Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Benchmarking - Indicators of Sustainability of Thermal Groundwater Management

Joerg Prestor[1], Teodóra Szőcs[2], Nina Rman[1], Annamária Nádor[2], Radovan Černák[3], Andrej Lapanje[1], Gerhard Schubert[4], Daniel Marcin[3], Katarina Benkova[3], Gregor Götzl[4]

Mailing address, [1] Geological Survey of Slovenia, Dimičeva ulica 14, 1000 Ljubljana, Slovenia

[2] Geological and Geophysical Institute of Hungary, 1143 Budapest, Stefánia u. 14; Hungary

[3] State Geological Institute of Dionýz Štúr, Mlynská dolina 1, 817 04 Bratislava 11; Slovakia

[4] Geological Survey of Austria, Neulinggasse 38, A-1030 Wien; Austria

E-mail address, joerg.prestor@geo-zs.si; szocs.teodora@mfgi.hu

Keywords: thermal water, over-exploitation, indicators of use, transboundary, geothermal aquifer, TRANSENERGY project

ABSTRACT

The purpose of this study was to develop a methodology for comparison of different management entities to evaluate the sustainability of management of transboundary low- and intermediate temperature geothermal aquifers situated between Slovenia, Austria, Hungary and Slovakia, situated within the TRANSENERGY project area. Differences and similarities of actual management were investigated on a case study of five selected areas with various utilization conflicts: Bad Radkersburg-Hodoš (AT-SI), Danube basin (HU-SK), Komárno-Štúrovo / Komárom-Párkány (HU-SK) and Lutzmannsburg-Zsira area (HU-AT). We adjusted the "Lake Lemano" idea and defined 10 indicators: 1) Monitoring status, 2) Best available technology, 3) Energy efficiency, 4) Utilization efficiency, 5) Bathing efficiency, 6) Reinjection rate, 7) Status of water balance assessment, 8) Over-abstraction, 9) Quality of discharged waste thermal water and 10) Public awareness. Each indicator was first assessed by assigning relevant number of points to an individual source, and these were later weighted by the amount of produced thermal water, and averaged for the whole regional aquifer in an individual country. In order to provide sufficient and very detailed datasets, we performed detailed interviews with thermal water users and elaborated the User database, containing over 300 wells. The results reflect the long tradition of using thermal water for balneological purposes, and show very good utilization efficiency in the whole western part of the Pannonian Basin. In contrast to these positive results, poor monitoring status and water balance assessment, low energy efficiency, extremely low reinjection rate and insufficient public awareness materials show that significant actions are needed in all countries to improve management of these geothermal resources. There are still some weaknesses within this approach, especially regarding the evaluation procedure for bathing efficiency, quality of discharged waste thermal water and public awareness indicators. However, they were often not assessed due to lack of information. All information is available on website: http://transenergy-eu.geologie.ac.at/.

1. INTRODUCTION

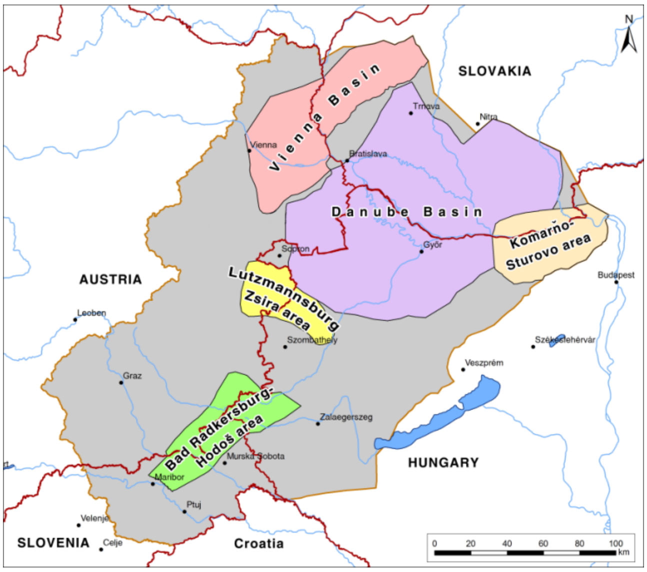

Figure 1: Study area of TRANSENERGY (red line) encompasses the western part of the Pannonian Basin. Detailed studies were performed on five selected cross-border pilot areas.

The geothermal potential of the Pannonian basin is outstanding in Europe, as it lies on a characteristic positive geothermal anomaly, with heat flow density ranging from 50 to 130 mW/m^2 with a mean value of 90-100 mW/m^2 and geothermal gradient of about 45 °C/km (Dövényi and Horváth 1988). This increased heat flux is related to the Early-Middle Miocene formation of the Pannonian

Basin, when the lithosphere stretched and thinned (thus the crust is "only" 22-26 km thick) and the hot asthenosphere got closer to the surface (Horváth and Royden 1981). During the continuing subsidence a large depression formed, occupied by a huge lake (Lake Pannon), which was gradually filled up by sediments transported by rivers, originating in the surrounding uplifting Alpine and Carpathian mountain belts (Magyar et al. 1999).

These several thousand meter thick multi-layered porous sediments (Upper Miocene-Pliocene "Pannonian sequence") show low heat conductivity and are composed of successively clayey and sandy deposits. Within this basin-fill sequence the main thermal-water bearing sandy aquifers are those 100-300 m thick sand-prone units which are found in a depth interval of ca. 700-1800 m in the interior parts of the basin, where the temperature ranges from 60 to 90 °C. These are the main reservoirs, with bulk porosity of 20-30% and permeability of 500-1500 mD, and with an almost uniform hydrostatic pressure, widely used for direct heat purposes (agriculture and district heating) as well as for balneology. The karstified zones of the Palaeozoic-Mesozoic carbonates, as well as fractured zones in the crystalline rocks in the basement are also good thermal water reservoirs. They are characterized by high secondary porosity. At this depth (on average 2000 m or more) temperature can exceed 100-120 °C, and may provide favorable conditions for development of medium-enthalpy geothermal systems (e.g. CHP plants).

These large geothermal aquifers are being determined by geological structures and are often cut by state borders and 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. Studying such cross-border geothermal reservoirs and making suggestions for an integrated management of thermal groundwater and geothermal energy utilization among Hungary, Slovenia, Austria and Slovakia at the western part of the Pannonian Basin was carried out in the frame of the project TRANSENERGY (2010-2014). One of the project aims was to prepare a comparative overview on the current state of thermal water utilization in the entire region and to elaborate and test a method that allows the assessment of transboundary (geothermal) aquifers and utilizations through a set of indicators, carried out at selected cross-border pilot areas (Figure 1).

2. OVERVIEW OF CURRENT USE OF THERMAL GROUNDWATERS – A FRAMEWORK

An extensive survey of the existing thermal water users, utilization parameters and exploited aquifers (Rman 2011; Rman et al. 2011) identified altogether 175 users (23-SLO, 28-SK, 20-AT, 104-HU) out of which 144 were active, with current production of thermal groundwater (outflow temperature > 20 °C) from 308 boreholes (35-SLO, 39-SK, 50-AT, 184-HU).

The overwhelming type 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 the northeastern 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 produce thermal water above 60 °C (mostly in the Slovakian part of the Danube Basin and in the northeastern Slovenia), the low percentage of geothermal heat production is still striking. Thermal water is produced mainly by pumping, and natural outflow prevails only in Slovakia.

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 production 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 and bathing 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 that granted or requested for thermal water demand is at least double the current production rate. It forecasts a hypothetical but legally allowed production of thermal water of above 60 million m^3 (neglecting assumptions related to confidential production data in Austria).

The threat of overexploitation was further supported by the observed changes in operation that was reported from many inspected boreholes. Only 1% of the boreholes targeting the Mesozoic carbonate aquifers indicated yield decrease, showing that they receive enough natural 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 unfavorable trends affected most seriously the Palaeozoic fractured metamorphic aquifers, where drop in yield/temperature was reported from 67% of the boreholes.

As analyses (Rman 2011; Rman et al. 2011) showed, only four sites with energy applications have reinjection, and only one operates continuously (Bad Blumau, Austria, re-injection into Palaeozoic dolomite aquifer). 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 inactive. 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.

3. BENCHMARKING METHODOLOGY

To quantify and evaluate different parameters of thermal water utilization that are decisive on the sustainable use of transboundary geothermal aquifers, and to compare them between the neighboring countries, an objective and transparent method composed of a set of reliable indicators was necessary. Therefore a methodology originally elaborated for better management of the region of Lake Léman (Lachavanne and Juge 2009) was modified and applied for the TRANSENERGY pilot areas based on 10 indicators:

- Monitoring status.
- Best available technology.
- Energy efficiency.
- Utilization efficiency.
- Bathing efficiency.
- Reinjection rate.
- Status of water balance assessment.
- Over-abstraction.
- Quality of discharged waste thermal water.
- Public awareness.

All indicators are based on an objective calculation method as described below. The results are marked in five descriptive categories: bad, weak, medium, good and very good, which allows a transparent comparison. The benchmarking evaluation was carried out for each pilot area, except for the Vienna Basin, where no hydrogeothermal utilization exists at present.

3.1 Monitoring Status

The first indicator is a mandatory, unified and integrated active monitoring. 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). Where reinjection takes place, the required measurements should also be performed at the reinjection 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 systematical overview of changes in aquifers, and making regional evaluations of the available thermal water resources that are necessary for leasing new water permits.

Table 1: List of points for monitoring status assessment.

Monitoring status	Points
Sporadic observations	0
Active monitoring carried out by water producers: Continuous measurements of discharge (produced water), piezometric level, temperature and regular chemical water analysis of production/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 given in Table 1 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 as set up in Equation 1. Results are interpreted according to Table 2.

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

Table 2: Evaluation of points based on the calculated monitoring indicator.

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

3.2 Best Available Technology of Use

Enhanced use of best available technology (BAT) including good conditions and appropriate technical parameters of installations and cascade use as outlined in Table 3 have a direct impact on decreasing the need for additional thermal water, thus increasing usage efficiency, mitigating potential system failures and diminishing environmental pollutions. Reinjection wells were not evaluated here.

Table 3: List of points for best available technology assessment.

BAT use	Response	Points
Well-maintained wellheads which are isolated and protected from unfavorable weather conditions and unauthorized 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
Installations avoid 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
Produced 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. This happens if wells are well-maintained and over-exploitation of the aquifer does not occur.	Yes	0
	No	1

The requirements in Table 3 are independent. BAT is applied if as little points as possible are calculated in Equation 2 and interpreted in Table 4.

$$\bar{I}_{BAT} = \frac{\sum_{i=1}^{n} I_i \cdot Q_i}{\sum_{i=1}^{n} Q_i} \qquad (2)$$

Table 4: Evaluation of points based on the calculated BAT indicator.

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

3.3 Thermal Efficiency

Thermal efficiency is the ratio between used and available annual heat energy. Only a few users in the research area cool thermal water near to the mean annual air temperature (12 °C). Higher thermal efficiency should lead to a reduction in the total amount of produced thermal water as well as lower thermal and chemical pollution of surface streams into which most waste water is emitted. To indicate good thermal efficiency, a value of at least 70% use of available energy should be reached (Table 5).

Table 5: Evaluation of points based on the calculated thermal efficiency indicator.

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

If no reinjection is applied, the thermal efficiency is calculated by Equation 3:

$$\eta_i = \frac{T_{whd} - T_{out}}{T_{whd} - T_o} \qquad (3)$$

If the produced thermal water is partly reinjected, then thermal efficiency is calculated by Equation 4:

$$\eta_{r\,i} = \frac{Q_i(T_{whd}-T_{out})}{Q_i(T_{whd}-T_{out})+Q_{ww\,i}(T_{out}-T_o)} \quad (4)$$

If all produced thermal water is re-injected then the thermal efficiency (at $\eta_{r\,i} = 1$) is 100%. Otherwise, the thermal efficiency is calculated as follows by Equation 5:

$$TE = \frac{\sum_{i=1}^{n} \eta_i \cdot Q_i}{\sum_{i=1}^{n} Q_i} [\%] \quad (5)$$

3.4 Utilization Efficiency

Utilization efficiency is the ratio between the average annual water production and the maximum quantity that could be produced (Equation 6), i.e. the higher proportion of the available resource is utilized the better the utilization efficiency is. Installed capacity is a technical parameter and represents the maximum possible production rate of a well and it is normally designed for the potential peak water demand. Nevertheless, the latter often forms the basis of the licensed maximum water quantity defined in water permits. Within this research we collected information on yields and conditions stated in water permits and took these values as the maximum allowable production rates (Table 6). We did not account for naturally discharged thermal waters (from springs), which are utilized by the ecosystems.

$$F_u = \frac{\sum_{i=1}^{n} Q_i}{\sum_{i=1}^{n} Q_{cap\,i}} \cdot 100 [\%] \quad (6)$$

Table 6: Evaluation of points based on the calculated utilization efficiency indicator.

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

3.5 Bathing Efficiency

The indicator of bathing efficiency can be calculated on the basis of reported water use, i.e. the volume of 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 to account for water's medical effects.

3.6 Reinjection Rate

Where a closed system (doublet) is used, all water is returned into the aquifer - although probably more than one reinjection well is required. In open systems only non-treated and not polluted thermal water can be reinjected and therefore fewer reinjection wells might be necessary. Reinjection wells represent a large investment cost, which – without suitable financial support – are rarely feasible. Even though reinjection is a legal requirement when thermal water is exploited for geothermal heat production, it currently takes place only at a few sites. Within this survey we checked only whether reinjection is applied or not. In the future it will be necessary to differentiate between reinjection into the aquifer from where the water is being produced, and reinjection into other aquifers. This latter case is applied often but is against the Water Framework Directive guidelines. This question is important when a groundwater with high organic and/or trace element content is reinjected into a shallower aquifer with a different chemical composition.

Table 7: Evaluation of points based on the calculated reinjection rate indicator.

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

The reinjection indicator expresses the ratio between the reinjected and produced annual volume of thermal water used for geothermal energy production (Equation 7) and is interpreted according to set up ranges in Table 7:

$$\overline{RI}_Q = \sum_{1}^{n} \frac{Q_{reinj\,i}}{Q_{abs\,i}} [\%] \quad (7)$$

3.7 Status of Water Balance Assessment

This indicator describes to which depth knowledge is available on the quantity status of the aquifer and the reliability of data on which these assessments are based on (Table 8). The need for reinjection 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 program is implemented by the competent authorities, which should combined and interpreted with data from users' active monitoring. Annual data for water balance assessments and regional hydrogeological evaluations should be analyzed every 3-6 years, since in this period the trends should become evident (Goldbrunner et al. 2007). Until regional numerical models are established, this monitoring scheme should be sufficient tool for granting new licenses and supervising existing ones. The indicator should be developed in the successive cumulative levels:

Table 8: List of points for status of water balance assessment.

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 and only one statement has to be selected and valued as a point for calculation of the indicator by Equation 8. The interpretation possibilities are given in Table 9.

$$I_{wba} = \frac{P_i}{N_{tot}} \cdot 100\ [\%] \tag{8}$$

Table 9: Evaluation of points based on the status of water balance indicator.

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

3.8 Over-abstraction (Status of the Aquifer Based on the Impact of Thermal Water Production)

This indicator provides information on the quantity status of the aquifer in strong connection with reinjection rate and water balance assessment indicators. Points for each geothermal object have to be assigned according to statements in Table 10, summed up according to Equation 9 and interpreted as suggested in Table 11.

Table 10: List of points for over-abstraction assessment.

Status of the aquifer based on the impact of production	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 are caused by thermal water production	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 groundwater production	Yes	1
	No	0

$$\bar{I}_{OE} = \frac{\sum_{i=1}^{n} I_i \cdot Q_i}{\sum_{i=1}^{n} Q_i} \tag{9}$$

Table 11: Evaluation of points based on the over-abstraction indicator.

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

3.9 Quality of Discharged Waste Thermal Water

All countries have legislation in which monitoring procedures and standards for the emitted waste (thermal) water are regulated, concerning direct emissions or indirect through sewage purifying plants. With this parameter we investigated how many 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 (Equations 10 and 11). Because this type of information was not collected during the survey of current utilizations, we could not test the applicability of this indicator in practice (Table 12).

$$I_{Qual\ ww\ i} = \frac{N_{positive\ i}}{N_{tot\ i}} \cdot 100\ [\%] \quad (10)$$

$$\bar{I}_{Qual\ ww} = \frac{\sum_{i=1}^{n} I_{Qual\ ww\ i} \cdot Q_i}{\sum_{i=1}^{n} Q_i}\ [\%] \quad (11)$$

Table 12: Evaluation of points based on the quality of discharged waste thermal water indicator.

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

3.10 Public Awareness - Accessibility of Reliable Information

Table 13: List of points for public awareness assessment.

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

Table 14: Evaluation of points based on the public awareness indicator.

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

For this indicator we overviewed companies' websites and media material, where we searched for (even very short) information on thermal water and/or geothermal energy use. We analyzed whether the material contained information (in the national language mostly) on geothermal objects, their monitoring, cascade use, efficiency, geothermal energy, thermal water, pollution, chemical analysis of thermal water, waste water management, reinjection, water level decline, aquifer, etc. (Table 13) and calculated the points according to Equation 12. The interpretation has to be performed as given in Table 14.

$$I_{inf} = \frac{\sum_{i=1}^{n} P_i}{N_{tot}} \quad (12)$$

Data for evaluation 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.

4. RESULTS AND DISCUSSION

4.1 Komárno-Štúrovo (Komárom-Párkány) Pilot Area

The Komárno-Štúrovo pilot area is situated in the northeastern part of the Transdanubian Range in Hungary and its basinal part in Slovakia (Figure 1). The main and most important aquifers (and hydrogeothermal reservoirs) are the Upper Triassic limestones and dolomites (Dachstein Limestone and Main Dolomite). The main users are baths in both countries in the northeastern part of the pilot area, who produce lukewarm (23-39 °C) water from the blocks close to the surface recharge area with fast water circulation. The subsided parts (<-1600 m asl) of the Upper Triassic carbonate aquifer are characterized by higher temperatures which accommodate the reservoir: the 40-60 °C water is produced by few wells utilized mainly for heating of greenhouses. The benchmarking assessment was based on an overview of 34 geothermal wells, 8 on the Slovakian and 26 on the Hungarian side. The reported values for utilization on the Slovak side were from 2009 and for the Hungarian side from 2011.

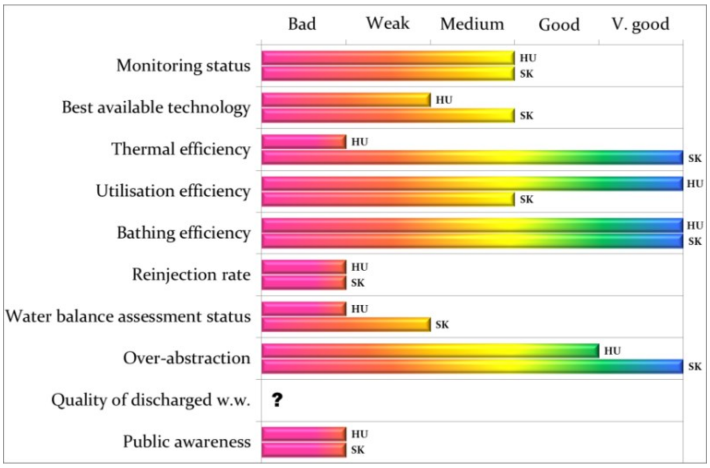

Figure 2: Benchmarking analysis of the Mesozoic carbonate thermal aquifer of the Komárno-Štúrovo pilot area.

The benchmarking comparison shows that the general management of geothermal aquifer has to be improved in both countries (Figure 2). The monitoring evaluation is based only on active wells and shows a medium category in both countries. It is based on reported production (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 karstic water level monitoring wells, as part of the "areal monitoring" can be found only in Hungary. Thermal efficiency shows bad status in Hungary, but this is due to the methodology applied which was developed for higher 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). 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). No reinjection wells have been drilled or commissioned, shown by the bad reinjection indicator. Nevertheless, the aquifers are not over-exploited yet as shown by a good indicator 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-appeared due to abandoning of the Tata mining area. Joint studies performed by the national geological institutes (surveys) and monitoring of the whole geothermal reservoir is advised. 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 not monitored.

4.2 Lutzmannsburg-Zsira Pilot Area

The Lutzmannsburg-Zsira pilot area is situated in the transboundary zone between Austria and Hungary (Figure 1). Balneology is an important part of regional economy. Extensive groundwater production exists for several decades. The majority (53%) of it happens from the Upper Pannonian aquifer, 9% from the Quaternary aquifers, while 3.5% is produced from the Sarmatian reservoirs. Production from the Devonian basement aquifers is 1.5% of total rates. 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. 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.

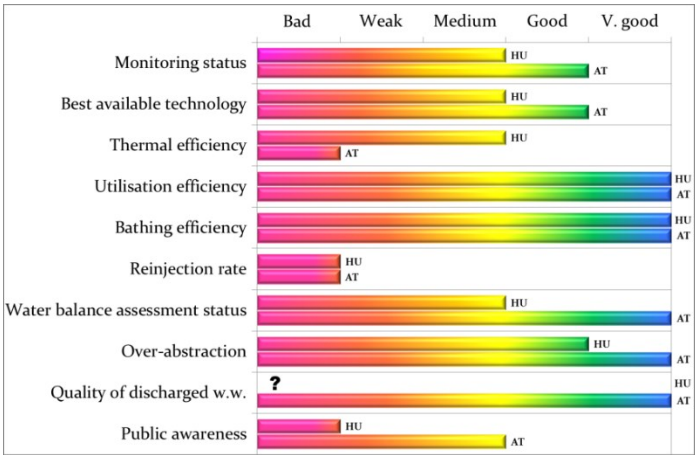

Figure 3: Benchmarking analysis of the Upper Pannonian, Lower Miocene and Devonian aquifers of the Lutzmannsburg-Zsira pilot area.

The benchmarking comparison shows that general management of the investigated transboundary geothermal reservoirs must be improved in both countries, but especially on the Hungarian side (Figure 3). The monitoring indicator of active wells is medium on the Hungarian side, while better value is reported for the Austrian side. In all cases, there monthly production values are annually reported. However, there is one monitoring well in Hungary providing continuous piezometric level measurements. As some of the Western Pannonian basin's most famous thermal spas and heath care centers are located in this region, many commercial developments have been made in the last 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. The extracted thermal water is used for different purposes within the spas, but cascade use of thermal water is not applied in Hungary. This utilization would improve the indicator of thermal efficiency, especially on the Hungarian side. In Austria, no temperature of effluent water is available and therefore thermal efficiency could not be calculated. 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. No reinjection wells have been drilled or commissioned. Recharge of geothermal water has been evaluated for Austria. Water balance calculations and the amount of maximum production rate were calculated for both major thermal spas on the Hungarian side, including the maximum allowed extraction. The indicator of over-abstraction shows good to very good status, but chemical changes may indicate the first signs of it for the Palaeozoic basement aquifer. No data on over-abstraction are reported on the Austrian side. 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 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 temperature and chemical composition of thermal water and their health benefits is available for the public on the Hungarian public websites.

4.3 Danube Basin Pilot Area

The Danube Basin pilot area is situated in Slovakia, Hungary and Austria, representing a large and very deep Tertiary basin (Figure 1).

There is a widespread utilization of thermal water from the Upper Miocene-Pliocene (Pannonian) intergranular aquifers, 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 water, however, this dominates on the Slovak side. Balneology is widespread on both sides. Although major deterioration in the quality and quantity status has not been identified, the extensive utilization has caused some temperature and pressure drops locally. For benchmarking, several evaluation criteria were set up to characterize geothermal water that is part of the regional transboundary flow of the Upper-Pannonian aquifer. Other geothermal water or wells in the marginal zones of the Danube Basin were not evaluated. The assessment is based on an overview of 31 geothermal wells, 18 on Slovakian side and 13 on Hungarian side. The reported values were from 2009 on Slovak side, and from 2011 on the Hungarian side.

The benchmarking comparison clearly shows that general management of the investigated geothermal aquifer has to be improved in both countries (Figure 4). The monitoring indicator of active wells is medium. This assessment is based on compulsory reported production (yield and temperature) data by the thermal water users on an annual basis with monthly reported values in both countries. Independent (passive) monitoring (observation wells) is not established in any of the countries. 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. Pumps with frequency converters are sometimes installed, while cascade usage of thermal water is not applied in Hungary. The main reason for medium thermal efficiency is the lack of use of cascade systems. 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. 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). No reinjection wells have been drilled or commissioned. Apart from a test of the reinjection rate in the intergranular environment in Slovakia, no additional steps have been made in this field. Recharge of geothermal water has been evaluated in a number of studies in Slovakia, focusing on the regional conditions for geothermal water circulation and water regime along with calculations of water sources and reserves. Periodic updates based on monitored data are not performed. The water balance calculations are not representative in the Hungarian side of the pilot area. The production rate is defined for most of the wells and is stated in water permits. The indicators of over-abstraction highlight a slight deterioration in the quantity status. 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, quality of waste water or energy efficiency are not available to general public and sometimes they are possibly not even monitored.

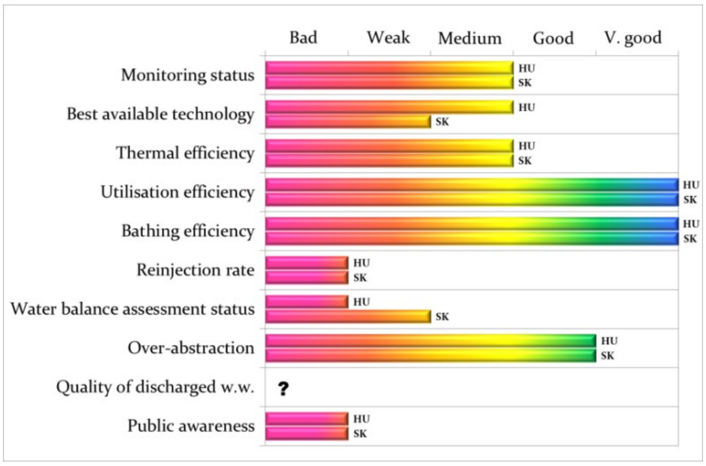

Figure 4: Benchmarking analysis of the Upper Pannonian thermal aquifer of the Danube Basin pilot area.

4.4 Bad Radkersburg - Hodoš Pilot Area

The Bad Radkersburg – Hodoš pilot area is situated along the national borders of Austria, Slovenia and Hungary (Figure 1). The Upper Miocene intergranular aquifer is exploited for balneological and agricultural use in Hungary. The water from the Middle Miocene sandstone aquifer is used for balneology. Exploitation of thermomineral water (72-78 °C) from the pre-Neogene basement aquifer occurs in the transboundary zone between Austria and Slovenia. The assessment 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. No wells exploit this aquifer in Hungary.

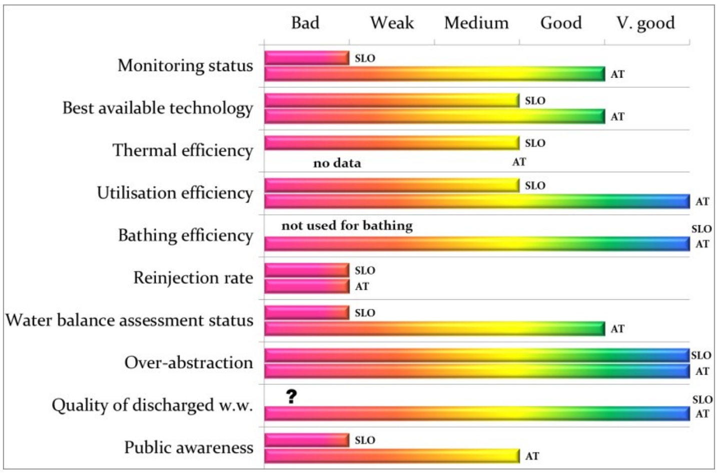

Figure 5: Benchmarking analysis of the pre-Neogene geothermal aquifer of the Bad Radkersburg-Hodoš pilot area.

The benchmarking comparison shows that management of the geothermal aquifer has to be improved in both countries, especially on the Slovenian side (Figure 5). 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. Thermal efficiency is medium 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. 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 wells do not have granted concession permits yet, and therefore we used the assumed amounts which may be demanded for. 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. 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. Information about exploitation of the resources is 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.

5. CONCLUSIONS

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 western part of the Pannonian Basin. In contrast to these positive results, the indicators on the reinjection 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 active geothermal wells is mostly medium or bad, which means that it is essential to develop monitoring systems for appropriate observation of geothermal aquifers. The information on quality of emitted waste water was not collected within this research and therefore this parameter could not be evaluated. The indicator values of best available technology vary between weak and good categories and the good values might only be due to a lack of reliable information, thus this is also a field for improvement. The geothermal aquifers are not yet over-exploited, 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 at least locally. Thermal efficiency indicator shows a bad or weak status in general, so the annual used heat energy 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 properly reflect the efficiency of the well. The status of water balance assessment is bad to medium in Hungary, Slovenia and Slovakia, so there is much to do in defining the critical level points and critical limits of thermal water production in all four countries, especially in those cases where the wells are located close to the national borders. The bathing parameter is planned to be further developed and to include effects on healing processes in the future.

Sometimes, the officially „inactive" wells do produce thermal water in practice but they do not have valid concessions/water licenses and therefore they could not be incorporated in the benchmarking evaluation due to lack of reliable information. Since they are important for joint resource management, they should be considered in future evaluation and when the developments of existing sites or new production licenses are requested. We also did not incorporate naturally discharging thermal waters (from springs) which are utilized only by ecosystems.

We believe that due to the positive effects on aquifer hydraulic conditions and mitigation of environmental pollution, reinjection into the same aquifer should be required for all users utilizing non-treated thermal water for production of geothermal energy. Limited time of derogation and appropriate financial support should be given to current users for the implementation of (new) reinjection wells, while new users should establish the necessary doublet system before starting production. Location and design of reinjection wells should be based on numerical simulation of aquifer capacities, appropriate technical design of reinjection wells and cost-benefit analyses, but poor economic conditions should not be used as an excuse for exemption.

We plan to continue developing the benchmarking methodology presented here for geothermal resource management, also expanding it to cover new transboundary sites. At the same time, we invite the readers to test this methodology on their cases and inform us about their experience and suggestions for improvement of the proposed benchmarking indicators.

ABBREVIATIONS

AT - Austria
F_u = utilization efficiency indicator (%)
HU - Hungary
i = individual geothermal object (production well or thermal spring)
$\bar{I}_{BAT}$ = indicator of BAT use
I_i = number of assigned points to a geothermal object i
I_{inf} = indicator of public awareness
I_{MON} = monitoring indicator
$\bar{I}_{OE}$ = indicator of over-abstraction
$\bar{I}_{Qual\ ww}$ = indicator of quality of discharged waste thermal water (%)
$I_{Qual\ ww\ i}$ = share of samples which meet the requirements for emitted waste water quality of a geothermal object i (%)
I_{wba} = indicator of water balance assessment status (%)
mD – milidarcy is a unit of permeability of rocks, 1 mD is equivalent to 9.869233×10^{-16} m²
$N_{positive\ i}$ = total number of positive samples (which meet the waste water emission requirements) per year of a geothermal object i
N_{tot} = total number of geothermal objects on the basin level in the investigated country
$N_{tot\ i}$ = total number of taken chemical samples per year of a geothermal object i
η_i = thermal efficiency of a geothermal object i without applied reinjection (%)
$\eta_{r\ i}$ = thermal efficiency of a geothermal object i with applied reinjection (%)
P_i = number of assigned points to a geothermal object i
Q_i = annual production rate of a geothermal object i (m^3/y)
$Q_{abs\ i}$ = annual production rate of thermal water of a geothermal object i used solely for geothermal heat production (m^3/y)
$Q_{cap\ i}$ = installed capacity of a geothermal site i ($\approx$ maximum allowed annual production as defined in water permit) (m^3/y)
$Q_{reinj\ i}$ = annual reinjection rate of thermal water of a geothermal object i used for geothermal heat production (m^3/y)
$Q_{ww\ i}$ = annual discharge rate of waste thermal water of a geothermal object i (m^3/y)

$\overline{RI_Q}$ = indicator of reinjection rate (%)
SI - Slovenia
SK - Slovakia
TE = indicator of thermal efficiency (%)
T_o = average annual air temperature at a geothermal site, e.g. 12 °C
T_{out} = temperature of waste thermal water at an individual geothermal site (°C)
T_{whd} = outflow temperature of a geothermal object i (at the wellhead of a well or at a spring) (°C)
y = year

ACKNOWLEDGEMENT

The TRANSENERGY project was co-financed by the European Union Central Europe Program 2007-2013 (Contract No. 2CE124P3). Some authors are members of the SI ARRS Program P1-0020-0215 Groundwaters and Geochemistry.

REFERENCES

Axelsson, G. and Gunnlaugsson, E.: Course on long-term monitoring of high- and low- enthalpy fields under exploitation, *Proceedings*, World Geothermal Congress, Short Courses, IGA, Kokonoe-Kyushu (2000).

Dövényi, P. and Horváth, F.: A review of temperature, thermal conductivity and heat flow data form the Pannonian Basin, In: Royden, L.H., Horváth, F. (Eds): The Pannonian Basin a Study in Basin Evolution, *American Association of Petroleum Geologist memoirs*, Tulsa, Oklahoma, **45**, (1988), 195-233.

Goldbrunner, J., Shirbaz, A. and Heiss, H.P.: Wasserwirtschaftliche Bewertung der Thermalwassernutzungen in Oberösterreich, *Berichtszeitraum 2000-2005*, Wasserwirtschaft (2007).

Horváth, F. and Royden, L.H.: Mechanism for formation of the intra-Carpathian basins: A review, *Earth Evolutionary Sciences*, **1**, (1981), 307-316.

Lachavanne, J-B. and Juge, R.: LEMANO, pour une gestion durable de l'eau, *Lemaniques, revue de L'association pour la sauvegarde du Léman,* **72**, (2009).

Magyar, I., Geary, D.H. and Müller, P.: Paleogeographic evolution of the Late Miocene Lake Pannon in Central Europe, *Palaeogeography, Palaeoclimatology, Palaeoecology*, **147**, (1999), 151-167.

Prestor, J., Nádor, A. and Lapanje, A.: Methodology for joint groundwater management, final report, http://transenergy-eu.geologie.ac.at/, (2012).

Rman, N.: Database of users, Database of current and potential utilization parameters, final report, http://transenergy-eu.geologie.ac.at/, (2011).

Rman, N., Fuks, T. and Kumelj, S.: Utilization maps, final report, http://transenergy-eu.geologie.ac.at/, (2011).