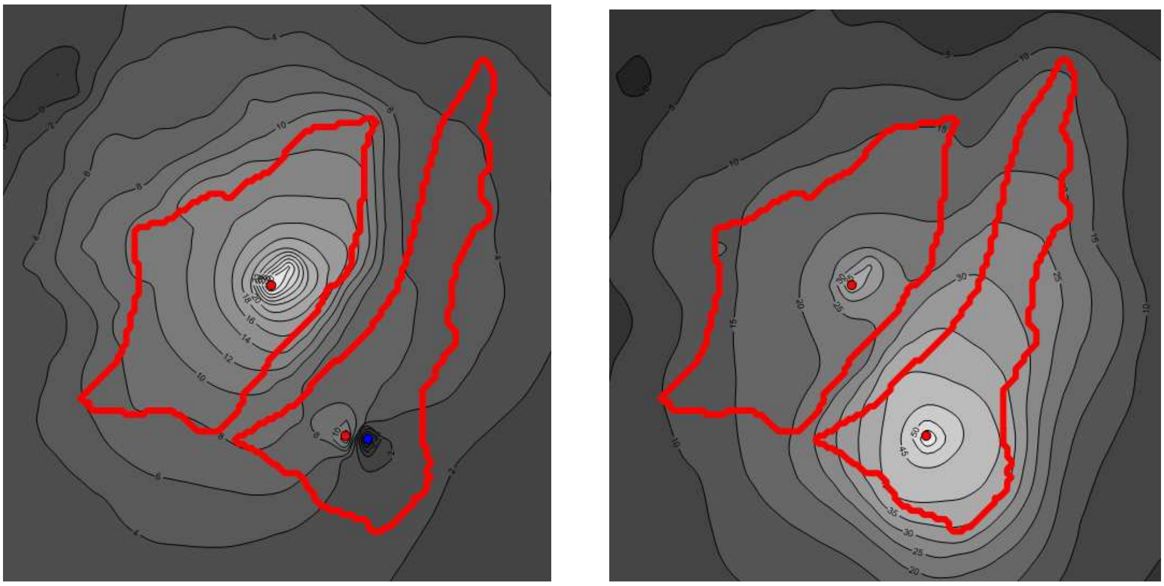


Figure 32: Steady-state drawdown rates around a virtual bore doublet installed in the Eastern Bük dolomite block with (left) and without (right) re-injection. Simulated extraction rate is 1500 m^3/day, re-injection temperature is 20 C. Red dot towards the NW represents existing Bük production well at the W-ern dolomite block. Red lines show the areal distribution of the Bük Dolomite (W-ern and E-ern blocks)

4.9.2.6. Benchmark evaluation

The benchmarking survey was carried out based on an overview of 12 active and 3 inactive geothermal wells on the Hungarian, and 2 active wells on the Austrian side of the pilot area. Summaries of the indicator values are shown in Table 15 and Fig. 33.

No	**Benchmarking parameter**	**Hungary**			**Austria**		
		Value	**Points**	**Evaluation**	**Value**	**Points**	**Evaluation**
1	**Monitoring status**	5.79	50	Medium	7	75	Good
2	**Best available technology**	1.97	50	Medium	1	75	Good
3	**Thermal efficiency**	58%	50	Medium	**	**	**
4	**Utilization efficiency**	95%	100	Very good	>30%	100	Very good
5	**Bathing efficiency**	100%	100	Very good	0.32	100	Very good
6	**Re-injection rate**	0%	0	Bad	0%	0	Bad
7	**Status of water balance assessment**	53%	50	Medium	>95%	100	Very good
8	**Overabstraction**	0.46	75	Good	0	100	Very good
9	**Quality of discharged waste thermal water**	no information			>95%	100	Very good
10	**Public awareness**	0	0	Bad	4	50	Medium

****** In Austria no temperature of effluent water is available, therefore thermal efficiency could not be calculated

Table 15: Calculated values of benchmarking indicators for the interconnected Upper Miocene (Upper Pannonian), Lower Miocene and Devonian aquifers of the Lutzmannsburg-Zsira pilot area

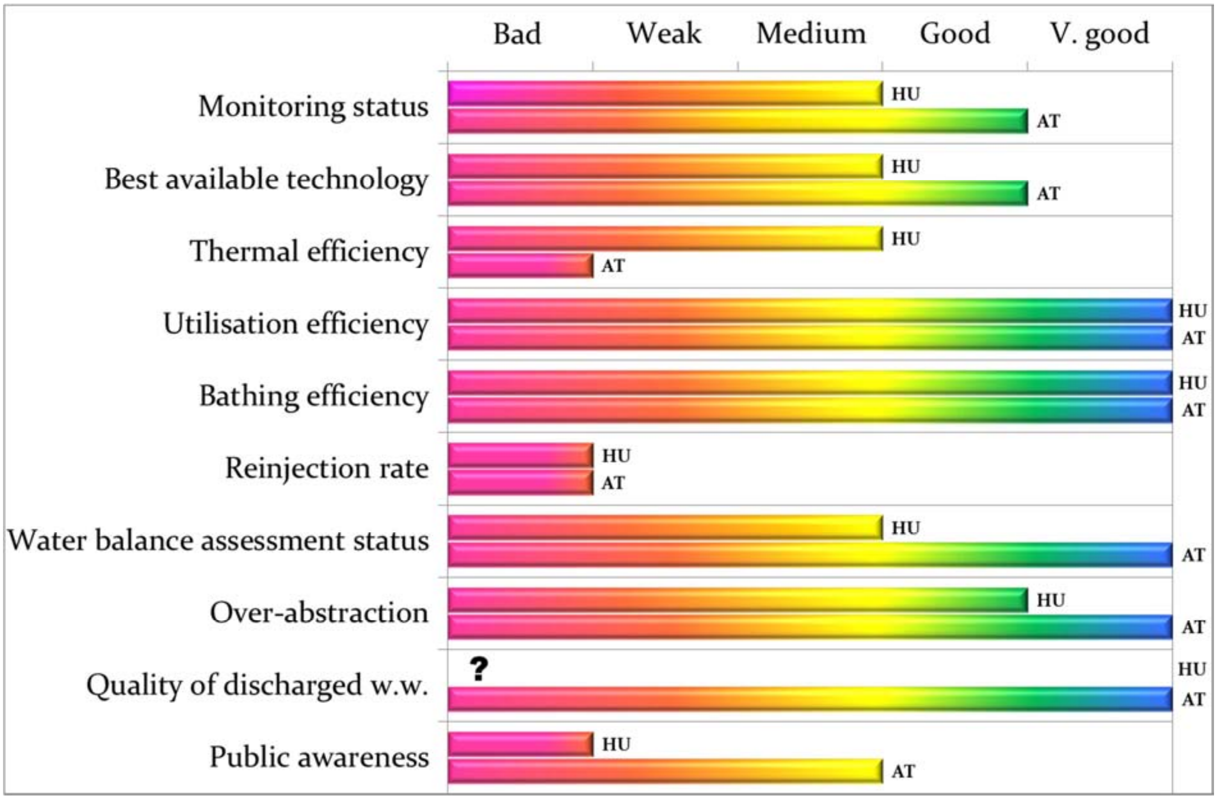


Figure 33: Overview of thermal groundwater management sustainability for the the interconnected Upper Miocene (Upper Pannonian), Lower Miocene and Devonian aquifers of the Lutzmannsburg-Zsira pilot area, based on ten benchmarking parameters.

The benchmarking comparison shows that the general management of the investigated transboundary geothermal reservoirs must be improved in both countries, but especially on the Hungarian side. The results of the benchmarking can be summarized as follows:

1) The monitoring indicator for the active thermal water wells is medium on the Hungarian side, while better value is reported for the Austrian side. In all cases there are annually reported monthly abstraction values. However there is one monitoring well on the Hungarian side of the pilot area (Zsira-1) which is screened in the Lower Miocene Lajta limestone Formation providing continuous piezometric level measurements.
2) As some of the Western Pannonian basin's most famous thermal spas and heath care centres are located in this region, many commercial developments have been made in the last couple of years, which is reflected in the use of the best available technology (medium to good indicator values), even if further improvements can still be made.
3) The extracted thermal water is used for different purposes within the spas, but cascade use of thermal water is not applied in Hungary. This type of utilization would improve the indicator of thermal efficiency, especially on the Hungarian side. In Austria no temperature of effluent water is available, therefore thermal efficiency could not be calculated
4) Utilization and bathing efficiencies are very good in both sides of the pilot area. The utilization efficiency is almost 100% on the Hungarian side, which also reflects the boom in thermal spa and thermal health care developments in Hungary.
5) No re-injection wells have been drilled or commissioned.
6) Recharge of geothermal water has been evaluated for Austria. Water balance calculations and the amounts of maximum abstraction were calculated for both major

(Bük, Sárvár) thermal spas on the Hungarian side, including the the maximum allowed extraction amounts in case of further commercial developments.

7) The indicators of overabstraction show good to very good status, but the changes with time in the chemical composition of the wells in Bük may indicate the first signs of overabstraction of this reservoir, especially the Devonian aquifer. No data on overabstraction are reported on the Austrian side.
8) There is no information on the quality of discharged thermal waste water on the Hungarian side. The reported values show very good quality for the Austrian waste waters, which means no improvement is needed in this respect in Austria.
9) Data on monitoring, BAT, quantity status of the aquifers, quality of waste water or energy efficiency of thermal water exploitation are not available to the general public in Hungary, while information on BAT and quality of waste water can be accessed in Austria through the "Wasserbuch" which is publically available. Information on the temperature and chemical composition of thermal water and their health benefits is available for the public on the Hungarian public websites.

4.9.3. Danube Basin Pilot Area

4.9.3.1. Introduction

The Danube Basin pilot area is situated in Slovakia, Hungary and partly in Austria, covering around 12,170 km^2 (Fig. 34). The Danube Basin is geographically represented by the Danube Lowland in Slovakia (about 51%) and by the Little Hungarian Plain in Hungary (about 40%), while a small part (cca 9%) lies within Austria. On the west it is bordered by the Eastern Alps, Leitha Mts. and Male Karpaty Mts. On the north the basin has finger like extensions which penetrate among the mountains of Male Karpaty, Povazsky Inovec and Tribec. On the northeast it is bounded by the Middle Slovakian Neovolcanics and the Burda volcanics, on the southeast by the emerging units of the Transdanubian Range.

The Danube Basin pilot area has a moderate population density, about 50-300 inhabitants/km^2, however there are some major cities (Bratislava, Trnava, Komarno, Nové Zámky, Dunajská Streda in Slovakia; Győr, Mosonmagyaróvár, Komárom, Kapuvár in Hungary). Although there are some industrial zones around Bratislava, Komárom-Komarno and Győr, the majority of the area is characterized by a high share of agriculture activities.

Similarly to the Komarno-Sturovo pilot areas (with which it is slightly overlapping), major porous groundwater bodies, also storing thermal water are divided by national boundaries. The upper cold zones are in the focus of the International Commission for the Protection of the Danube River (ICPDR).

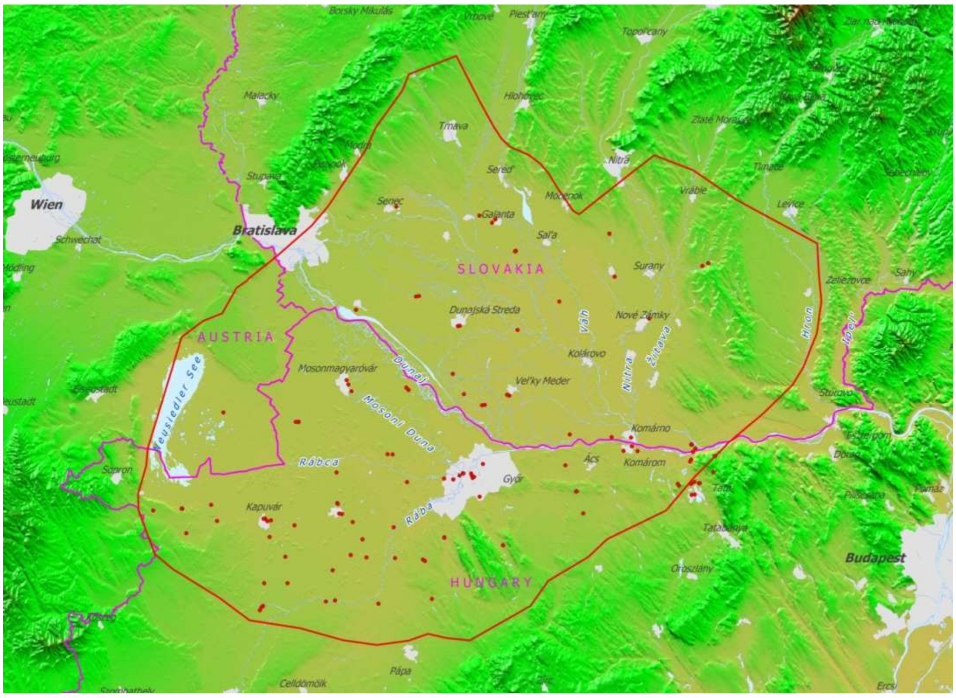


Figure 34: Delineation of the Danube Basin pilot area with the production wells.

4.9.3.2. Geology, hydrogeology and geothermal conditions

The pilot area is a large and very deep Tertiary basin, composed of several depocenters (depressions) of various geological ages, surrounded by mountains. The central part of the basin is the Gabcikovo depression, which is more than 8500 m deep. The pre-Tertiary basement is built up of crystalline and mainly Upper Palaeozoic and Mesozoic (dominantly Triassic – Jurassic) sedimentary rocks belonging to various stratigraphic units. The crystalline basement is characterized by fissure-type permeability, however due to the great depth has no significant influence on the groundwater flow system. Improved hydraulic conductivity may exist only along major tectonic lines. Some smaller blocks of carbonate aquifers are known in the basement, the most important is the Levice block at the NE-ern part of the Danube Basin, composed of Triassic dolomite. This aquifer (together with the overlying basal Badenian clastic sediments) stores thermal water of 69-80 °C, with 19 g/l TDS.

At the base of the Tertiary basin fill sequence Badenian and Sarmatian clays, siltstones, sandstones and conglomerates and some limestones are found. These older Miocene aquifers are connected to the basement reservoirs, especially on basement highs, and form separate systems. They contain fossil waters with high salinity. Such a special basement aquifer composed of basal Badenian clastics (conglomerates, sandstone) is found in the Dubnic depression at a depth between 1000-2000 meters underlain by crystalline schists and granitoids of the Veporicum. It represents a closed reservoir, with temperature of 52-75 °C, and mineralization ranging from 10 to 30 g/l.

The majority of the Tertiary basin fill is however represented by a several thousand meter thick Upper Miocene – Pliocene (Pannonian) sedimentary succession which consists of deposits of a gradually filling up huge lake basin (Lake Pannon) into which large delta systems supplied sediments from the uplifting marginal mountains (Alps and Carpathians) (Fig. 35). The main intergranular reservoir of the Danube Basin pilot area is represented by the Upper Pannonian sediments deposited in a dish-like shape depression located between Bratislava and Komárno/Komárom. This thermal water aquifer is built up of alternations of clays and sandy clays with sands and sandstones of different ratios of intergranular permeability and is characterized by confined groundwater levels which are recharged through interlayer leakage from higher horizons. The topmost boundary of this hydrogeothermal reservoir is at a depth of 1000 m, while the bottom is represented by a relatively impermeable aquiclude (clay), which deepens from its periphery to the centre of the basin and reaches its maximum at a depth of 3400 m in the central part of the depression. It contains thermal waters of 42–92 °C temperature, which are mainly stored in sands to sandstones aquifers. The chemical type of the waters is Na-Cl, Na-HCO_3-Cl, Na-HCO_3, Na-Ca-HCO_3, Ca-Mg-HCO_3. The Upper Pannoninan sediments are covered by Quaternary fluvial deposits — up to a thickness of 600 m in the Gabcikovo depression — and loess in the hills..

Regarding the geothermal conditions, the highest heat flow densities have been recorded in the central part of the depression ($q > 85$-90 mW/m^2) which do not correspond to measured lower temperatures ($T < 45$°C), or thermal gradients. Whereas heat flow decreases towards the margins of the Danube Basin, temperature increases. This irregularity is caused by a cold water body up to 700 m thick (groundwater stored in the thick alluvium of the Danube river), forming the uppermost hydrogeological unit in the central part of the depression.

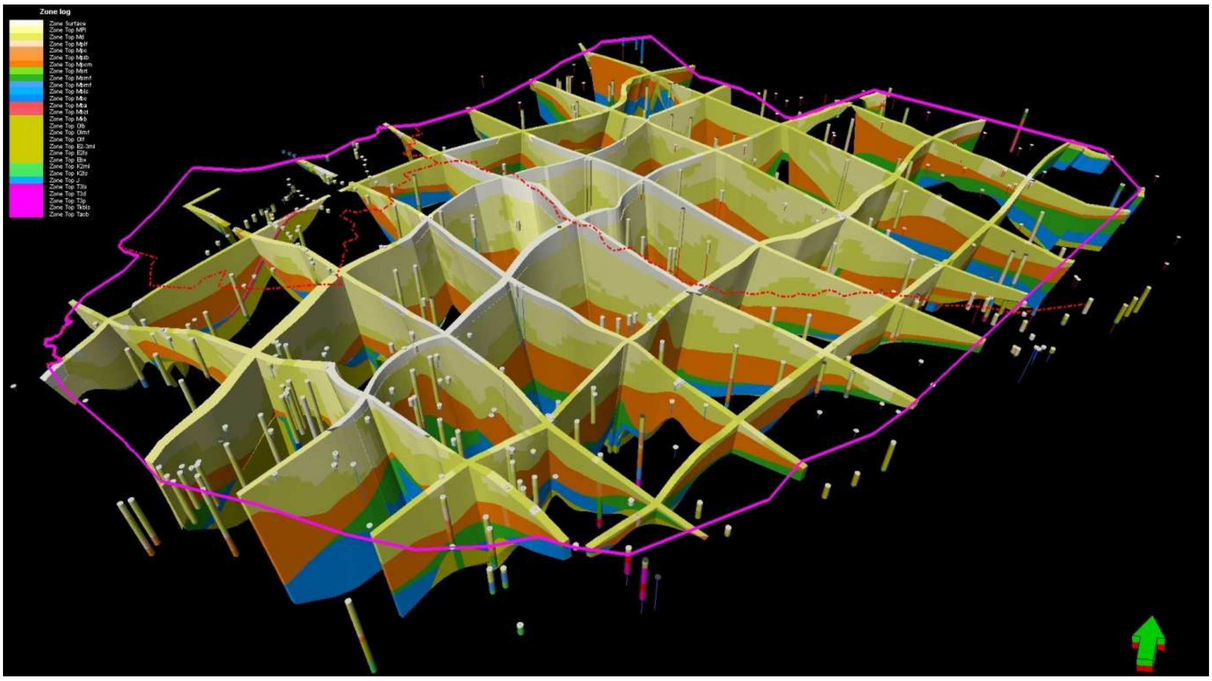


Figure 35: 3D geological model of the Danube Basin pilot area.

The main identified hydrogeothermal reservoir which was in the focus of investigations in the Danube Basin pilot area is the Upper Miocene-Pliocene (Upper Pannonian) intergranular geothermal aquifer. Its general characteristics and estimated geothermal potential are shown in Table 16. The description and methods of geothermal potential assessment are summarized at the beginning of Chapter 4.9.

General attributes	Gross volume (km^3)	9127
	Aquifer volume (km^3)	1278
	Average thickness (m)	985
Estimated reservoir temperature (°C)	Min	10
	Max	136
	Average	46
Estimated transmissivity 10^{-3} (m^2/s)	Min	0.072
	Max	1.544
	Estimated	0.423
Rock parameters	Bulk Heat Capacity (J/(m^{3x}K)	n.a.
	Bulk Density (kg/m^3)	n.a.
	Porosity (%)	14
Heat In Place (MW$_{th)}$	Balneology (single well)	34325
	Heat Supply (doublet)	176868
	Electricity (doublet)	0
Inferred Resources (MW$_{th}$)	Balneology (single well)	1075
	Heat Supply (doublet)	6205
	Electricity (doublet)	0
Measured Resources (MW$_{th}$)	Balneology (single well)	24
	Heat Supply (doublet)	137
	Electricity (doublet)	0
Installed Capacities (MW$_{th}$)	Balneology (single well)	36.7
	Heat Supply (doublet)	23.9
	Electricity (doublet)	0

Table 16: Characteristics and estimated geothermal potential of the Upper Miocene hydrogeothermal reservoir in the Danube Basin pilot area

4.9.3.3. Current utilizations of thermal waters

There is a widespread utilization of thermal water from the Upper Miocene-Pliocene (Upper Pannonian) intergranular aquifers throughout the whole pilot area both on the Slovak and Hungarian sides. The major sectors are direct heat: greenhouse and soil heating as well as individual space heating and heating of sanitary waters, however this dominates the Slovak side of the pilot area (Fig. 36). Balneological use is widespread on both sides (Fig. 37). There is only one utilization with smaller amount of exploited thermal water in Frauenkirchen at the Austrian part. Wells are pumped, but many of them have natural outflow, showing different reservoir conditions. The average yield of utilized thermal water on the Hungarian side of the Danube Basin pilot area is 51 349 m^3/year, while on the Slovak side it is 87 631 m^3/year. Although major deteriorations in the quality and quantity status of the thermal water aquifers have not been identified yet, the extensive utilization already caused some temperature and pressure drops in some parts. Due to the large size of the pilot area (more than 12 000 km^2), detailed studies of existing utilizations and their effects were restricted to 2 main transboundary regions: Mosonmagyaróvár-Lipót-Šamorín (Area 1) and Győr-Veľký Meder (Area 2), where temperature and hydraulic heads are prone to decrease due to extensive production, furthermore transboundary flow of thermal groundwaters is significant (Tables 17, 18).

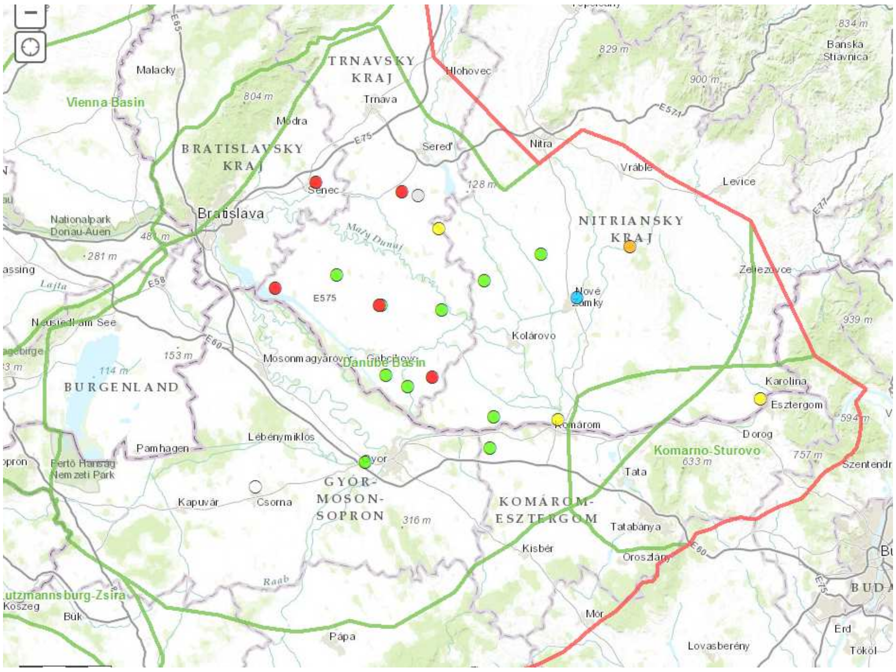


Figure 36: Utilization of thermal water for direct heat in the Danube Basin pilot area (green: heating of greenhouses and soil, red: individual space heating and sanitary water heating, yellow: individual space heating, orange: individual space heating and greenhouse and soil heating, blue: sanitary water heating).

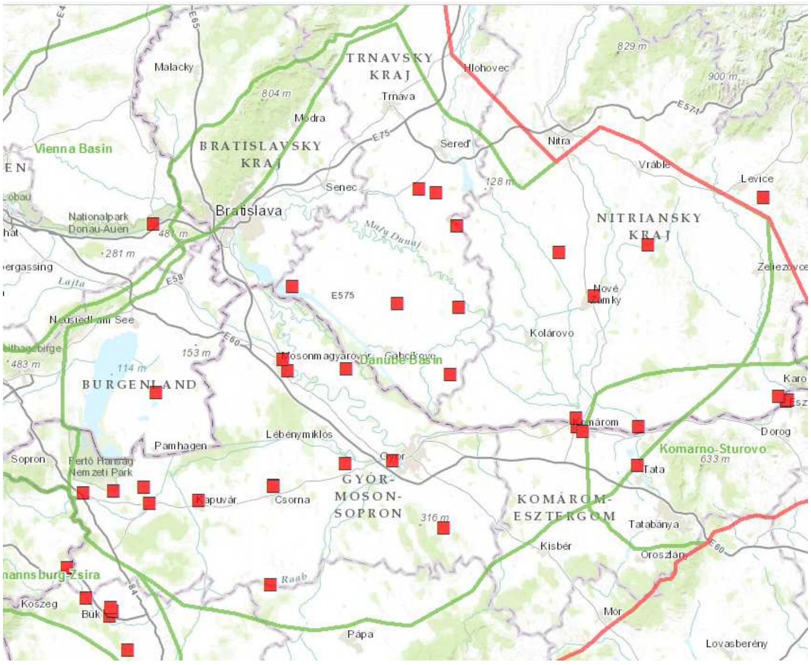


Figure 37: Utilization of thermal water for balneology in the Danube Basin pilot area

Name	Depth	Formation	Water temp. [℃]	Water utilization [m^3/year]			Water use	Monitoring
				2007	2008	2009		
FGČ-1	2500	Ivánka formation	54	89 310	84 990	180 813	bathing and swimming (including balneology)	no monitoring
Moson-magyaróvár B-123	2000	Újfalu Sandstone Formation	75	395 295	395 280	320 105	industrial water	continuous data
Moson-magyaróvár K-136	2000	Újfalu Sandstone Formation	78	215 827	249 978	200 020		annual data
Mosonmagyaróvár K136.	1994.9	Zagyva Formation	60	0	0	0	bathing and swimming (including balneology)	no monitoring
Lipót K-10	1806	Somló and Tihany Formation	61	85 387	99 377	158 103		annual data
Máriakálnok K-32	1182.6	Upper Pannonian sand	50.1	0	0	0	bathing and swimming (including balneology)	no monitoring
Lipót K-7	2206.5	Újfalu Sandstone Formation	64	47 071	30 145	39 340		annual data

Table 17: Overview of thermal groundwater utilization in Area 1 (Mosonmagyaróvár-Lipót-Šamorín)

Name	Depth	Formation	Water temp. [℃]	Water utilization [m^3/year]			Water use	Monitoring
				2007	2008	2009		
Gyõr B-12/A	367.8	Zagyva Formation	22	8 281	3 500	3 500	bathing and swimming (including balneology)	no monitoring
Gyõr K-139	466	Somló and Tihany Formation	24	507 874	6 980	6 635		monthly data
Gyõr B-181	398.5	Somló and Tihany Formation	23.2	471 951	407 920	273 032	bathing and swimming (including balneology)	monthly data
Gyõr B-60	1998	Újfalu Sandstone Formation	66	160 594	21 630	186 788		annual data
Gyõr K-80/A	0	Somló and Tihany Formation	29	14 423	22 735	2 356	bathing and swimming (including balneology)	monthly data
Gyõr B-87/a	360	Somló and Tihany Formation	21	17 833	0	23 489	bathing and swimming (including balneology)	monthly data
ČR-1	2513	Beladice formation	80.5	86 600	85 000	838 000	bathing and swimming (including balneology)	no monitoring
VČR-16	1800	Beladice formation	62	0	0	0	bathing and swimming (including balneology)	no data
Č-1	2502	Beladice formation	69	0	170 820	145 498	bathing and swimming (including balneology)	no monitoring
Č-2	1503	Beladice formation	53	410 057	363 067	354 151	bathing and swimming (including balneology)	no monitoring
Abda K-12	1850	Újfalu Sandstone Formation	65	110 000	110 000	30 381		monthly data

Name	Depth	Formation	Water temp. [℃]	Water utilization [m^3/year]			Water use	Monitoring
				2007	2008	2009		
Gyõr B-148	2034	Újfalu Sandstone Formation	68	242 768	23 338	253 748		monthly data
Gyõr B-81	2004	Újfalu Sandstone Formation	69	92 725	20 341	175 886	bathing and swimming (including balneology)	monthly data
Gyõr K-109	551	Somló and Tihany Formation	27	0	0	0	bathing and swimming (including balneology)	no monitoring

Table 18: Overview of thermal groundwater utilization in Area 2 (Győr- Veľký Meder)

4.9.3.4. Existing and potential future conflits

Although no utilization conflicts exist yet on this large area, the current utilization magnitudes and forecasted growing demand for future geothermal installations and balneological sites may threat the currently good status of the hydrogeothermal reservoirs. Modeled groundwater temperatures and pressures forecast that these parameters may significantly drop due to excessive production, especially after long-term exploitation.

The majority of production (even for direct heat) takes place from the Upper Miocene-Pliocene intergranular aquifers without re-injection. Therefore steady state and scenario models were focusing on the quantification of limit values of sustainable thermal water production and also whether re-injection is feasible into the intergranular aquifers (based on today technology) and its conditions. Partial re-injection to basement aquifer happens only at Podhájska (Slovakia). At the other utilization sites (mostly discharging the Upper Miocene-Pliocene intergranular aquifers) most of the utilized geothermal water is discharged to surface streams after their direct heat use. Although they have acceptable values (temperature and TDS limits) for the environment, this is not sustainable on long terms. Some installations include heat pumps for better thermal efficiency, or use of methane (if present in water after the gas separation, e.g. Zlatná na Ostrove, well VZO-13) and thus mitigating thermal pollution of the streams, or production of greenhouse gases.

4.9.3.5. Towards a sustainable management

Steady state models (Svasta et al 2013a) quantified the hydraulic head and temperature distributions (Fig. 38) in the main aquifers on the entire pilot area at pre-utilizing “natural” state, and at a situation assuming theoretical infinite pumping at all existing operating thermal wells maintaining present state production levels. The comparison of these two model results allowed drawing conclusions on the future evolution of the pressure and thermal fields in the area, and identifying potential adverse impacts of current utilization of thermal water resources in certain sensitive regions. Results showed that continuing pumping of thermal water is causing a decrease in hydraulic pressure and some temperature drops in the targeted aquifers as well as in the adjacent aquitards, however present productions do not initiate significant changes. The results also confirmed the significant cooling effect of the infiltrating cold (10 °C) groundwater through the thick (up to 713 m) Quaternary alluvial sediments of the Danube with high permeability which propagates down to a depth of 3 km.

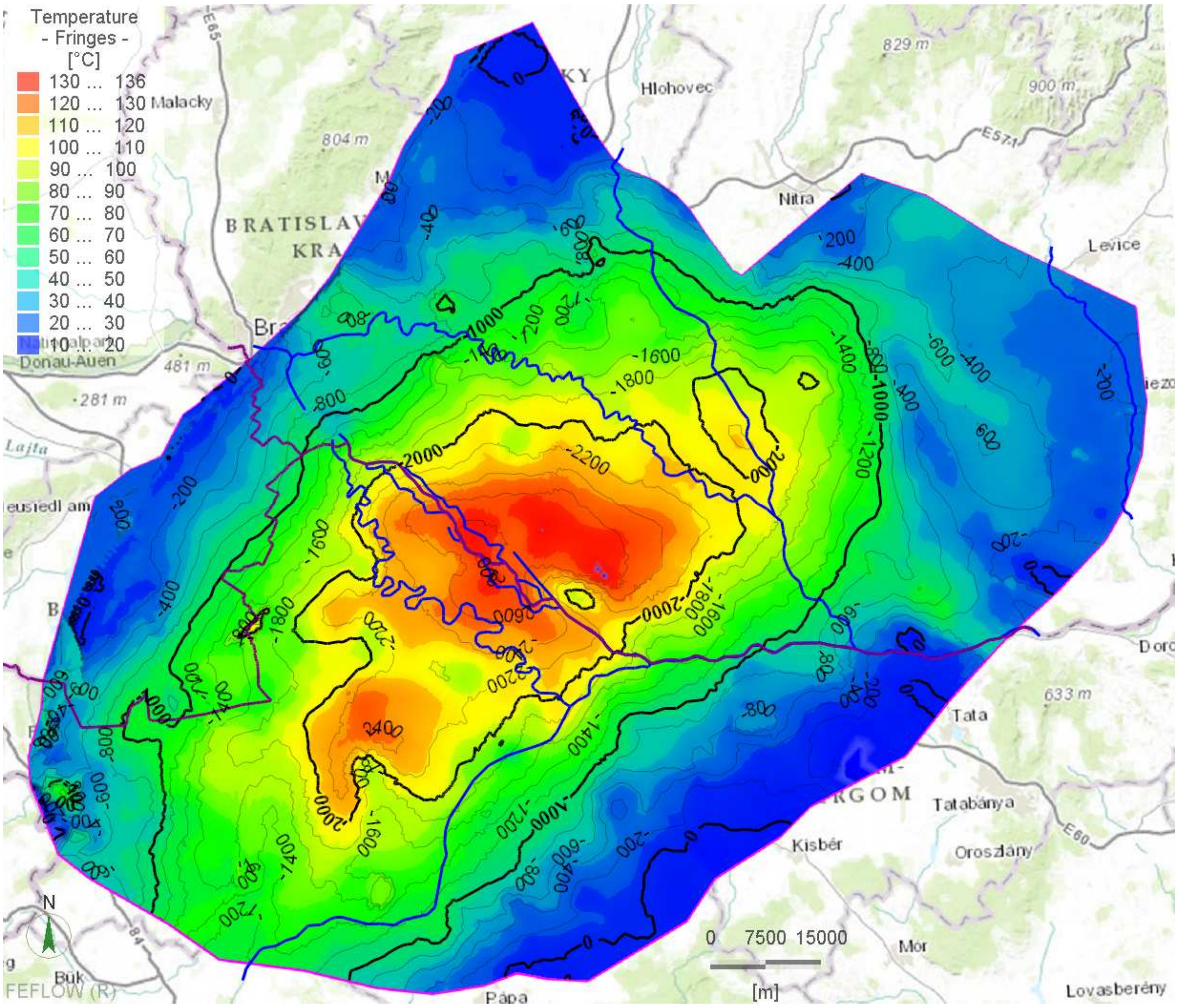


Figure 38: Groundwater temperature at the base of the main thermal reservoir – Upper Pannonian sediments (depth contours, m a.s.l.).

Steady state models also visualized groundwater flow trajectories with travel times of active thermal wells (Fig. 39). The results draw attention not only to transboundary effects, but to the interactions of closely spaced wells in areas of intense utilization. Water budgets calculations confirmed a significant amount of groundwater flow across national borders (Fig. 40). The columns show that mainly the Hungarian parts of the Upper Pannonian aquifer pass thermal groundwater to the Slovak and Austrian parts.

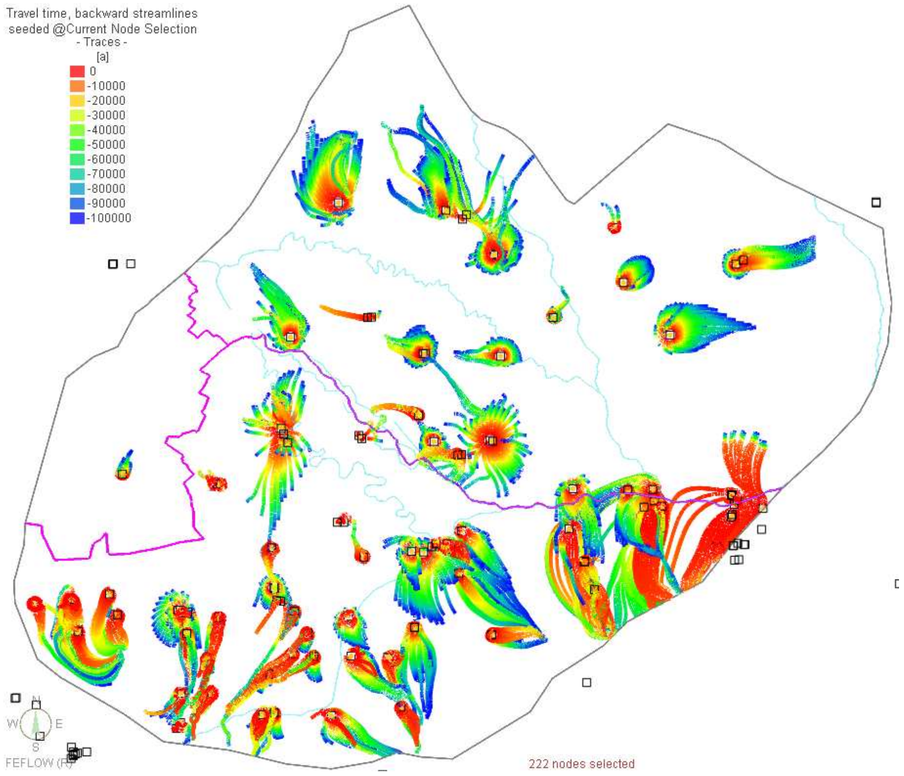


Figure 39: Vertical projection of 3D flow paths towards thermal wells with travel time [years].

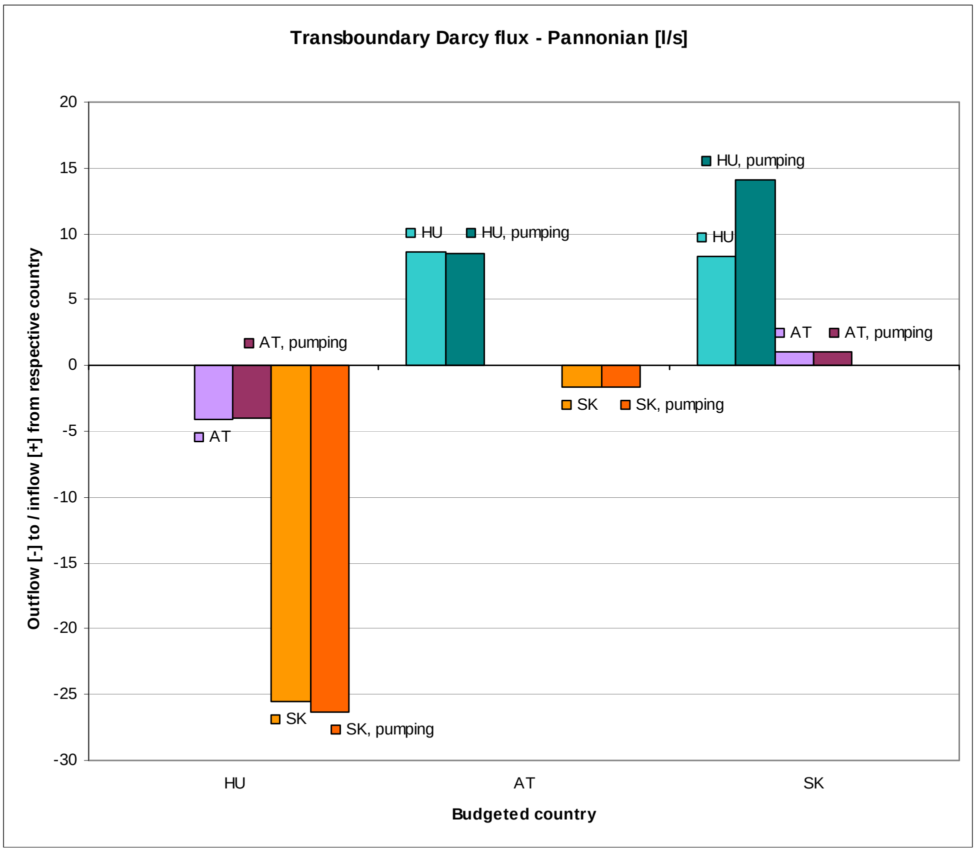


Figure 40: Transboundary flow within Upper Pannonian sediments between Hungary, Slovakia and Austria quantified for two model scenarios

To be able to assess the impacts of future additional geothermal installations on thermal and pressure conditions in the Upper Pannonian intergranular aquifer, in ***scenario models*** (Svasta et al. 2013b) 21 new geothermal doublets were placed randomly within the pilot area away from existing geothermal installations. Pumping and re-injection wells were separated by a distance of 2 km (Fig. 41). Different parameters and boundary conditions are summarized in Svasta et al. (2013 b). The scenario with re-injection was compared with the hypothetical situation, when only abstraction happens at these sites without re-injection (Fig. 42). The differences in the modelled thermal field clearly show a more extended cooling in broader vicinity of the production wells without re-injection comparing to the doublet scenario. The results therefore revealed a significant effectiveness of the thermal energy harvesting with re-injection and also showed that in some areas a potential for additional installations still remains.

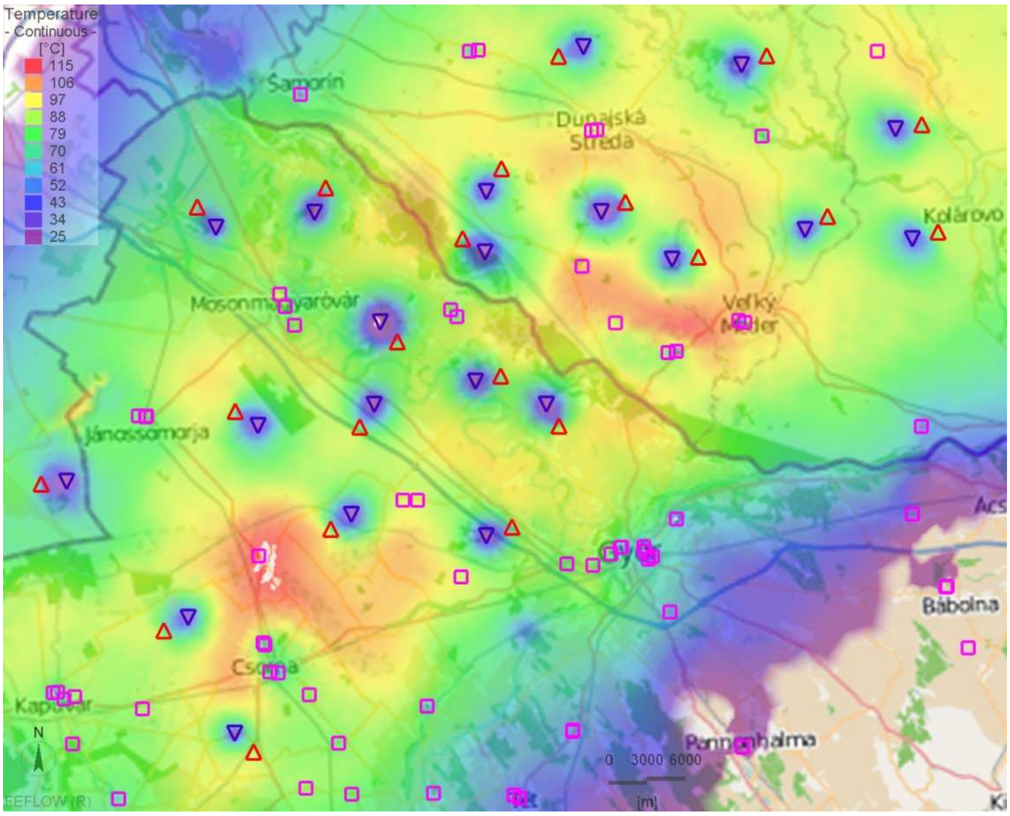


Figure 41: Modification of the thermal field at the top of the Upper Pannonian geothermal reservoir caused by 21 hypothetical geothermal doublets (triangles: red - pumping, blue – re-injection wells). Purple squares are showing the locations of existing utilized geothermal wells.

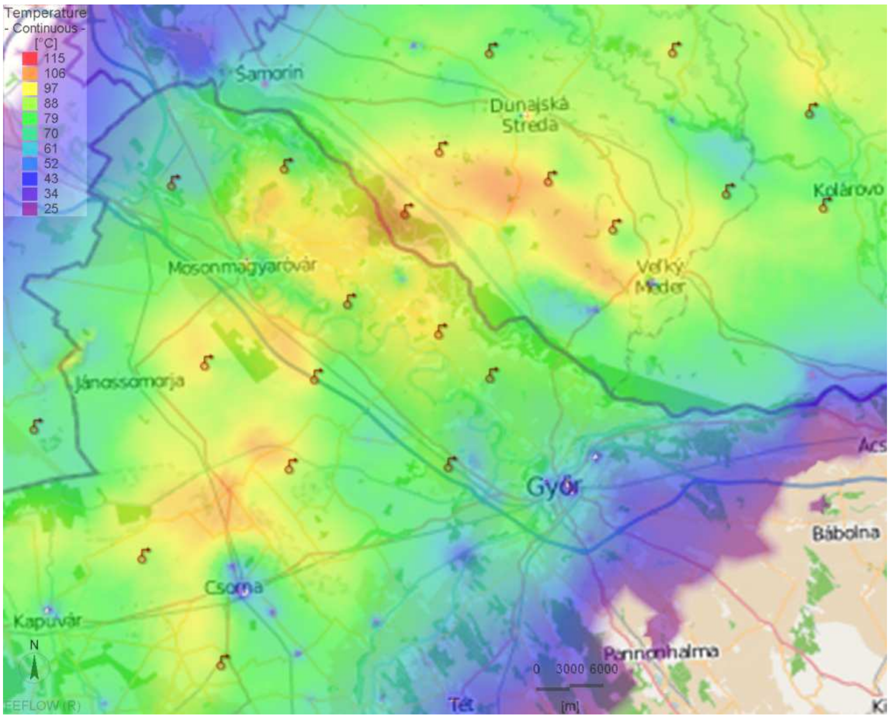


Figure 42: Modification of the thermal field at the top of the Upper Pannonian geothermal reservoir caused by pumping wells (symbols).

The two scenarios differ more significantly when groundwater pressures are compared. As in the doublets scenario the extracted water is returned into the same aquifer and the negative pressure changes are compensated by the increasing groundwater head near the re-injection wells, the dropping hydraulic heads are limited only to the relatively close vicinity of the wells (Fig. 43). In the case of production without re-injection, the pressure drop affects large parts of the aquifer, with magnitudes increasing towards the basin center, also displaying significant transboundary effects (Fig 44). In large areas the groundwater head would drop over more than 100 meters, which would significantly affect technical limits of pumping, not only at new wells, but also at existing ones.

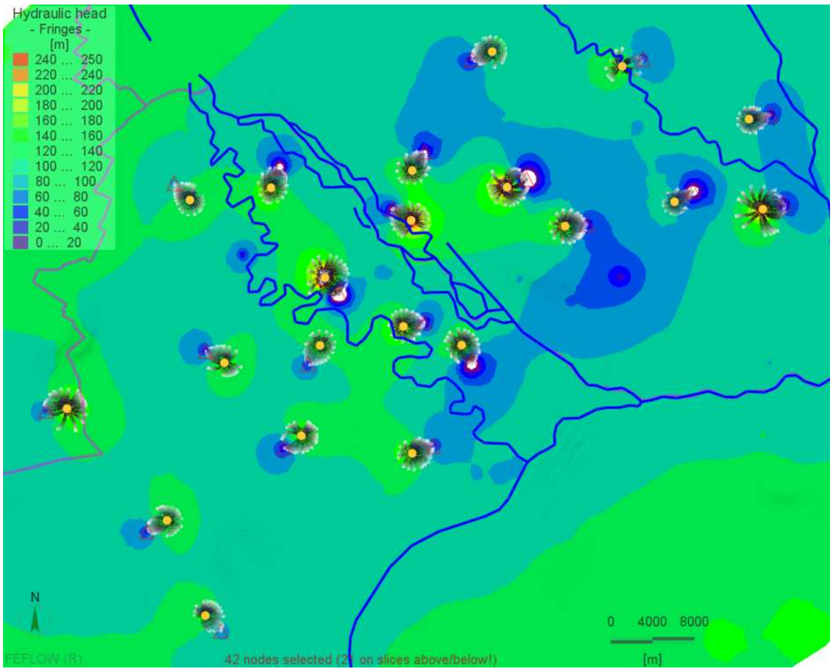


Figure 43: Hydraulic heads field in the Upper Pannonian geothermal aquifer, doublets scenario.

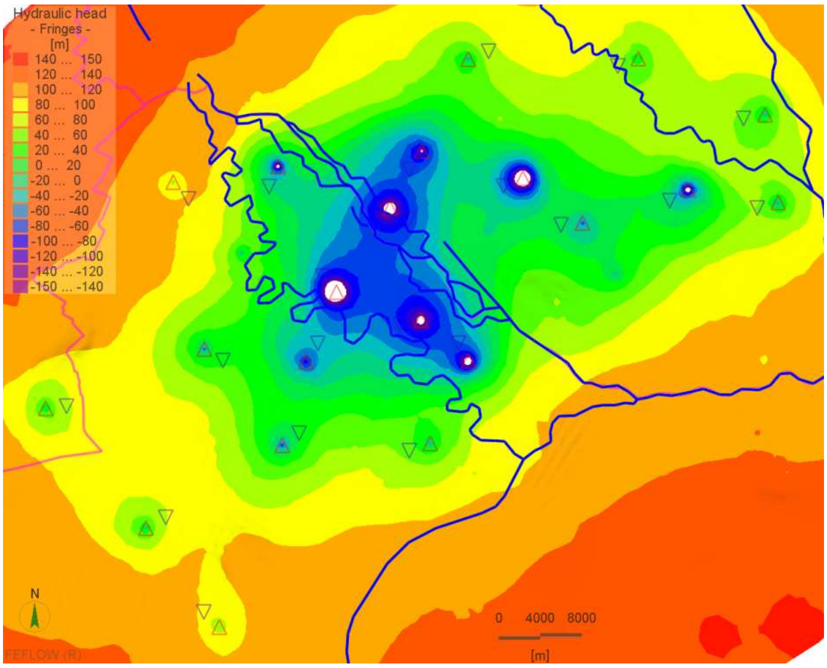


Figure 44: Hydraulic heads field in the Upper Pannonian geothermal aquifer, production/pumping wells scenario.

4.9.3.6. Benchmark evaluation

For benchmarking several evaluation criteria were set up to characterize the geothermal water that is part of the regional flow, which is in the Upper Pannonian aquifer and is of transboundary interest. Geothermal water that is not part of the regional flow (with high content of TDS, Na-Cl chemical type of water), or wells in the marginal zones of the Danube

Basin were not evaluated in this study. The assessment is based on an overview of 31 geothermal wells, 18 on Slovakian side and 13 on Hungarian side. For assessment the reported values were from 2009 on Slovak side, and from 2011 on the Hungarian side. The summaries of the indicator values are shown in Table 19 and Fig 45.

No.	Benchmarking parameter	Hungary			Slovakia		
		Value	Points	Evaluation	Value	Points	Evaluation
1	**Monitoring status**	4.67	50	Medium	4.44	50	Medium
2	**Best available technology**	1.64	50	Medium	0.78	25	Weak
3	**Thermal efficiency**	53%	50	Medium	58%	50	Medium
4	**Utilization efficiency**	61%	100	Very good	52%	100	Very good
5	**Bathing efficiency**	100%	100	Very good	100%	100	Very good
6	**Re-injection rate**	0%	0	Bad	0%	0	Bad
7	**Status of water balance assessment**	0%	0	Bad	25%	25	Weak
8	**Overabstraction**	0.37	75	Good	0.14	75	Good
9	**Quality of discharged waste thermal water**	no information			no information		
10	**Public awareness**	0	0	Bad	0	0	Bad

Table 19: Calculated values of benchmarking indicators for the Upper Pannonian thermal aquifer of the Danube Basin pilot area.

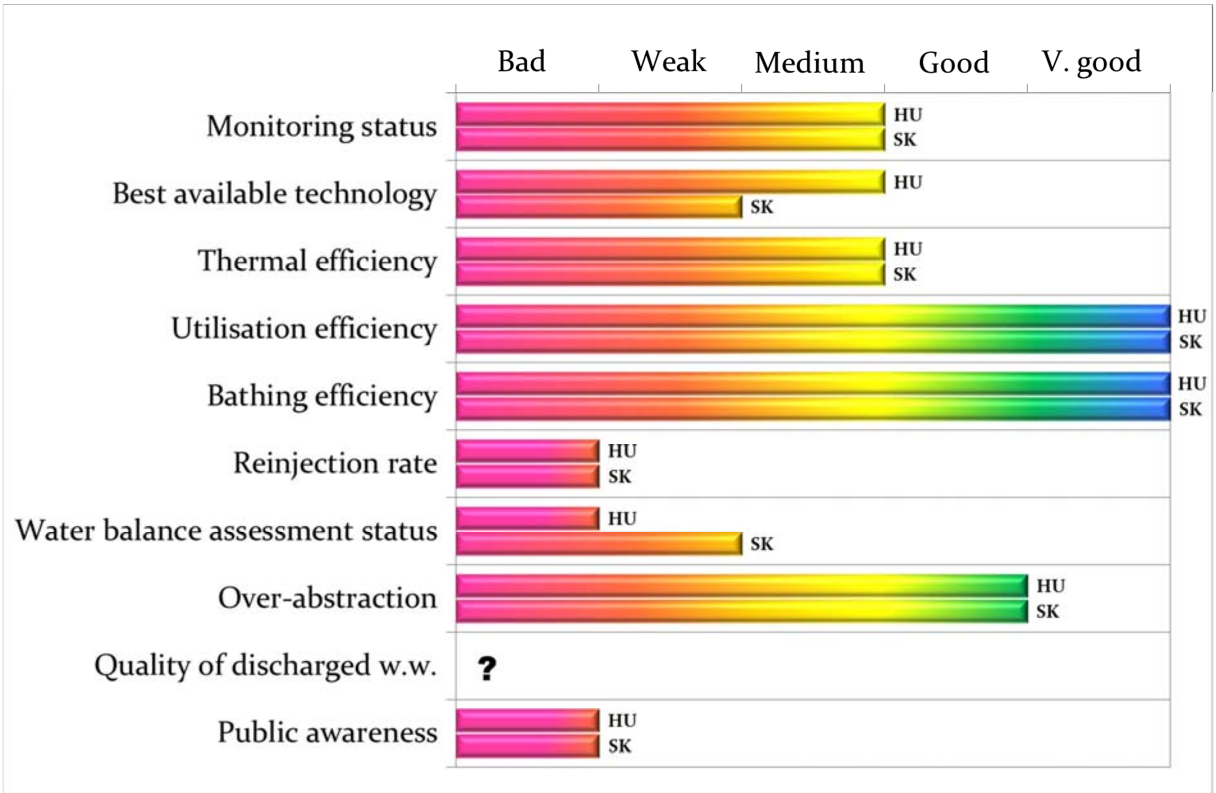


Figure 45: Overview of thermal groundwater management sustainability for the Upper Pannonian thermal aquifer of the Danube Basin pilot area, based on ten benchmarking parameters.

The benchmarking comparison clearly shows that the general management of the investigated geothermal aquifer has to be improved in both countries. The results and the main priorities are:

1) The monitoring indicator for the active wells is medium. This assessment is based on compulsory reported abstraction (yield and temperature) by the thermal water users on an annual basis with monthly reported values in both countries. Independent (passive) monitoring (through monitoring wells constructed exclusively for this purpose) of the geothermal aquifer is not established in any of the countries.
2) The exploitation of thermal water is not always done using the best available technology. Wellheads are sometimes poorly maintained and installation may have gas or water leaks in the system. Pumps with frequency converters are sometimes installed, while cascade usage of thermal water is not applied in Hungary.
3) The main reason for medium thermal efficiency is the lack of use of cascade systems (absence of heat pumps in technology). We anticipate that these problems are mainly due to the lack of appropriate financial support and incentives. Thermal efficiency has to be improved in both countries, while utilization and bathing efficiency do not require special improvement.
4) Bathing efficiency is focused only on the amount of the water that is available for recreation and does not reflect its healing effects as stated in literature (and in Slovakia Act 538/2005).
5) No re-injection wells have been drilled or commissioned. Apart from a test of the re-injection rate in the intergranular environment in well VHP-12-R in Horna Poton (Slovakia), no additional steps have been made in this field. The test, which was carried out in the middle 80’s revealed very complicated conditions for re-injection into such a geological environment, based on the available technology at that time. Nowadays well VHP-12-R is used as production well.
6) Recharge of geothermal water has been evaluated in a number of studies in Slovakia, evaluating the regional conditions for geothermal water circulation and water regime along with calculations of water sources and reserves. They lack periodic updates based on monitored data in the geothermal aquifer. The water balance calculations are not representative in the Hungarian side of the pilot area. The amount of abstraction is defined for most of the wells and is stated in permission for abstraction.
7) The indicators of overabstraction highlight the slight deterioration in the quantity status of the studied geothermal aquifer, although it was not reported explicitely before.
8) There was no information collected on the quality of discharged thermal waste water within this research, and therefore we were not able to evaluate this parameter.
9) Information about the reported yield (thermal water consumption), chemical composition and temperature of thermal water is partly available on WEB sites, but mainly in institutions responsible for data storage. Data on monitoring, BAT, quantity status of the aquifers, quality of waste water or energy efficiency of thermal water exploitation are not available to general public and sometimes they are possibly not even monitored.

4.9.4. Bad Radkersburg - Hodoš Pilot Area

4.9.4.1. Introduction

The Bad Radkersburg – Hodoš pilot area is situated along the national borders of Austria, Slovenia and Hungary. The SW-ern border is defined by the water divided between Drava and Pesnica Rivers. Towards the NE the pilot are passes across Mura River, Goričko hills to the Hungarian national territory. The NW and SE borders are set along geological structures, South Burgenland Swell and Murska Sobota extension block respectively. It covers an area of 2078 km^2, of which 40% belongs to Slovenia, 32% to Austria and 28% to Hungary (Fig. 46). Around 110 000 inhabitants live on this area. The biggest settlement is Szentgotthárd (HU) with more than 8000 inhabitants, followed by Jennersdorf (AT), Gornja Radgona, Lenart and Radenci (SI). Land use is predominantly agricultural, but machine industry and tourism are also important.

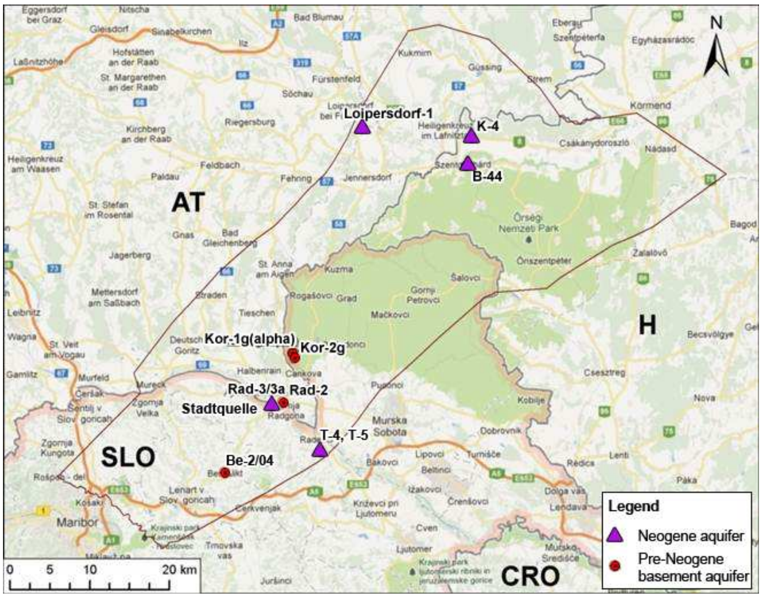


Figure 46: Geographical settings of the Bad Radkersburg-Hodoš pilot area with the location of utilization sites

4.9.4.2. Geology, hydrogeology and geothermal conditions

The pre-Neogene basement composed of Mesozoic carbonate and Paleozoic fissured metamorphic rocks are situated in the narrow and deep Radgona – Vas tectonic half-graben developed along the Rába fault system in SWS – ENE direction. These fractured basement aquifers were in the focus of research, which are arranged inbetween 2 important hydraulic barriers: the South Burgenland Swell on the north and the Murska Sobota High. The thermal water flow direction in this tectonically controlled narrow and elongated aquifer is from SW to NE. The flow velocity is higher in the Raba fault zone, where the hydraulic conductivity is higher. The top of the basement reservoir is at 290 m b.s.l. in the SW (545 m below the ground), and it deepens to over 5000 m b.s.l. (5350 m below the ground) in the NE. The depth of the bottom of the reservoir is not known.

The basement is overlain by Tertiary clastic sediments which form less important aquifers on this area. The Upper Miocene Mura/Újfalu intergranular aquifer is exploited in the Mura-Zala Basin near Szentgotthárd (HU), while the Middle Miocene sandstone aquifers in Bad Radkersburg, Radenci and near Loipersdorf in the Styrian basin.

Temperature at depth of 1000 m varies between 38 and 80°C, with the highest values at Benedikt and the Murska Sobota high. Temperatures at 2500 m are between 94 and 118°C, with higher values towards NE, while 170 to 240°C are calculated at 5000 m. Due to higher thermal conductivity in the basement rocks, the NE part of the area (where the thickness of the Neogene layers is bigger) is characterized by higher temperature in the basement (Fig. 47). Based on measured heat anomalies at Benedikt, local convection cells are supposed to exist at this site.

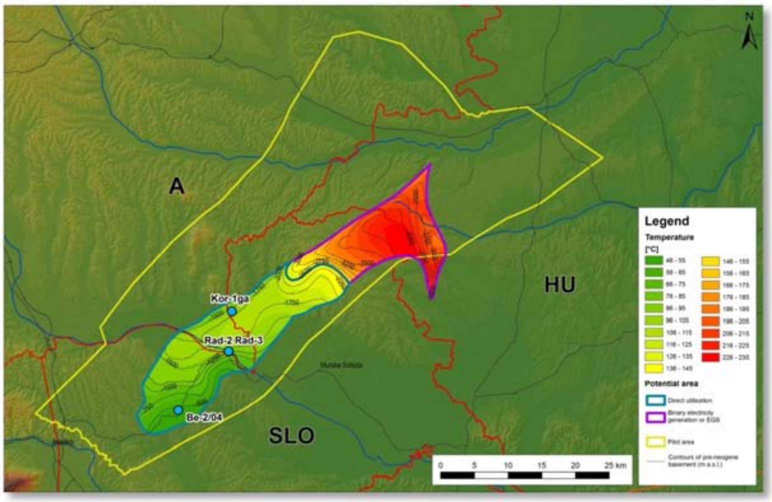


Figure 47: Depth and temperature at the top of the pre-Neogene basement aquifer

The general characteristics and estimated geothermal potential of the pre-Neogene basement hydrogeothermal reservoir in the Bad Radkersburg - Hodoš pilot area are summarized in Table 20. The description and methods of geothermal potential assessment are reviewed at the beginning of in Chapter 4.9.

General attributes	Gross volume (km^3)	1779
	Aquifer volume (km^3)	356
	Average thickness (m)	3100
Estimated reservoir temperature (°C)	Min	45
	Max	243
	Average	148
Estimated transmissivity 10^{-3} (m^2/s)	Min	0.755
	Max	4.70
	Estimated	3.12
Rock parameters	Bulk Heat Capacity (J/(m^{3x}K)	1000
	Bulk Density (kg/m^3)	2850
	Porosity (%)	0.2
Heat In Place (MW$_{th)}$	Balneology (single well)	29945
	Heat Supply (doublet)	374354
	Electricity (doublet)	250455
Inferred Resources (MW$_{th}$)	Balneology (single well)	846
	Heat Supply (doublet)	122253
	Electricity (doublet)	81791
Measured Resources (MW$_{th}$)	Balneology (single well)	n.a.
	Heat Supply (doublet)	n.a.
	Electricity (doublet)	0
Installed Capacities (MW$_{th}$)	Balneology (single well)	10
	Heat Supply (doublet)	0
	Electricity (doublet)	0

Table 20: Characteristics and estimated geothermal potential of the pre-Neogene basement hydrogeothermal reservoir in the Bad Radkersburg - Hodoš pilot area

4.9.4.3. Current utilization of thermal waters

The Upper Miocene Mura/Újfalu intergranular aquifer is exploited for balneological and agricultural use by 2 wells in Szentgotthárd (HU). The water from the Middle Miocene sandstone aquifer in used for balneology, and produced by one well in Loipersdorf, and in Bad Radkersburg (AT) and also in Radenci (SI). Exploitation of thermomineral water from the pre-Neogene basement aquifer occurs in the transboundary zone between Austria and Slovenia. Two wells in Bad Radkersburg (AT) produce it for balneology with an outflow temperature of 78 °C and 22.2 l/s yield, while the well in Benedikt (SI) for district heating (72 °C, 5 l/s). A research borehole in Korovci (SI), less than 5 km away from Bad Radkersburg (AT), tapped the same aquifer in 2008 (80 °C, 20 l/s), but its development is currently at a standstill, however its utilization caused concerns on the Austrian side due to a potential impact on existing wells in Bad Radkesburg (Table 21).

Geothermal site	Aquifer	Thermal water use	Actual production (m^3/year)	Water permit (m^3/year)
Szentgotthard (HU)	Upper Miocene	Bathing and balneology, drinking water	60 000	No information
Radenci (SI)	Middle Miocene	Bathing and balneology	8000	31 500
Loipersdorf (AT)			No information	157 680
Bad Radkersburg (AT)			No information	73 000
Bad Radkersburg (AT)	Pre-Neogene basement		No information	700 000
Benedikt (SI)		District heating	65 000	315 360*
Korovci (SI)		No use	0	158 000*

* This is only an informative amount, as the applications are not yet granted

Table 21: Current users of thermal water

4.9.4.4. Existing and potential future conflicts

Drinking water resources do not compete with thermal water exploitation in this area, as in many other cases, the latter is too mineralized to be used for drinking. The pre-Neogene basement aquifer is currently underdeveloped since only three wells produce thermal water (Table 21). The produced water temperature is about 80°C, which is applicable for direct heat use and balneology but not for geothermal electricity production.

There is a contest between an existing thermal water user of the pre-Neogene basement aquifer in Bad Radkersburg (AT) and a developer in Korovci (SI). Waste thermal water of the spa is treated at a sewage purifying plant in Bad Radkersburg (AT) before it is released to the Mura River. The potential Slovenian user at Korovci plans to reinject part of the water which will be used for heating, but the other part used for balneology will have to be treated to prevent pollution of the transboundary stream Kučnica. The monitoring data on Austrian wells are not available, and therefore the assessment of impact of Korovci is uncertain. The Mura Commission has discussed the Bad Radkersburg-Korovci conflict, but very poor data exchange exists among the two countries.

The main utilization in the area takes place in Benedikt (SI). There is no re-injection, the water is cooled but chemically untreated before it flows to Drvanja stream.

Zones of thermal water concessions are proposed for Benedikt and Korovci sites (SI), but they have not been granted yet. No protection zones are outlined in Austria. The identified hydrogeothermal aquifer is currently used moderately, utilizations for balneological and energy purposes don't show interferences or regional scale changes in the quality or quantity of the used thermal waters yet. However, the Mesozoic and Palaeozoic fractured aquifer in pre-Neogene basement represents a transnational hydrodynamic system, so any national interventions have to be handled considering its possible transboundary effects.

4.9.4.5. Towards a sustainable management

Elaborated ***steady state model*** (Fuks et al. 2013a) is the first numerical representation of geothermal conditions in the pilot area which is the basis for future efficient management and sustainable utilisation. Due to the lack of data and scarce information, it is based on many assumptions. It indicated the highest temperatures in the NE part of the pilot area (Fig. 47) and possibility of convective heat transfer in the Benedikt area. Due to geological settings and the model results it is possible that local convection cells also developed elsewhere.

The ***scenario models*** (Fuks et al. 2013b) addressed questions on the impacts of thermal water production in Korovci on the Bad Radkersburg wells. Two types of scenarios including existing exploitation in Benedikt and Bad Radkersburg were tested; thermal water production in Korovci with and without re-injection. All production scenarios were simulated for 50-years period.

According to these scenarios, hydraulic influence (even supposing different rates of hydraulic conductivity, aquifer thickness and specific storage values in the different scenarios) of a production well in Korovci has a negligible effect on the Bad Radkersburg site. Abstraction (20 l/s) without re-injection causes a 14-15 m computed drawdown at the production site, but does not have a transboundary influence (Fig. 48). The results pointed out that the interference between Korovci (SI) and Bad Radkersburg (AT) sites can be expected only if there are preferential flow paths along well permeable faults (shown by scenarios where hydraulic conductivity in the Raba fault zone was set to a higher value) (Fig. 49). In this scenario the computed drawdown is lower than at the production well (11m), but the effects extend further away from the production borehole Kor-1gα and reach the Bad Radkensburg area. Consequently, the planned exploitation of a geothermal doublet in Korovci can be realized, but joint transboundary monitoring has to be managed in both countries to identify and mitigate potential undesirable effects of this enhanced exploitation.

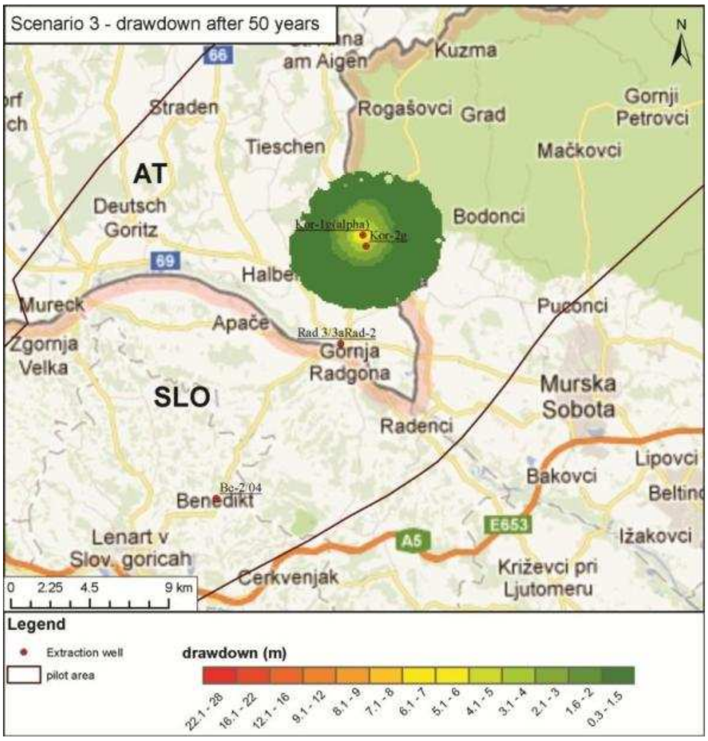


Figure 48: Computed drawdown after 50 years of production in Korovci (without re-injection).

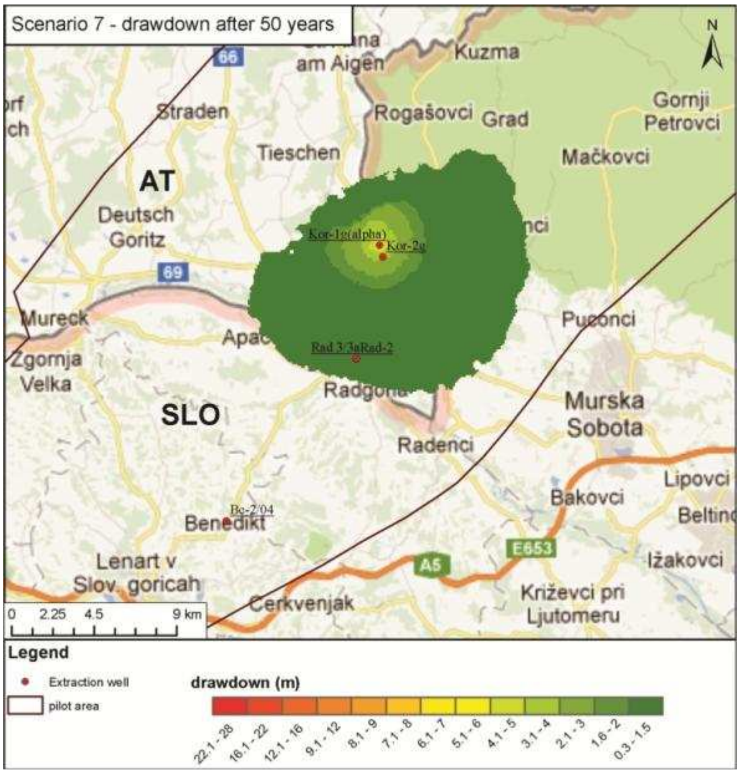


Figure 49: Computed drawdown after 50 years of production in Korovci (without re-injection) assuming higher hydraulic conductivity. The drawdown in the production borehole Kor-1gα is decreases, however the depression reaches Bad Radkersburg.

Model results also showed that when re-injection at Korovci is assumed (Kor-2g) in a distance of 700 m from the production well (Kor-1gα), the cooling effects reach the production borehole in roughly 500 years. However, the temperature decrease after 1000 years of simulation is still very low and does not exceed 1 °C (the temperature of the reinjected water was set at 35 °C) (Fig. 50).

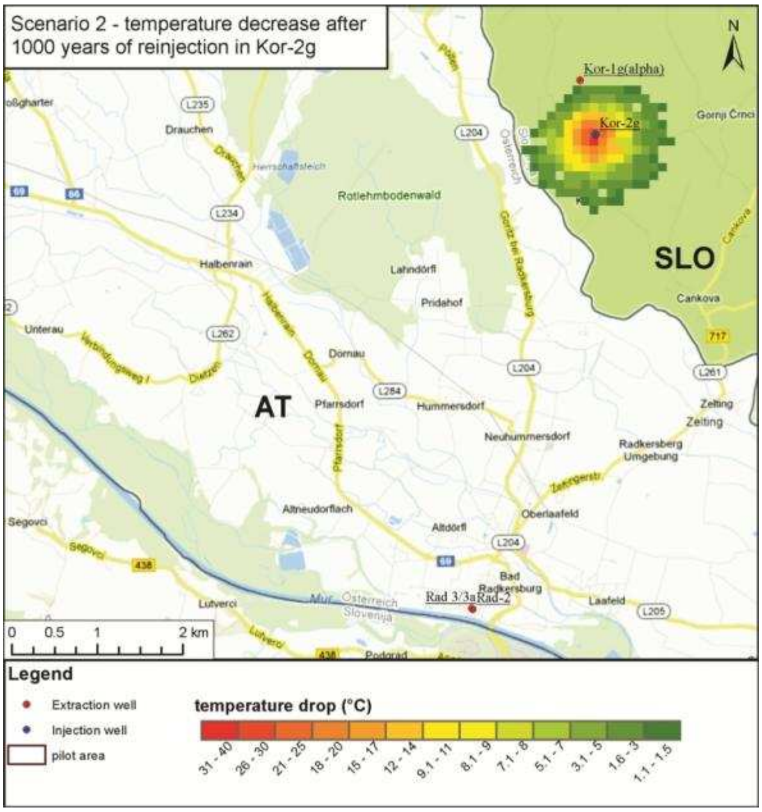


Figure 50: Modelled temperature decrease and extend of the thermal plume after 1000 years of re-injection in Korovci.

4.9.4.6. Benchmark evaluation

The assessment of the management sustainability is based on a review of one active and one inactive geothermal well on the Slovenian side and on two active wells on the Austrian side. Summaries of the indicator values are shown in Table 22 and Fig. 51. No wells exploit this aquifer in Hungary.

No.	Benchmarking parameter	Slovenia			Austria		
		Value	Points	Evaluation	Value	Points	Evaluation
1	**Monitoring status**	0.0	0	Bad	7.0	75	Good
2	**Best available technology**	2.0	50	Medium	1.0	75	Good
3	**Thermal efficiency**	45%	50	Medium	*	*	*
4	**Utilization efficiency**	21%	50	Medium	>30%	100	Very good
5	**Bathing efficiency**	Not used for bathing			100%	100	Very good
6	**Re-injection rate**	0%	0	Bad	0%	0	Bad
7	**Status of water balance assessment**	0%	0	Bad	75-95%	75	Good
8	**Overabstraction**	0.0	100	Very good	0.0	100	Very good
9	**Quality of discharged waste thermal water**	no information			>95	100	Very good
10	**Public awareness**	1.0	0	Bad	4.0	50	Medium

*In Austria no temperature of the effluent water is available, therefor thermal efficiency could not be calculated

Table 22: Calculated values of benchmarking indicators for the pre-Neogene carbonate and metamorphic geothermal aquifer of the Bad Radkersburg-Hodoš pilot area in Slovenia and Austria.

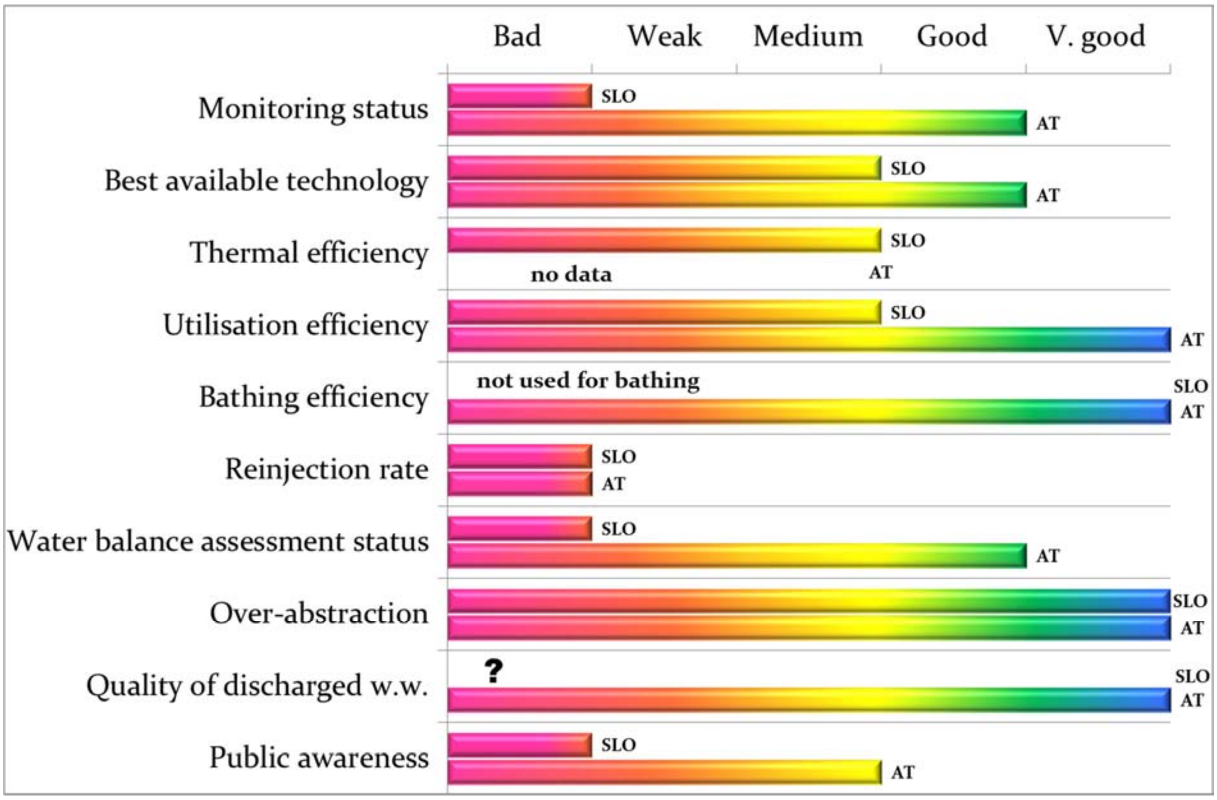


Figure 51: Overview of thermal groundwater management sustainability for the pre-Neogene geothermal aquifer of the Bad Radkersburg-Hodoš pilot area in Slovenia and Austria, based on ten benchmarking parameters.

The benchmarking comparison shows that management of the geothermal aquifer has to be improved in both countries, especially on the Slovenian side. The main priorities are the following:

1) Monitoring of existing users is not operational in Slovenia, while data are confidential in Austria, however reported as good. No bilateral monitoring or reporting procedures have been implemented. In bilateral SI-AT Mura commission on water management this issue has been raised for several years, but no conclusions have been done, but a common surveillance of the pumping test was performed in Korovci in 2009.
2) Thermal efficiency is poor in Slovenia due to high waste water temperature and lack of end users in Benedikt. In Austria, the water is used only for bathing and balneology despite having a temperature of almost 80°C. In Austria, no temperature of the effluent water was available and therefore thermal efficiency could not be calculated.
3) Very good utilization efficiency in Austria indicates that the capacity of the wells is well used, while in Slovenia this parameter is reduced due to one inactive well, which represents half of all the wells included in investigation. The included Slovenian geothermal wells do not have granted concession permits yet, and therefore we used the assumed amounts which may be demanded for.
4) The water balance assessment and evaluation of the groundwater recharge is not applied in Slovenia, while in Austria the critical level points are defined and used in the annual evaluation of the exploitation and management of the resource.
5) The quality of the discharged thermal water is regularly controlled as demanded by legislation in general in Slovenia, however data were not collected within this research and therefore this indicator was not evaluated. In Austria, the used water is treated in a water treatment plant and therefore regularly controlled.
6) Information about exploitation of the resources is currently only partly available in professional papers. Data on monitoring, BAT, quality and quantity status of the aquifers are available (but not easily accessible) to the general public in Austria, while no data on these indicators are published in Slovenia.

4.9.5. Vienna Basin Pilot Area

4.9.5.1. Introduction

Located at the NE-ern part of the TRANSENEGY region the Vienna Basin pilot area is shared by Austria and Slovakia offering home for more than 2 million habitants (Fig. 52). It is a region with different socio-economic situations. On the one hand, there is the still growing urban agglomeration zone between the capital cities of Vienna and Bratislava – a region of growing economic importance, the so called “Centrope Region”. On the other hand the vast majority of the region is dominated by rural zones showing comprising villages and small cities.

Irrespective of the different socio-economic framework the Vienna Basin has an increasing demand for energy: housing and industrial facilities at the urban agglomeration zones as well as agricultural utilizations at the rural zones. The increasing environmental concerns as well as the increasing price of fossil energy puts renewable, low-emission as well as local energy sources – such like geothermal energy in focus of regional development plans. Despite the favorable conditions, utilization of hydrogeothermal resources is absent in the Vienna basin, so the aim of the work related to this pilot area were, among others, to draw attention to these possibilities.

At the same time the N-ern part of the Vienna basin is one of the most important hydrocarbon exploitation areas in Central Europe, therefore an ideal site to study links and potential conflicts between the multi-purpose utilization of the same reservoirs.

The Vienna Basin pilot area covers the central and NE-ern parts of the Vienna Basin, but does not comprise its S-ern regions. Crystalline outcrops, namely the Leithagebirge in Austria and the Little Carpathian Mountains in Slovakia define the E-ern border of the model, the W-ern border is defined by the boundary between the Flysch Zone and the Upper Austroalpine Bajuvaric nappe system. The S-ern boundary is marked by the Leopoldsdorf fault system. The maximum extension of the model area is about 150x75 km laterally.

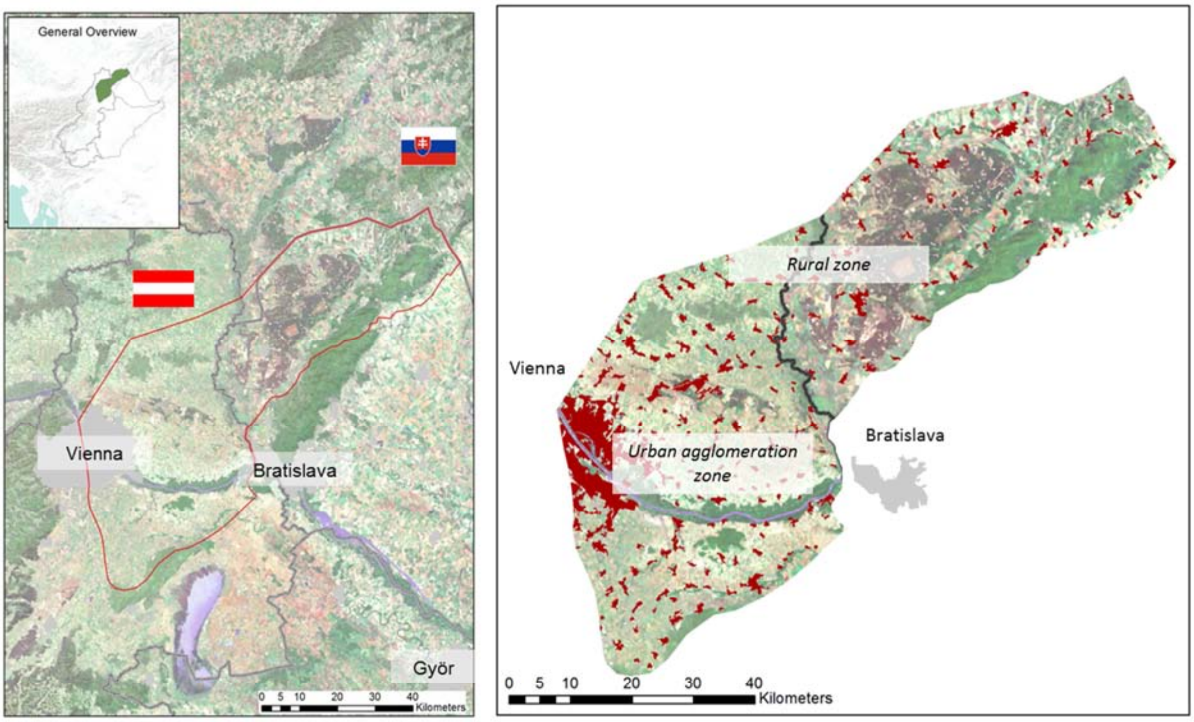


Figure 52: Geographical overview on the Vienna Basin pilot area

4.9.5.2. Geology, hydrogeology and geothermal conditions

The Vienna Basin has an extremely complex geological buildup, especially in its pre-Tertiray basement, where different geological units are overthrusted on each other. These units are the following:

i. Crystalline basement; including Bohemian Massive, Tatric and Lower Alpine Units (aquiclude)

ii. Flysch units (aquiclude)

iii. Mesozoic Carbonates: Mesozoic cover of the Central Alpine and Tatric units (aquifer)

iv. Calcareous Alpine (Upper Alpine) Units (aquifer). This can be further subdivided on the basis of 3D interpolation of the material properties into the following nappe systems: Bajuvaric-, Tirolic-, Juvavic- nappe systems as well as Gosau Units and the Greywacke Zone.

The pre-Tertiary basement can be as deep as 12 km, which is overlain by Neogene sediments (both aquicludes and aquitards).

Fig. 53 summarizes the hydrogeological conditions of the Vienna Basin pilot area. The major part of the pilot area is dominated by trapped fossil water, which has no connection to the surface and therefore shows high contents of dissolved materials. In contrast there are several zones of actively circulating thermal water systems (so called hydrodynamic systems), which are connected to the surface and get recharged by meteoric waters (grey colored areas), however most of them are out of the delineated pilot area of TRANSENERGY (The reason for this is that the other pilot areas were focusing on hydrogeothermal systems with active groundwater flow). These systems produce locally confined temperature anomalies, where thermal water is discharging to the surface. Most of these hydrodynamic systems show low contents of minerals and are therefore suited for balneological purposes. Medical as well as recreational treatment of thermal water has a long tradition in the Vienna Basin, especially in its southern part (which was not part of this pilot area and studies).

It is assumed, that the Central Alpine & Tatric Carbonates hydrogeothermal structure is representing a trans-boundary thermal water system having recharged from the eastward (Slovakia). Evidence is given in deep wells and hydrocarbon drillings showing clear aberrant geothermal conditions (see also cross section at Fig. 53).

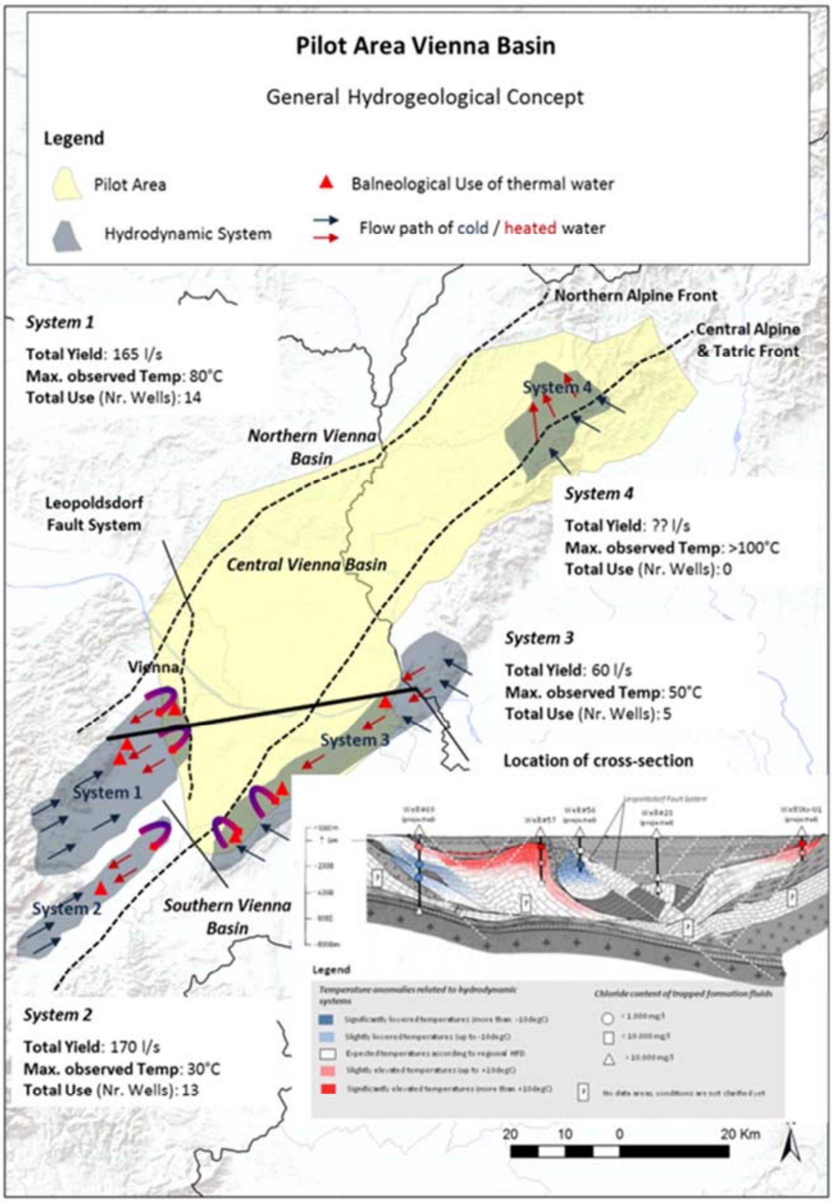


Figure 53: Hydrogeological overview on the Vienna Basin pilot area.

In total 6 different hydrogeothermal structures (plays) have been identified, of which 5 are located trans- or near-boundary (Fig. 54, Table 23). The general characteristics and estimated geothermal potential of these structures are summarized in Table 24A-E. The description and methods of geothermal potential assessment are described at the beginning of Chapter 4.9.

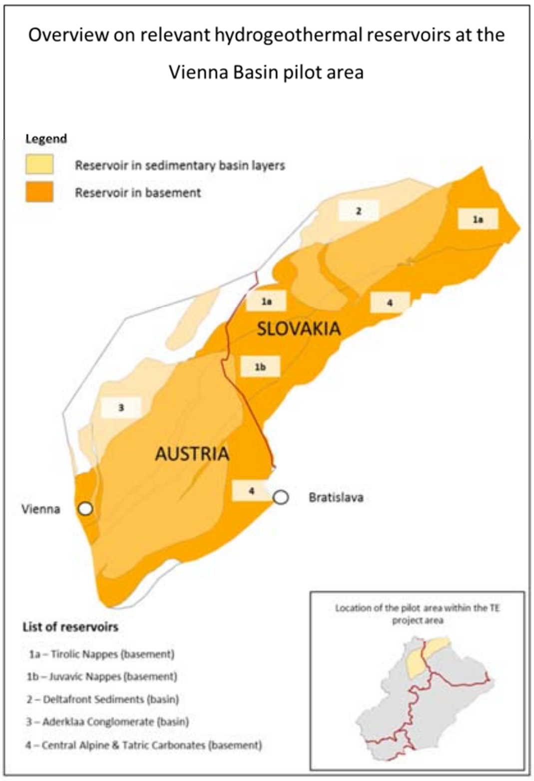


Figure 54: Overview on the identified hydrogeothermal reservoirs at the Vienna Basin pilot area.

No.	Name	Description	Average depth interval (top, base: m.b.s)	Existing utilization
1a	Tirolic Nappes	Fractured reservoir at the basement of the Vienna Basin. Connate waters showing locally overpressured conditions at high salinities.	645 - 3394	No
1b	Iuvavic Nappes	Fractured reservoir at the basement of the Vienna Basin. Connate waters showing locally overpressured conditions at high salinities.	1730 - 3260	No
2	Deltafront Sediments	Porous reservoir at sedimentary fillings. Connate waters at hydrostatic pressure. At marginal basin areas (SK) recharge possible.	1021 - 1187	No
3	Aderklaa Conglomerate	Double porosity reservoir at sedimentary fillings. Locally depressured conditions due intense hydrocarbon exploitation in the past. This reservoir is locally used for injection of formation water by the hydrocarbon industry	1972 - 2132	Yes (hydrocarbon industry)
4	Central Alpine & Tatric Carbonates	Fractured reservoirs at basement of the Vienna Basin. Active recharge as well as trans-boundary hydrodynamic circulation systems existing.	2145 - 4489	Yes (balneology)

Table 23: Summary of selected characteristics of the identified hydrogeothermal structures

General attributes	Gross volume (km^3)	4495
	Aquifer volume (km^3)	265
	Average thickness (m)	2239
Estimated reservoir temperature (°C)	Min	8
	Max	239
	Average	118
Estimated transmissivity 10^{-3} (m^2/s)	Min	0.00
	Max	3.426
	Estimated	1.159
Rock parameters	Bulk Heat Capacity (J/(m^{3x}K)	1126
	Bulk Density (kg/m^3)	2681
	Porosity (%)	5.9
Heat In Place (MW$_{th)}$	Balneology (single well)	52998
	Heat Supply (doublet)	858027
	Electricity (doublet)	587344
Inferred Resources (MW$_{th}$)	Balneology (single well)	459
	Heat Supply (doublet)	66624
	Electricity (doublet)	46242
Measured Resources (MW$_{th}$)	Balneology (single well)	36
	Heat Supply (doublet)	1007
	Electricity (doublet)	349
Installed Capacities (MW$_{th}$)	Balneology (single well)	0
	Heat Supply (doublet)	0
	Electricity (doublet)	0

Table 24A: Characteristics and estimated geothermal potential of the Tirolic Nappes hydrogeothermal reservoir in the Vienna Basin pilot area

General attributes	Gross volume (km^3)	900
	Aquifer volume (km^3)	31
	Average thickness (m)	1937
Estimated reservoir temperature (°C)	Min	58
	Max	193
	Average	129
Estimated transmissivity 10^{-3} (m^2/s)	Min	0.003
	Max	2.416
	Estimated	1.01
Rock parameters	Bulk Heat Capacity (J/(m^{3x}K)	1028
	Bulk Density (kg/m^3)	2735
	Porosity (%)	3.4
Heat In Place (MW$_{th)}$	Balneology (single well)	6533
	Heat Supply (doublet)	194102
	Electricity (doublet)	122013
Inferred Resources (MW$_{th}$)	Balneology (single well)	72
	Heat Supply (doublet)	15567
	Electricity (doublet)	10945
Measured Resources (MW$_{th}$)	Balneology (single well)	10
	Heat Supply (doublet)	461
	Electricity (doublet)	102
Installed Capacities (MW$_{th}$)	Balneology (single well)	0
	Heat Supply (doublet)	0
	Electricity (doublet)	0

Table 24B: Characteristics and estimated geothermal potential of the Juvaic Nappes hydrogeothermal reservoir in the Vienna Basin pilot area

General attributes	Gross volume (km^3)	124
	Aquifer volume (km^3)	21
	Average thickness (m)	182
Estimated reservoir temperature (°C)	Min	10
	Max	155
	Average	58
Estimated transmissivity 10^{-3} (m^2/s)	Min	0.02
	Max	1.305
	Estimated	0.356
Rock parameters	Bulk Heat Capacity (J/(m^{3x}K)	1154
	Bulk Density (kg/m^3)	2370
	Porosity (%)	17.2
Heat In Place (MW$_{th)}$	Balneology (single well)	1153
	Heat Supply (doublet)	7422
	Electricity (doublet)	1289
Inferred Resources (MW$_{th}$)	Balneology (single well)	199
	Heat Supply (doublet)	4455
	Electricity (doublet)	835
Measured Resources (MW$_{th}$)	Balneology (single well)	1
	Heat Supply (doublet)	28
	Electricity (doublet)	0
Installed Capacities (MW$_{th}$)	Balneology (single well)	0
	Heat Supply (doublet)	0
	Electricity (doublet)	0

Table 24C: Characteristics and estimated geothermal potential of the Deltafront sediments hydrogeothermal reservoir in the Vienna Basin pilot area

General attributes	Gross volume (km^3)	249
	Aquifer volume (km^3)	37
	Average thickness (m)	199
Estimated reservoir temperature (°C)	Min	26
	Max	114
	Average	80
Estimated transmissivity 10^{-3} (m^2/s)	Min	0.002
	Max	1.219
	Estimated	0.325
Rock parameters	Bulk Heat Capacity (J/(m^{3x}K)	1380
	Bulk Density (kg/m^3)	2273
	Porosity (%)	15
Heat In Place (MW$_{th)}$	Balneology (single well)	5449
	Heat Supply (doublet)	28794
	Electricity 8doublet)	454
Inferred Resources (MW$_{th}$)	Balneology (single well)	636
	Heat Supply (doublet)	14285
	Electricity (doublet)	229
Measured Resources (MW$_{th}$)	Balneology (single well)	7
	Heat Supply (doublet)	114
	Electricity (doublet)	0
Installed Capacities (MW$_{th}$)	Balneology (single well)	0
	Heat Supply (doublet)	0
	Electricity (doublet)	0

Table 24D: Characteristics and estimated geothermal potential of the Aderklaa Conglomerate hydrogeothermal reservoir in the Vienna Basin pilot area

General attributes	Gross volume (km^3)	3220
	Aquifer volume (km^3)	103
	Average thickness (m)	1930
Estimated reservoir temperature (°C)	Min	9
	Max	282
	Average	134
Estimated transmissivity 10^{-3} (m^2/s)	Min	0.274
	Max	3.328
	Estimated	1.006
Rock parameters	Bulk Heat Capacity (J/(m^{3x}K)	897
	Bulk Density (kg/m^3)	2860
	Porosity (%)	3.2
Heat In Place (MW$_{th)}$	Balneology (single well)	12628
	Heat Supply (doublet)	557686
	Electricity (doublet)	380336
Inferred Resources (MW$_{th}$)	Balneology (single well)	264
	Heat Supply (doublet)	60547
	Electricity (doublet)	41756
Measured Resources (MW$_{th}$)	Balneology (single well)	5.4
	Heat Supply (doublet)	20
	Electricity (doublet)	0
Installed Capacities (MW$_{th}$)	Balneology (single well)	4.9
	Heat Supply (doublet)	0
	Electricity (doublet)	0

Table 24E: Characteristics and estimated geothermal potential of the Central Alpine and Tatric carbonates hydrogeothermal reservoir in the Vienna Basin pilot area

4.9.5.3. Current utilizations of thermal waters

Currently the use of natural thermal water does not play an important role in the Vienna Basin except for traditional balneological use in its S-ern part (Baden, Bad Voeslau and Bad Fischau), which is not part of the studied pilot area.

On the TRANSENERGY pilot area hydrogeothermal utilization is limited to the Central Alpine & Tatric Carbonate reservoirs [hydrogeothermal structure nr. 4] at the E-ern margin with moderate thermal water temperatures and yields. At three locations a total yield of around 60 l/s is partly used for balneological purposes in Austria (Table 25).

Location	Water extract	Total Yield	Outflow temperature	Use
Leithaprodersdorf	1 trapped spring	<5 l/s	~20°C	Not Used
Mannersdorf	1 trapped spring	<5 l/s	~25°C	Balneological Use
Bad Deutsch Altenburg	3 wells	~50 l/s	20°C – 27°C	Balneological Use

Table 25: Summary of existing hydrogeothermal utilization in the Vienna Basin pilot area.

Energy use of the existing thermal water in the central and NE-ern part of the Vienna Basin has not been implemented yet, although there are great resources estimated. The first large scale geothermal heat-supply facility, which should have been in Vienna (project Wien – Aspern with a planned installed capacity of 40 MW$_{th}$ and temperature level around 140 °C) unfortunately failed in 2012 due to an unsuccessful drilling. The planned wells should have reached final depth of 3500 to 5000 meters and produce water from a dolomite reservoir belonging to the Eastern Alps with a production/re-injection rate of 100 l/s.

4.9.5.4. Existing and potential future conflicts

As hydrogeothermal utilization practically does not exist at the moment, no conflicts are known.

The subsurface of the Vienna Basin has been extensively used for the production of hydrocarbons since decades. Most of the above listed structures have been exploited for hydrocarbons in the past. Above all the so called Aderklaa Conglomerate structure [3] is locally showing depressurized conditions due to hydrocarbon exploitation and is furthermore used for re-injection of waste formation waters by the hydrocarbon industry.

However, as the production of crude oil continuously decreases since the past 40 years it offers future possibilities for hydrogeothermal utilization in the Vienna Basin by:

- Using the knowledge and data gained by the hydrocarbon industry for the assessment of geothermal reservoirs
- Using abandoned or non-profitable oil wells for a hydrogeothermal re-use
- Combined use of hydrocarbon infrastructure for hydrocarbon and heat recovery (e.g. implementation of heat exchangers in pooling stations)

In contrast increasing future geothermal use may also offer challenges and risks of conflicts due to:

- Competitive subsurface use between hydrocarbon production and geothermal heat recovery
- Over-exploitation due to intense use especially at near border regions due to a lacking trans-boundary management of natural thermal water.

Concerning the transboundary exploitation of hydrocarbons in the pilot area a bilateral Commission was founded in the late 1960s between Czechoslovakia (now Slovakia and Czech Republic) and Austria aiming bilateral reporting of HC production. Although exclusively coordinating hydrocarbon exploitation, this commission and its procedures may have an impact on a future monitoring and reporting for hydrogeothermal use in the pilot area, because most of the identified geothermal structures coincide with regions of hydrocarbon exploitation. Furthermore the existing reporting procedures are adapted for deep buried reservoirs, therefore also suitable for the identified hydrogeothermal structures.

In the Vienna Basin pilot area neither bilateral hydrogeothermal monitoring, nor reporting procedures have been implemented yet, due to the fact of currently low number of utilizations, although the cross-border flow has been proved in this case, too.

4.9.5.5. Towards a sustainable management

The ***steady state model*** (Goetzl et al. 2013a) was focusing on the regional scale thermal modelling of the entire pilot area to deliver data for the estimation of hydrogeothermal resources (Table 24A-E). In total 775 DST temperature values from 235 wells were used for validation of the modelled subsurface temperatures (Fig. 55). This evaluation showed that the applied simple 3D conductive thermal model was able to fit the observed subsurface temperatures in satisfying way although also demonstarting that thermal convection does not play an important role in this area. It also proved that high temperatures (above 120-140 °C) are present at several parts of the pilot area.

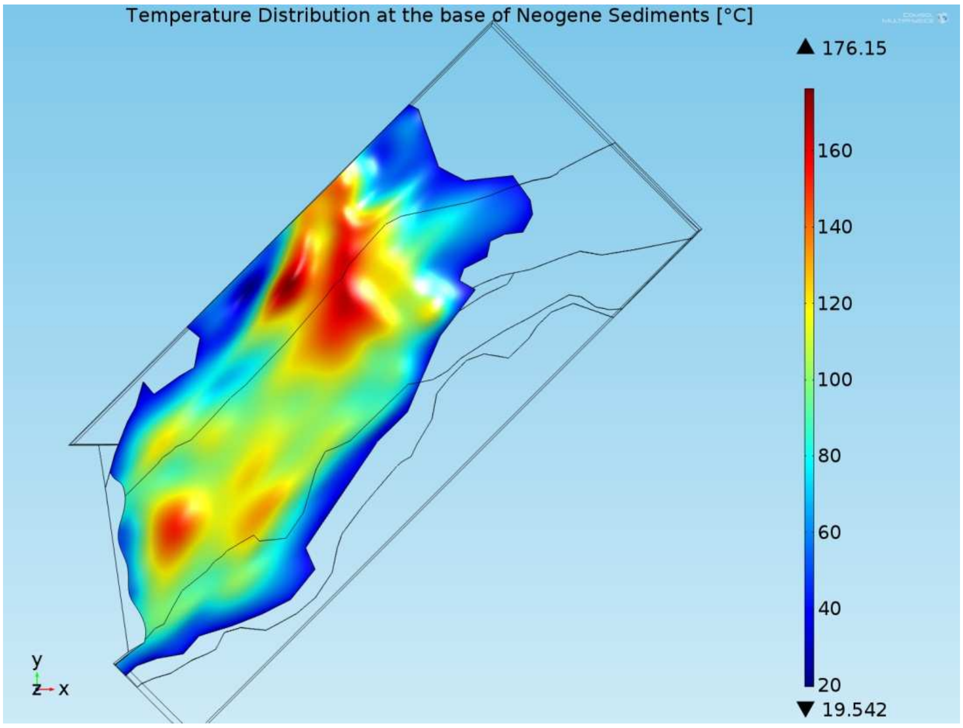


Figure 55: Temperature distribution at the base of the Neogene sediments [°C].

Scenario modeling (Gotzl et al. 2013b) was focusing on the detailed study of a Triassic (Wetterstein) Dolomite geothermal reservoir within the Juvaic Nappe (1b) hydrogeothermal structure, which has been figured out to be the most promising transboundary geothermal reservoir within the pilot area (Fig. 56). Due to the high salinity of the fluids of this aquifer, the trapped thermal water is not suitable for balneological purposes. Hence, the only possible utilisation can be a pure energy usage, realized by a doublet installation with complete re-injection of the thermally deployed brine. As this Hydrogeothermal Play has not been used for geothermal use yet, the scenario modelling was focusing on its possible future near-boundary utilization studying the effects of various doublet arrangements, also considering the influence of highly conductive (fault) zones and overlying porous sediments.

The area of interest has a lateral extension of about 15 km x 3 km, striking approximately along a SE-NW direction (Fig. 56). The river March and the Austro-Slovakian border crosses the body right in the middle in N-S direction. On the Austrian side of the reservoir, three abandoned hydrocarbon wells (SCH-T1, SCH-1 and BG-4) could possibly be used (re-entry) for geothermal usage and supply the Gänserndorf / Strasshof area (approx. 20.000 inhabitants) with energy (heat and electric power). On the Slovakian side we considered the Zohor – Láb – Záhorská Ves triangle containing about 10.000 inhabitants as a plausible area for geothermal heat demand.

The modelling investigated different arrangements of the doublets assuming a minimum yield of 100 l/s, a production temperature of at least 100 to 120 ° C in the fractured dolomite reservoir at a depth of 3-4 km. At each modelling run of two doublets - one on the Austrian and one on the Slovakian side of the reservoir - were simulated taking into consideration the influence of a fault zone and overlying porous sediments (Table 26).

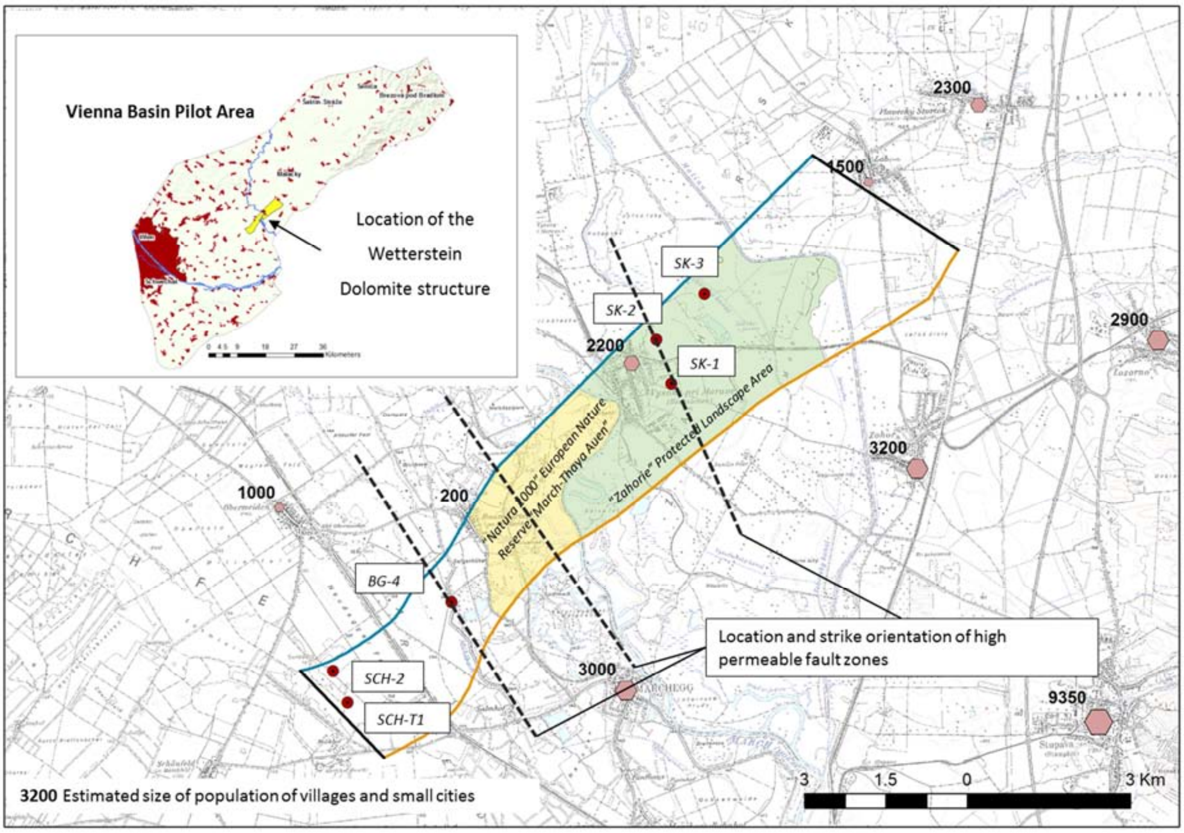


Figure 56: Outline of the scenario model „Schoenfeld-Láb“. The red dots show possible well locations,

Scenario	Involved Doublets	Description
1	Austria: Sch2 (P) – BG4 (I) Slovakia: SK1 (P) – SK2 (I)	**High influence of fault zone**: At the Austrian doublet the injection well is located at the fault zone, which may lead to a fast propagation of the cold water plume. In contrast it also may reduce the technical effort of the water injection. At the Slovakian side both wells are influenced by a high permeable fault zone, which may strongly enhance both hydraulic and thermal short-cuts.
2	Austria: Sch2 (P) – Sch (I) Slovakia: SK2 (P) – SK3 (I)	**Moderate influence of fault zone**: Both wells of the Austrian doublet are located at tectonically undisturbed positions of the reservoir, which may on one hand lead to enhanced hydraulic resistivity at the wells but on the other hand inhibits thermal short-cuts. At the Slovakian doublet the production well is located within a high permeable fault zone. As the injection well is located at an assumed tectonically undisturbed position of the reservoir, the thermal breakthrough may be inhibited on the one hand, but the effort in order to inject the used water may be raised on the other hand.
3	Austria: SchT1 (P) – Sch 2(I) Slovakia: SK2 (P) – SK3 (I)	**Influence of high permeable porous layer**: Existence of a highly conductive layer at the lowermost 50 meters of the Neogene sedimentary deposits upon the reservoir, which may lead to thermal shortcuts. Additionally, the well screens on the Austrian side are set directly underneath the brecciated high permeability layer to demonstrate a quick thermal breakthrough.

Table 26: Overview on the investigated scenarios (P: Production well, I: Injection well)

Fig. 57 shows the results of the coupled thermal – hydraulic scenario modelling in terms of the predicted water temperature at the production wells of the Austrian as well as the Slovakian doublet for an overall time period of 100 years.

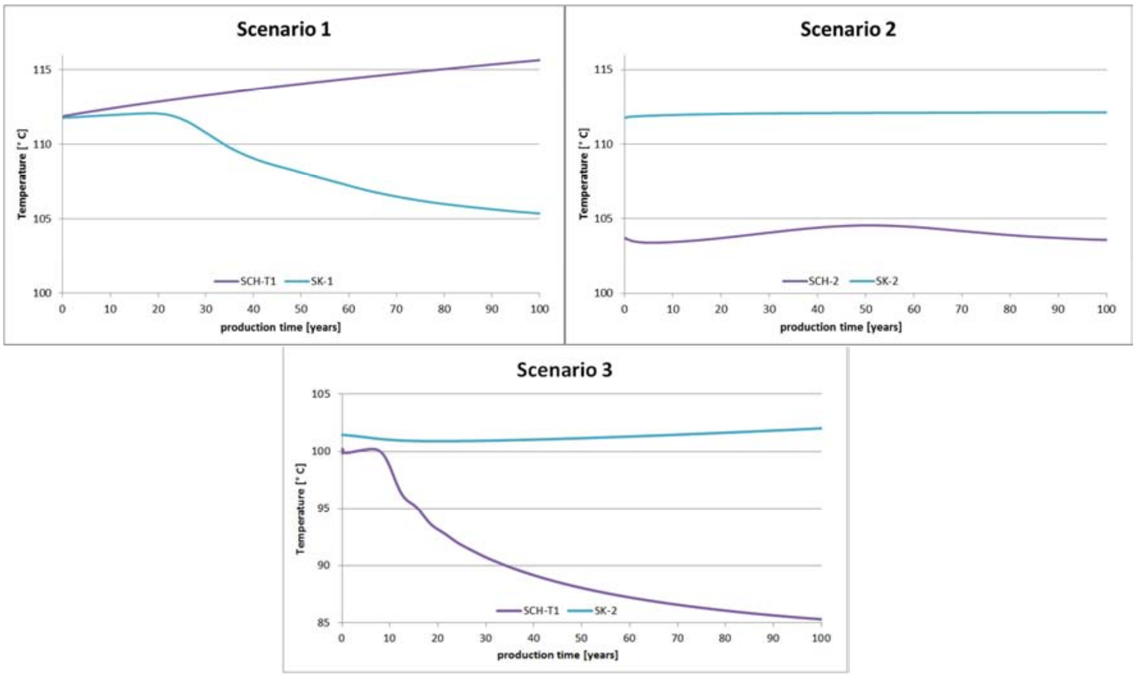


Figure 57: Time series showing the predicted temperature at the production wells of the Austrian and Slovakian doublets.

Scenario 1 (high permeable fault zone) is showing significant changes due to convective heat transport within the assumed high permeable fault zones. The temperature at the production well of the Austrian side is continuously rising during the production period of 100 years, which is related to hot thermal water from the deeper parts of the reservoir, which has been replaced by sinking injected cold water. In contrast, the thermal evolution of the production well at the Slovakian doublet is smoothly falling after an operational period of approximately 25 years due to enhanced interflow during the fault zones, where both wells are located.

Scenario 2 (low influence of fault zone) is leading to stable temperature conditions at both production wells.

Scenario 3 is investigating the influence of a highly conductive porous sedimentary layer on the top of the fractured basement. The wells of the Austrian doublet have been set in tectonically undisturbed locations within the Wetterstein Dolomite structure. Therefore the resulting flow paths are forced to pass the overlying conductive porous layer. In contrast to the situation at the Austrian doublet, the production well of the Slovakian well has been set on a highly conductive fault zone. The modelling results showed a strong interference between the injection and the production well of the Austrian doublet. After a time period of approximately 10 years a massive temperature decline (15°C) was observed at the production well as the cold water plume is preferentially passing the highly porous sedimentary layer at the top of the reservoir. In contrast, the production well of the Slovakian doublet does not show any interference, although the injected cold water plume also passes the highly conductive sedimentary layer above the reservoir. This is due to the fact, that the water pathways associated to the production well are preferably located within the highly conductive fault zone. This in turn reduces the pressure gradient within the overlying, highly conductive porous layer and inhibits the propagation of the cold plume.

To evaluate the thermal anomaly caused by geothermal exploitation, Fig. 58 shows the lateral extent of the thermal plumes of the different scenarios. This can be used to estimate the maximum number of possible doublets.

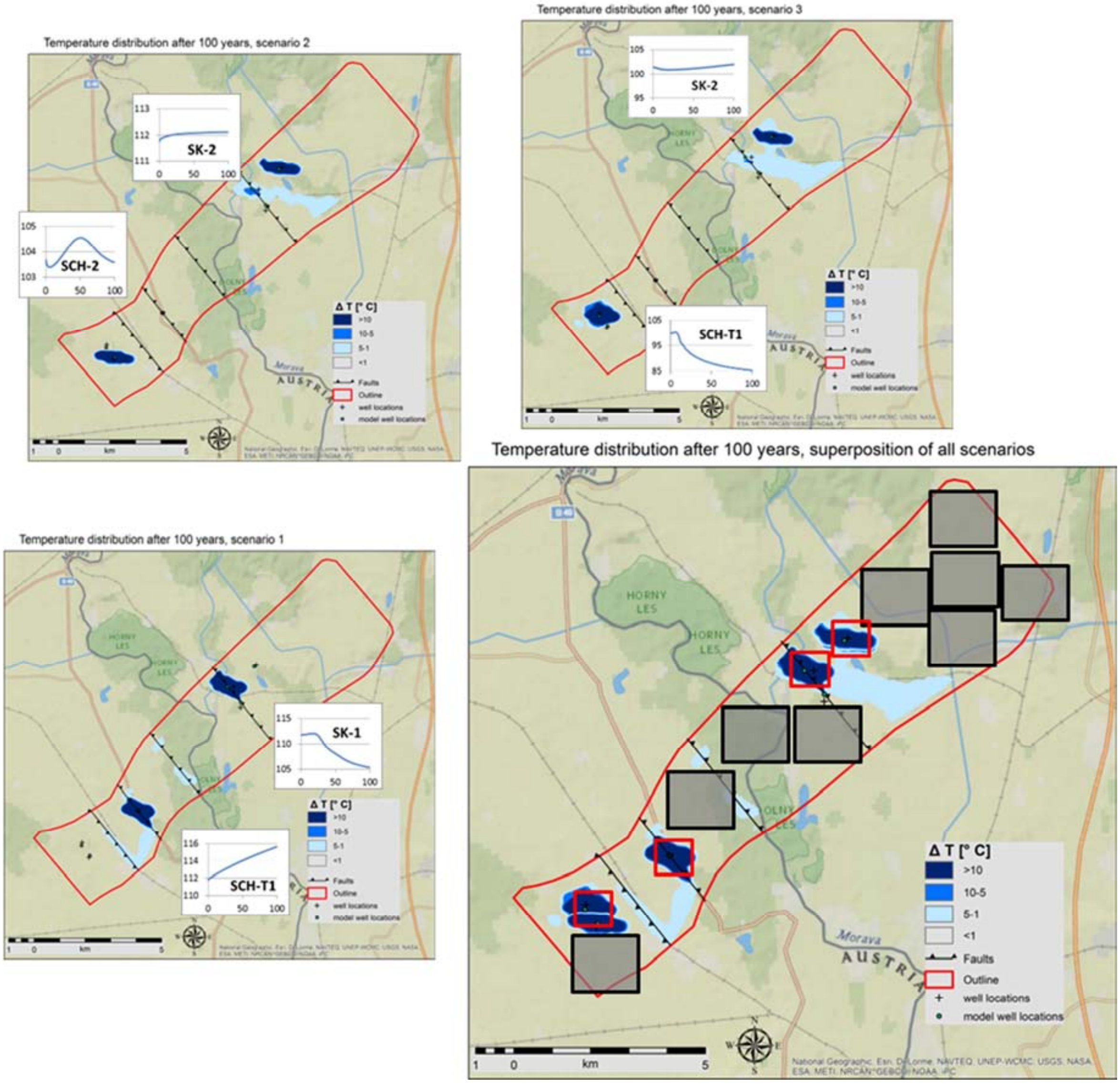


Figure 58: Temperature distribution at the depths of maximal plume at the re-injections. The overlain diagrams show the temperature evolution of the produced water.

4.9.5.6. Benchmark evaluation

As no hydrogeothermal utilization exists at the Vienna Basin, benchmark evaluation was not performed for this pilot are.

4.10. SWOT Analysis

Based on the extensive state-of-the-art assessment of different aspects of the entire TRANSENERGY area, as well as the 5 cross-border pilot areas, a SWOT analysis was prepared (Table 27) that provided the basis to set up goals and tangible recommendations which are summarized in the following chapters.

Strengths • favourable geothermal conditions of the study area • well identified stakeholder group with identified needs • appropriate tools developed (geoscientific models) to answer stakeholders' questions • qualified project consortium • compulsory WFD and RES framework for each country (e.g. monitoring, reporting) • well established methodology and functioning assessment and reporting of environmental measures of groundwater bodies (in the frame of the national River Basin Management Plans – Water Framework Directive) (including monitoring at national levels) • delineated hydrogeothermal reservoirs in the entire TRANSENERGY area with characterization and potentials for different types of use • geothermal potential assessment of 9 selected hydrogeothermal plays at 5 pilot area based on a method developed in TRANSENERGY (compliant to CanGea reporting methods) • benchmark assessment of 5 pilot areas – new methodology developed in TRANSENERGY (10 indicators of sustainable management of thermal groundwaters and geothermal energy resources) • tangible recommendations for integrated thermal groundwater monitoring at 5 pilot areas	**Weaknesses** • heavily exploited areas with signs of overexploitation • low share of energy use • low share of re-injection • thermal / chemical pollution of surface waters by emitted and untreated thermal water, little information on the quality of discharged thermal water, • practical lack of cascade systems • low thermal efficiency • poor BAT indicators (technical installations at the well and pipeline system) • different concepts for the delineation of (thermal) groundwater bodies in the partner countries that impede direct comparison of aquifers in the transboundary zones • classification and terminology of monitoring sub-systems are different and confusing in partner countries • passive monitoring of thermal water aquifers is insufficient • compulsory reporting related to NREAP-s are too general for regional / sectorial assessments of geothermal energy use • inhomogenous datasets and databases impede harmonized cross-border evaluations • data confidentiality policy of Austria
Opportunities • future delineation of joint thermal groundwater bodies to be incorporated in international water policies (UNECE, etc.) • maintenance / updating, further development and adjustments (more user friendly) of the established joint, multi-lingual borehole database and users' database and its public part s at the project website • improve all benchmark indicators • outline protection zones for existing energy utilizations • carry on and expand well-established cooperation of partner geological surveys • rising karst water level in the Komarno-Sturovo pilot area enhances the rehabilitation of the groundwater-dependent ecosystems	**Threats** • unharmonized management strategies at national levels • controverting interest and framework of water management and energy policies at international and national levels(protection vs. use of resources) • dual character of regulation (production with and without thermal water abstarction) shared by ministries of „environment" and „energy/economics" • complicated and time-consuming licensing procedures • lack of sufficient financial incentives • low rate of public awareness (information available on monitoring, cascade use, efficiency, geothermal energy, thermal water,

• potential for transboundary energy utilization with doublets in the Komarno block (Komarno-Sturovo pilot area) • potential for energy utilization with doublets in the E-ern block of the Bük Dolomite (Lutzmannsburg-Zsira pilot area) • potential for transboundary energy utilization with doublets in the Danube Basin pilot area (additional installations in the basin) • establish of cascade system at Korovci (Bad Radkensburh-Hodos pilot area) as no major transboundary effect was verified by modelling • use of the knowledge, abandoned hydrocarbon wells and infrastructure for geothermal development in the Vienna Basin • potential for transboundary energy utilization with doublets in the Triassic dolomite of the Juvaic Nappe System in the Vienna Basin	pollution, waste water management, re-injection, water level decline, geothermal aquifers, etc.) • surface seepages due to rising karst water level in the Komarno-Sturovo pilot area threatens new surface installations (buildings, garages) • competing water demands of drinking water, balenology and GW-dependent ecosystems in the Komarno-Sturovo pilot area • excessive utilization causes changes in water chemistry in the Lutzmannsburg-Zsira pilot area • competitive subsurface use between hydrocarbon production and geothermal heat recovery in the Vienna Basin

Table 27: SWOT analysis

5. VISION

The envisioned cut-off date of the desired circumstances is set up as ***2022***, as this matches the time-frames of the National Renewable Energy Action Plans (2020) and the cycles of the national River Basin Management Plans (2021).

The ultimate ***general goal*** is to fulfil Water Framework and RES Directive obligations and proceed ahead. This includes the official delineation of joint transboundary thermal groundwater bodies (based on joint delineation concepts), as major planning / administrative units for which environmental objectives and measures as well as concrete management strategies including joint monitoring systems are phrased in the W-ern part of the Pannonian Basin based on TRANSENERGY results. The Bilateral Water Commissions play an active role to achieve this goal..

Parallel with this, all four countries reach their NREAP target numbers (Fig. 59) with maximum possible proportional contribution from the TRANSENERGY cross-border reservoirs.

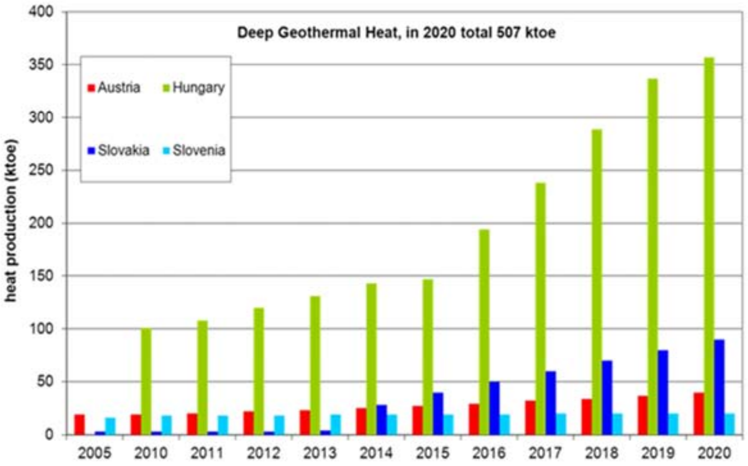


Figure 59: NREAP targets of TRANSENERGY countries

The envisioned amount of abstracted thermal water in the region will be approximately 70 million m^3/year. This estimation is based on the already granted/requested amount and an additional 15% increase. A major shift in the share of utilisation is expected: only a small increase in the balneological use and a ***significant growth in the direct-heat applications***, especially in ***heating of greenhouses*** (Danube basin, major agricultural area in Hungary and Slovakia), and in ***district heating*** (areas where good geothermal potential matches heat demand of larger towns (e.g. Dunajska Streda, Nové Zamky, Vienna, Zalaegerszeg). Due to reservoir properties only 1 or 2 small size (1-3 MW$_e$) combined heat and power plants are foreseen in the region, targeting basement reservoirs, especially in SW-Hungary and in the Vienna basin.

The increased rate of energy utilization is achieved as much as possible with increasing thermal efficiency, utilization efficiency and re-injection, application of best available technologies (including cascade systems) and not via increasing the amount of abstracted thermal water.

To achive these golas the following tasks have to be fulfilled:

To ***increase thermal efficiency*** users cool down the thermal water as much as possible, preferably near to the mean annual air temperature (12 °C). This is done in a way that at least 70% of available thermal energy is used. Higher thermal efficiency thus leads to a reduction in the total amount of abstracted thermal water, as well as lower thermal and chemical pollution of the surface streams into which waste water is emitted.

To ***increase utilization efficiency*** the available resources are utilized as much as possible, at least at a rate of 30%.

The increased energy application is not sustainable unless ***re-injection is established***. A full re-injection is feasible and required into the fractured-karstified basement reservoirs, whereas at least a 60% rate of re-injection is needed into porous sandstone reservoirs (into the same layer from where production happens) which is the envisioned future situation. For other emitted waters, the waste water treatment is established.

Nevertheless the need for re-injection is evaluated on the basis of regional numerical models performed by independent governmental organizations (e.g. geological surveys) to reveal its necessity in comparison with the local/regional hydrogeological conditions. On those araes where the natural recharge of the targeted reservoirs is sufficient and scenario models do not predict exhaustion of the aquifer, re-injection MAY be skipped. However on araes where numerical models predict the decline of the quantity status of the reservoirs new permissions are not licensed without re-injections systems and the already existing sites are obliged to establish re-injection wells step by step (with appropriate financial support). The investigation of re-injection technologies (into intergranular environment) is supported through non-refundable funds.

Best available technologies are applied widespread, i.e. wells are equipped with well-maintained wellheads, which are isolated and protected from unfavourable weather conditions and unauthorised persons. Materials installed in and above the wells are inert for aggressive water/gas mixtures and higher temperatures. Where necessary, scaling problems are effectively mitigated. Installations avoid areas of gas or water leaks. Abstracted water is precisely and continuously following the water demand. The exploitation system from well to emitted waste water area is based on the principles of cascade use, with both computerised and individual phases controlled as much as possible.

Irrespect of depth of screened intervals, a ***"protection zone"*** is outlined (3D equivalent of a mining plot), from where the user can exclusively abstract thermal groundwater. The maximum allowed values of temperature and pressure drop (depending on reservoir characteristics) are determined case-by-case by coupled heat and transport models. These models are prepared by indepenedent governmental organizations (e.g. geological surveys) and are updated regularly (e.g. 5 years).

The ***geothermal aquifers*** are envisioned to be in ***good quality and quanity status***, i.e. not overexploited. This means that there is no significant decrease in the regional piezometric level, the water quality and/or temperature does not change due to abstraction, groundwater dependent ecosystems are sustained and there is no soil subsidence caused by abstraction. To be able to reach this the ***critical level points and the critical points of abstraction*** are defined, and the renewable and available volumes of water are assessed by regional numerical models which are calibrated by data of passive monitoring wells. The critical level of point at the abstraction site is max 100 m below the natural water level of the pre-exploitation state, while at passive monitoring wells (observing more distant parts of the reservoir) max 30 m. Nevertheless in regions of intensive exploitation, the critical points of abstraction (the maximum amount of abstractable amount of thermal groundwater) is defined based on numerical models

Before issuing a new water license, the granting authority has all relevant information to be able to decide whether the new production would not threat the already existing productions (interactions are avoided), does not lead to an excessive water use or does not threat the environmental objectives.

To continuously follow the statues of the geothermal aquifers both active and passive ***monitorings*** are established. In the active monitoring, executed by the user, the wells' discharge, piezometric level and temperature are continuously measured and complemented by regular water analyses. The licence holder submits a yearly report, which is approved by the granting authority. A complementary passive monitoring in non-exploited observation wells is performed by governmental bodies, where the piezometric level is regularly measured and there is an occasional sampling for chemical / isotope analyses to be able to identify changes at a regional scale.

Regarding ***data policy*** there are up-dated and reliable national database about the annual production (and re-injection) of the exploited thermal water. Registers are maintained by the water management authorities and energy authorities (register of productions related only to energy appilications) and are cross-checked, harmonized and compatible. Furthermore all important technical and non-technical data which are necessary for the evaluation of status assessment and monitoring of transboundary hydrogeothermal reservoirs are regularly maintained and they are public and freely accessible. National databases are INSPIRE compliant.

There is a regular data exchange between neighboring countries.

The databases established in the frame of TRANSENERGY are sustained and regularly updated.

Sufficient financial support schemes (tax incentives, off-take of green-heat, feed-in-tariff, risk insurance) are established to support viable geothermal projects. Regarding the geological conditions of the investigated regions, especaially the support of green-heat, and the establishment of risk-insurance systems are important.

The ***regulatory framework*** (including licensing procedures) is simplified and more transparent. There are no discriminations towards any sector (e.g more favorable waste water threshold values for balneological use, higher taxation of energy users, etc.). Preferably one single Renewable Energy Act (with special provisions for geothermal) exists.

Integrated management policy, or at least coordinated actions between the environmental and energy sectors both at international (EU) and national levels, are established for the sustainable management of hydrogeothermal resources.

Public awareness is increased, there is freely accessible and regularly updated information at least about the quantity status of the geothermal aquifer, the quality status of waste water, energy efficiency, BAT use and monitoring for each geothermal site.

6**. RECOMMENDATIONS**

As the previous chapters confirmed, sustainable management of hydrogeothermal resources is a complex task with many unsolved technical and non-technical problems. Despite serious efforts, TRANSENERGY does not provide any quick solution, however based on a ***holistic approach*** it provides a comprehensive framework for the understanding of the transboundary geothermal energy resources at the W-ern part of the Pannonian Basin for the first time. Based on the carefully elaborated and scientifically established working methods and the achieved results, TRANSENERGY provides a ***good example*** how to achive harmonized management and sustainable utilization of hydrogeothermal systems ***in other regions*** in Europe sharing trans-boundary resources.

The recommended approach is based on the ***MODELING-MONITORING-MANAGEMENT (3M)*** principle.

As it was shown by many examples in Chapter 1, most of the management-related questions can be answered by ***geoscientific models***, performed by the experts of ***independent governmental organizations.*** The basis of this is a common understanding and uniform databases that provide input data for joint assessments. Therefore it is recommended:

To strenghten cooperation among national geological surveys and reinforce the maintenance of national geoscientific (including hydrogeological and geothermal) databases and modeling among their tasks.

Geological, hydrogeological and geothermal models should be based on ***harmonized databases containing reliable data***. Various national datasets managed by ***different organizations*** (e.g. water production data by licensing authorities, geoscientific data by geological surveys, high resolution reservoir data by project developers) should be ***integrated*** with transparent regulations on their use including data confidentiality. As many valuable data concerning the same reservoirs are produced in the hydrocarbon industry, ***a stronger cooperation between the geothermal and hydrocarbon sector*** is required. This includes data transfer as well as joint interpretations. Nevertheless for the assessment of transboundary geothermal resources, cross-border harmonization would not require the creation of a single uniform transnational database (in a way duplication of national databases in different formats), but making ***national databases INSPIRE compliant,*** which thus makes possible to keep national characters and structures, and provide their access via standardized metadata catalogues.

In terms of ***modelling,*** the ***following workflow*** (successfully tested by TRANSENERGY) is recommended:

- establishment of conceptual models (general understanding of the targeted system)
- determination of the most important hydrostratigraphic units
- establishment of geological model (3D distribution of the hydrostratographic units, e.g. by delineating their bounding surfaces, complemented by the most important tectonic lines)

- numerical heat and flow model (calibrated). Steady-state models provide history matching, i.e. show how the resources have been used so far (recommended versions: pre-exploited natural state and production state for the first decade of the 21th century), while scenario models forecast how the system will respond to future utilization. Recommended scenarios:
  - SC_1: exploitation of existing utilization sites with elevated production rates (3 or 5-times higher)
  - SC_2: exploitation with elevated production rates (3 or 5-times higher) including future possible sites (considering demands of new heat markets, district heating systems, agricultural use, etc.)
  - SC_3: exploitation at present sites, with max. allowed drawdown of 100 m (critical level)
  - SC_4: exploitation at present and foreseen future sites with max. allowed drawdown of 100 m (critical level)
  - SC_5: exploitation at present sites with elevated production rates (3 or 5-times higher) at existing utilizations with re-injection
  - SC_6: exploitation with elevated production rates (3 or 5-times higher) including future possible sites with re-injection

Results obtained from the performed simulations of the regional numerical flow and heat transfer models should enable accurate estimation of available thermal water reserves in individual aquifers, which will furthermore represent an expert basis for the redistribution of water licences. As such, the model should be continuously re-evaluated with new data (on production, monitoring, etc) in order to follow the current status of the geothermal aquifers.

The established ***transboundary monitoring system*** should sufficiently cover all aspects of monitoring activity, i.e. regularly repeated measurements covering quantitative and qualitative features, appropriate network infrastructure, data quality, data management and reporting. Monitoring should not focus only on utilization sites (active monitoring performed by users in the production wells), but at the entire geothermal structure itself through independent monitoring wells (passive monitoring) controlled by independent authority.

Frequency of measurements should be:

- Sufficient to reveal significant oscillation of parameter values and to statistically assess the standard deviation and error
- Sufficient to reveal any significant trend
- Sufficient to forecast any eventual need to implement additional measures on time for safe operation and not to increase costs.

Different intensity of thermal water exploitation requires different levels of monitoring. TRANSENERGY recommends using ***three levels of monitoring***: baseline monitoring, active monitoring and passive monitoring (Table 28).

Level of Utilization	Monitoring	Parameters to be measured and recommended frequency
1 –No utilization	**baseline monitoring:** summarize the initial / steady state hydraulic, thermal and hydrochemical conditions Existing exploration data (e.g. CH industry)	*reservoir characteristics* (temperature, pressure, hydraulic gradient, thermal rock parameters, hydraulic rock parameters *hydrochemistry* (main ions, salinity, isotopes) *recharge, discharge*
2 – Moderate utilization, no interference or regional scale changes	**active monitoring**: production data qualitative and quantitative performed by *users,* competent public agencies	*qualitative:* electric conductivity (1 hr), basic hydrochemical analyses (1 yr), comprehensive hydrochemical analyses (5 yr), *qualitative:* flow rate (1 hr), water level/operational pressure (1 hr), flow temperature (1 hr), total abstraction (1 day), closing pressure / static water level after shutdown of well (3 months)
3 – Intense utilization, interferences and regional scale changes evident	**active monitoring** **passive monitoring:** observation wells distant from production wells → regional effects of thermal water abstraction data acquisition and maintenance by *public authorities, agencies*	*passive monitoring:* *qualitative:* electric conductivity (6 hr), basic hydrochemical analyses (1 yr), comprehensive hydrochemical analyses (5 yr) *qualitative:* temperature (6 hr), static pressure / water level (6 hr)

Table 28: Monitoring concept on different levels

At intensive utilization (like in the case of TRANSENERGY area) the monitoring system relying only on users'/concessionaires' measurements and reports (active monitoring) wouldn't be enough. For this reason, some observation wells for passive monitoring should be selected that would serve to control the regional water level and water flow directions and the trends. This advanced network would also include deep thermal wells sufficiently far away from actual abstraction sites to monitor the background and boundary conditions of the regional thermal water system. This kind of monitoring wells would be of extremely importance for transboundary management, especially if the observation wells would be designed and/or equipped and maintained in the cooperation of the neighbouring countries, using best practices examples and the most advanced technology. Observation wells for passive monitoring have to be financed by public authorities. Synergies for cost reduction may be given at abandoned hydrocarbon wells and non-prospective exploration drillings.

Annual regional monitoring data should be analysed every 3-5 years, since in this period the quantity and quality of the aquifer trends should become more evident. Monitoring programs than may be revised, which may apply for monitoring frequency of different parameters also.

For the five studied pilot araes of TRANSENERGY, the following monitoring systems are recommended:

Komarno-Sturovo Pilot Area

Several springs and existing, but currently not operating thermal wells (especially in Slovakia) are recommended to be part of a future joint monitoring system (Fig. 60). These are the Mala-sping in Esztergom, where there is possibility to make continuous measurements of discharge, temperature and conductivity in the tunnel, as well as Lilla- and Csokonai-springs in Dunaalmás, and Fényes-spring in Tata, which need to be equipped with measuring objects. Sárisáp spring is involved in the recent monitoring, measurements are required to be continued in the future, too.

Further monitoring wells are proposed to be configured at Bábolna (Hungary), where K-52 and K-53 wells are out of order and at FGK-1, M-3, PGT-11, GTM-1, VZO-14 and VŠE wells in Slovakia, where existing and currently not-operating wells should be equipped with pressure/head transducers, temperature and electrical conductivity probes. Monitoring should be performed on daily basis. In addition active monitoring is expected in the operating thermal wells.

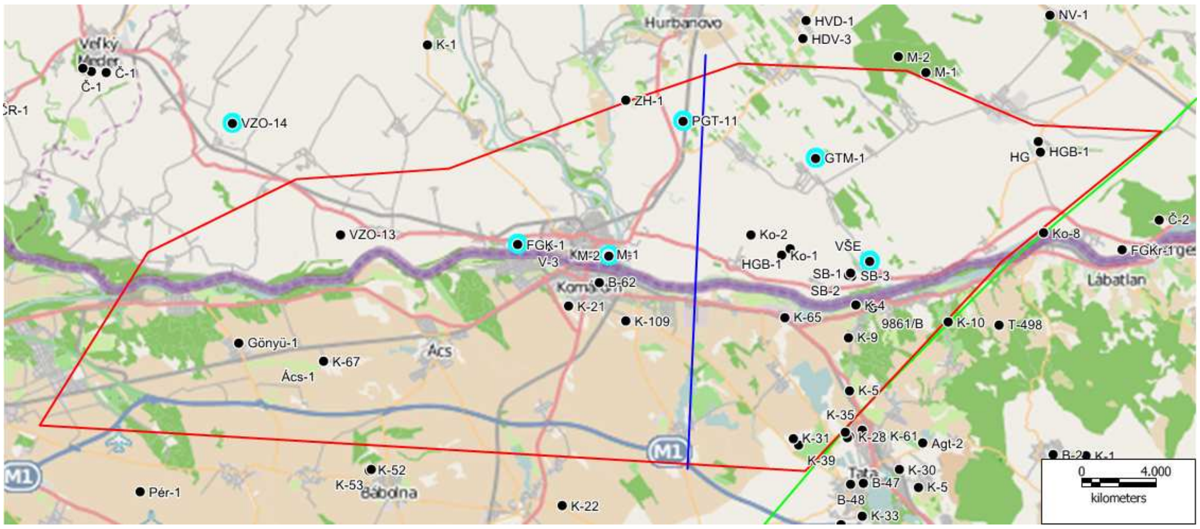


Figure 60: Proposed monitoring points (highlighted) for the Komárom-Štúrovo pilot area

Lutzmannsburg-Zsira Pilot Area

The present measurements of active monitoring must be continued. Additional measurements are required to get information about the of Devonian Dolomite basement reservoir. The monitoring well Csepreg K-15 was originally deepened to more than 1000 meters reaching the basement. Recently the well is only 300 m deep. The well is proposed to be reconstructed to be able to measure the karstwater head again. One well of the two Lutzmansburg thermal wells is alternately operating, while the other is set to standby. It is proposed to make continuous groundwater head measurements with data logger in the well which is currently out of order (Fig. 61).

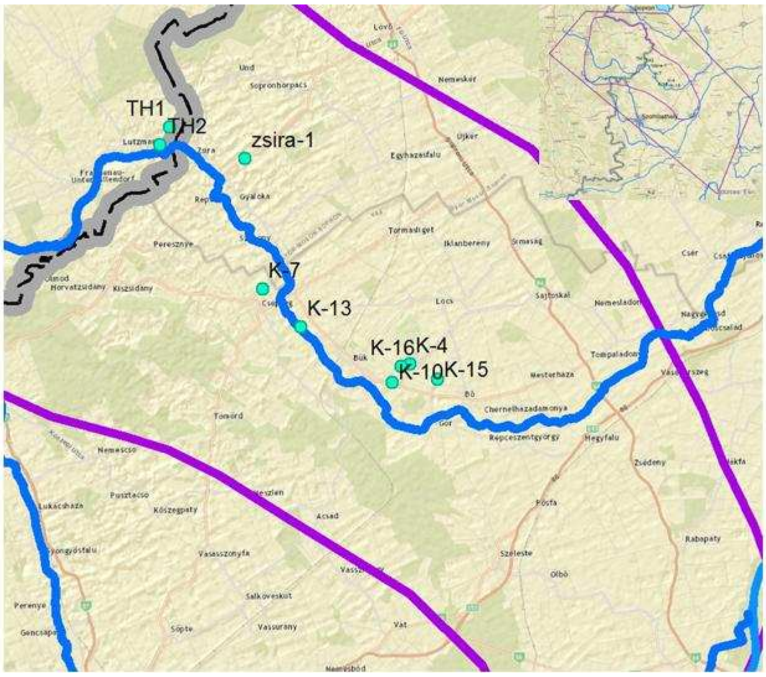


Figure 61: Proposed monitoring points in Lutzmannsburg-Zsira pilot area

Danube Basin Pilot Area

According to the pre-defined main criteria to select areas for a joint transboundary monitoring (Rotár-Szalkai et al. 2013c) two monitoring areas have been selected, based on the results of steady state models of the entire Danube Basin pilot area:

- Area 1 Mosonmagyaróvár – Lipót – Šamorín,
- Area 2 Győr – Veľký Meder,

Area 1

In this area, the Upper Pannonian intergranular thermal water aquifer is extending over a large region on both sides of the river Danube at depths from 1000 to 2500 m. Thermal waters are utilized by a number wells, almost solely for recreational purposes (Table 17). Although no pressure or temperature changes had been observed at the former monitoring well BL-1 at Boheľov, it cannot be excluded that as utilization continues, adverse effects may emerge. As the coupled hydrogeological and geothermal models showed (Chapter 4.9.3.5.), future decrease of temperature as well as pressure in the vicinity of the pumping wells may be expected. The proposed monitoring boreholes are shown on Fig. 62.

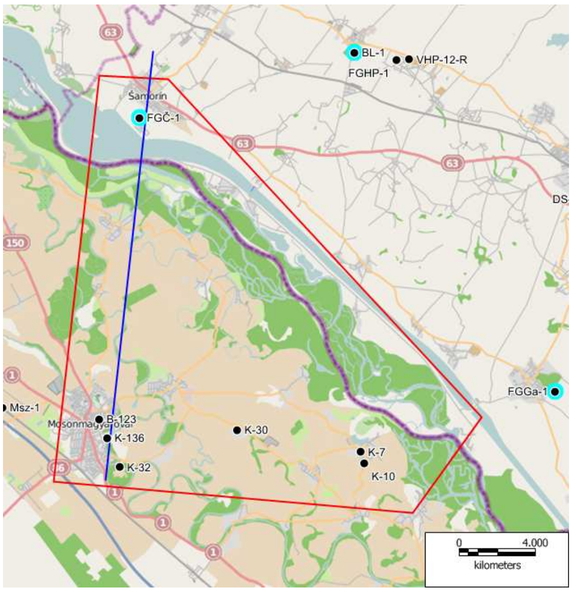


Figure 62: Proposed monitoring Area 1 Mosonmagyaróvár – Lipót – Šamorín (310 km^2), with thermal wells. Proposed monitoring boreholes are highlighted.

At least two new monitoring wells between Mosonmagyaróvár and Šamorín are recommended to be established and use existing currently non operated wells FGČ-1, BL-1 and FGGa-1 too. Continuous monitoring of groundwater heads and temperatures are recommended in Lipót K-7 or K-10 when they are out of order.

Area 2

Thermal groundwater of the Upper Pannonian intergranular aquifer between Győr and Veľký Meder is harvested for bathing at many sites (Table 18). The considerable amount of abstracted water (>200 000 m^3 per year) may cause deterioration of water quality, quantity and temperature, which raises the importance of common groundwater management based on reliable monitoring data.

Existing, but currently unused wells VZO-14 and VČR-16 can be easily converted into monitoring boreholes. Area close to river Danube, uncovered by deep hydrogeological boreholes, is of major importance for setting up another two monitoring boreholes (Fig. 63).

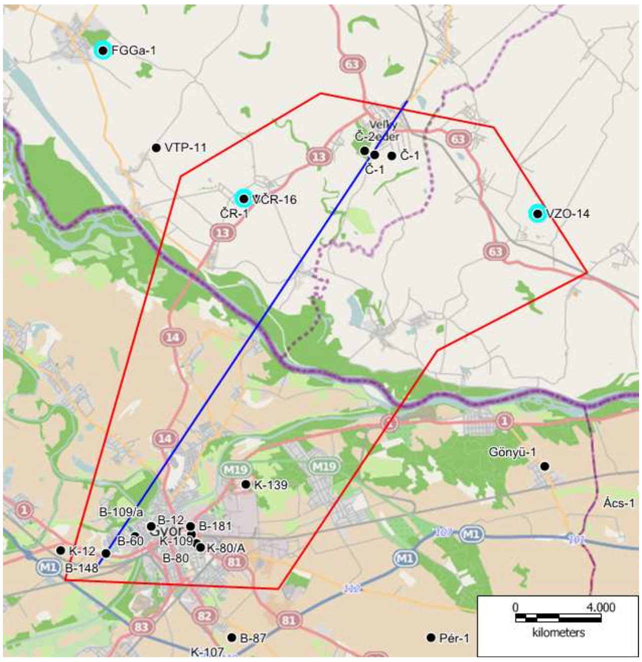


Figure 63: Proposed monitoring Area 2 Győr – Veľký Meder (315 km^2), with thermal wells. Proposed monitoring boreholes are highlighted.

Bad Radkensburg-Hodos Pilot Area

Due to the great depth of the aquifer, it is not convenient to establish a new monitoring network system, especially in HU part, where the thickness to the aquifer exceeds 4000 m. The proposed monitoring should be supplemented by running active monitoring of three production wells (Be-2, Rad-2 and Rad-3) and passive monitoring of one inactive production well in Korovci (SI) (Kor-1gα) and one observation well in Pečarovci (SI) (Peč-1) (Fig. 64). There are no applicable wells in Hungary. The two nearest existing wells (NK-2 and K-2) are not a part of the Bad Radkersburg – Hodoš geothermal aquifer, therefore they are not suitable as observation wells for this geothermal aquifer.

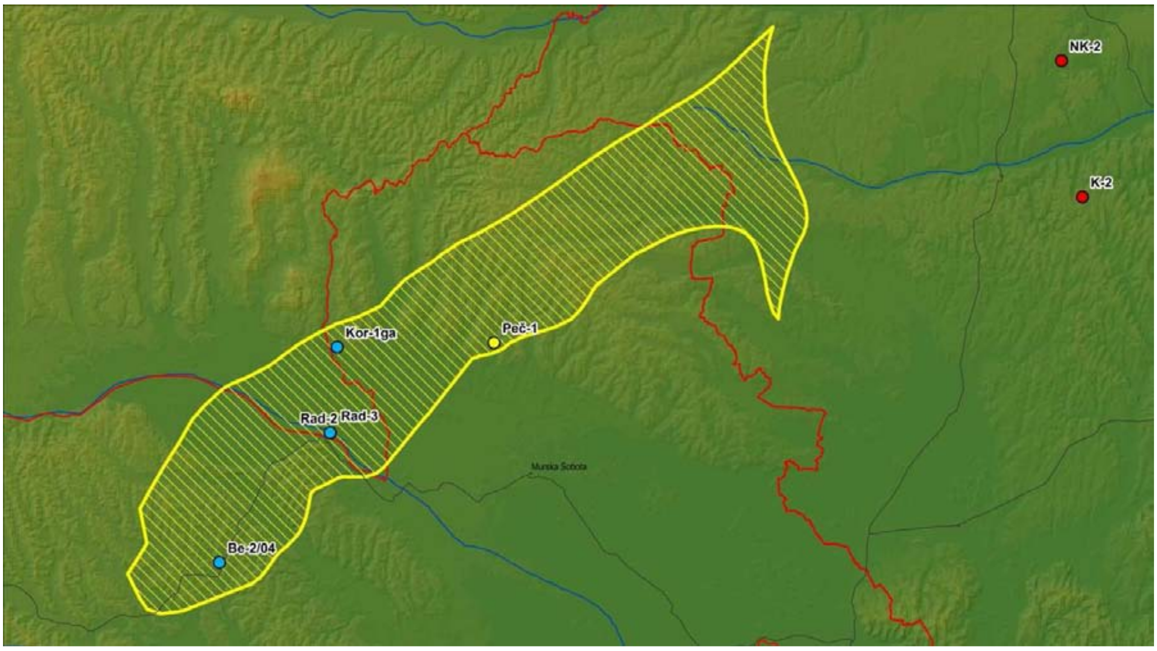


Figure 64: Proposed joint Bad Radkersburg - Hodoš monitoring network

Vienna Basin Pilot Area

The identified hydrogeothermal structures (Chapter 4.9.5.2.) [1] to [3] are currently still at baseline monitoring level as no hydrogeothermal utilization is currently installed. Hydrogeothermal play [4] can be classified at level 2 (Moderate utilization, no interference or regional scale changes). At Bad Deutsch Altenburg only minor utilizations for balneological purposes are installed and neither interferences nor regional scale changes of the quality or quantity of the used thermal waters have been observed. However, as the Central Alpine & Tatric Carbonate hydrogeothermal play [4] is assumed to represent a trans-national hydrodynamic system, a bilateral active monitoring focussing on the existing utilizations is needed, but not implemented yet.

Recommendations for a sustainable management based on benchmarking evaluation

The results of the benchmarking clearly reflect the long tradition of using thermal water for balneological purposes, and show very good utilization efficiency in the whole W-ern part of the Pannonian Basin. In contrast to these positive results the indicators on the re-injection rate and public awareness show that significant actions are needed in all four countries to improve the management of the geothermal resources. With the exception of Austria, the monitoring indicator for the active thermal water wells is mostly medium or bad, which means it is essential to develop monitoring systems for the appropriate observation of the thermal aquifers. The information on the quality of emitted waste water was not collected within this research and therefore this parameter could not be reliably evaluated. The indicator values of the best available technology vary between bad and good categories and the good values might only be due to a lack of reliable information, thus this is also a field for improvent. The thermal aquifers are not yet over-abstracted, but the „good” results can potentially act as an early warning indicator giving the first signals of deterioration in status, shown by decrease of piezometric levels or change in groundwater quality. An evaluation of the thermal efficiency indicator shows a bad or very bad status in general, so the annual heat energy of existing wells used should be increased rather than just exploiting new wells. In case of low (less than about 35°C) wellhead temperatures the thermal efficiency indicator does not correctly reflect the efficiency of the well. The status of water balance assessment is also mostly bad or weak in Hungary, Slovenia and Slovakia, so there is much to do in defining critical level points and critical limits of abstraction in all four countries, especially in those cases where the wells are located close to the national borders. The bathing parameter is planned to include measurements of the effects on healing processes in the future. Despite the few currently exisiting re-injection wells , we believe that due to the positive effects on aquifer hydraulic conditions and mitigation of environmental pollution, re-injection into the same aquifer should be required for all users utilising non-treated thermal water for the purpose of use of geothermal energy. Limited time of derogation and appropriate financial support should be given to current users for the implementation of (new) re-injection wells, while new users should establish the necessary doublet system before starting production. Location and design of re-injection wells should be based on numerical simulation of aquifer capacities, appropriate technical design of re-injection wells and cost-benefit analyses, but poor economic conditions should not be used as an excuse for exemption.

In some cases (eg. existing „inactive" wells with positive outflowing thermal waters but without licence) could not be incorporated in the actual benchmarking evaluation. However, since they are important in the geothermal resource management, they should also be taken into consideration when the developments of existing abstraction or new licences for thermal water exploitation are requested.

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