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The upper pannonian thermal aquifer: Cross border cooperation as an essential step to transboundary groundwater management

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ABSTRACT

Study Region: Pannonian Basin, Central and Eastern Europe.
Study focus: This study, carried out by the geological surveys of Hungary, Slovenia, Austria and Slovakia, combines a joint characterization of a transboundary thermal groundwater system based on harmonised geological and hydrogeological data, with hydrodynamic modelling, delivering recommendations for authorities and policy makers on how they could improve the long term management of thermal groundwater. A porous, intergranular, multi-layered, Upper Pannonian aquifer system was the focus of this investigation. This deep sedimentary basin, up to 8000 m deep, has favourable conditions for geothermal exploitation, with centuries old thermal water usage and plans for increased utilization in all countries.
New hydrological insights for the region: Cross border areas with significant transboundary flow rates were identified, which have decreased due to thermal water production, with flow direction reversal across the Hungarian-Slovakian border. Thermal water production causes significant transboundary effects with depression cones that can penetrate several tens of kilometres into the neighbouring countries. Simulated drawdowns at the state borders are in the range of 2–10 m. Thermal water should therefore be exploited using doublets.

Nine benchmark indicators (monitoring status, best available technology, thermal efficiency, utilisation efficiency, re-injection rate, quality of discharged thermal water, over-abstraction, status of water balance assessment, public awareness) were defined and tested at different transboundary regions and are demonstrated to be highly effective in groundwater management.

Abbreviations: F_u, utilization efficiency indicator (%); i, individual geothermal object (production well or thermal spring); I_{BAT}, indicator of BAT use; Ii, number of assigned points to a geothermal object i; I_{inf}, indicator of public awareness; I_{MON}, monitoring indicator; I_{OE}, indicator of over-abstraction; I_{Qualww}, indicator of quality of discharged thermal waste water (%); $I_{Qualwwi}$, share of samples which meet the requirements for emitted thermal waste water quality of a geothermal object i (%); I_{wba}, indicator of water balance assessment status (%); $N_{positivei}$, number of positive chemical samples taken per year of a geothermal object i; N_{tot}, total number of geothermal objects on the basin level in the investigated country; N_{toti}, total number of chemical samples taken per year of a geothermal object i; η_i, thermal efficiency of a geothermal object i without applied re-injection (%); η_{ri}, thermal efficiency of a geothermal object i with applied re-injection (%); Pi, number of assigned points to a geothermal object i; Q_i, annual production rate of a geothermal object i (m^3/y); Q_{absi}, annual production rate of thermal water of a geothermal object i used solely for geothermal heat production (m^3/y); Q_{capi}, installed capacity of a geothermal site i (≈ maximum allowed annual production as defined in water permit) (m^3/y); Q_{reinji}, annual re-injection rate of thermal water of a geothermal object i used for geothermal heat production (m^3/y); Q_{wwi}, annual discharge rate of waste thermal water of a geothermal object i (m^3/y); RI_Q, indicator of re-injection rate (%); TE, indicator of thermal efficiency (%); T_o, average annual air temperature at a geothermal site (°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

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1. Introduction

The transboundary survey of the aquifers in the Western part of the Pannonian Basin was a result of the determination of hydrogeologists and earth scientists to jointly investigate all natural resources, not only those which are visible on the surface, but also those which are hidden from our eyes. This cooperation dates back to the end of the 1980s (Császár, 2000), and became stronger from the middle of the first decade of the 21st century (Brezsnyánszky et al., 2008; Malík et al., 2012). Although several bilateral commissions exist in the region, their work focuses mainly on surface water issues and very little has been done in connection with groundwater. Following the economic and political changes in central Europe, in the late 80s, and after a downturn in the use of water and energy, private companies started to flourish. A boom in thermal spa and greenhouse developments started. At the same time it became clear that an increase in groundwater abstraction would follow (Rman et al., 2015). According to their Renewable Energy Action Plans (NREAPs) most of the Central European countries, but especially of Hungary, Slovenia, Austria and Slovakia planned a 3–3.5 fold increase in their geothermal heat production from 2010 to 2020 (COM (2015)293). In order to implement these ambitious goals it was essential to properly survey the aquifers and hydrothermal reservoirs, and get familiar with their physical and chemical characteristics. The quantitative and qualitative assessment of aquifers, independent of national borders, is also important in the framework of groundwater body status assessment within the River Basin Management Plans required by the 2000/60/EC Water Framework Directive (WFD).

The first joint transboundary aquifer management plan in the Pannonian Basin dealing with the Hungarian-Slovenian porous intergranular thermal aquifer, "Thermal Joint Aquifer Management (T-JAM)" (Nádor et al., 2012) was formulated within a Hungarian-Slovenian INTERREG IIIA project.

In order to support the sustainable management and further developments based on the use of transboundary thermal aquifers in the Western part of the Pannonian Basin, the geological surveys of Hungary, Slovenia, Austria and Slovakia jointly delineated (Fig. 1) and characterised potential geothermal aquifers (Rotár-Szalkai et al., 2017), their exploitation (Rman et al., 2015), carried out 3D hydrodynamic modelling (Tóth et al., 2016), and defined nine benchmarking indicators (Prestor et al., 2015). They also prepared a white paper for a harmonised management strategy for the sustainable utilisation of thermal water and geothermal energy, taking into account the goals of WFD and NREAP. The work was carried out within the framework of the Transboundary Geothermal Energy

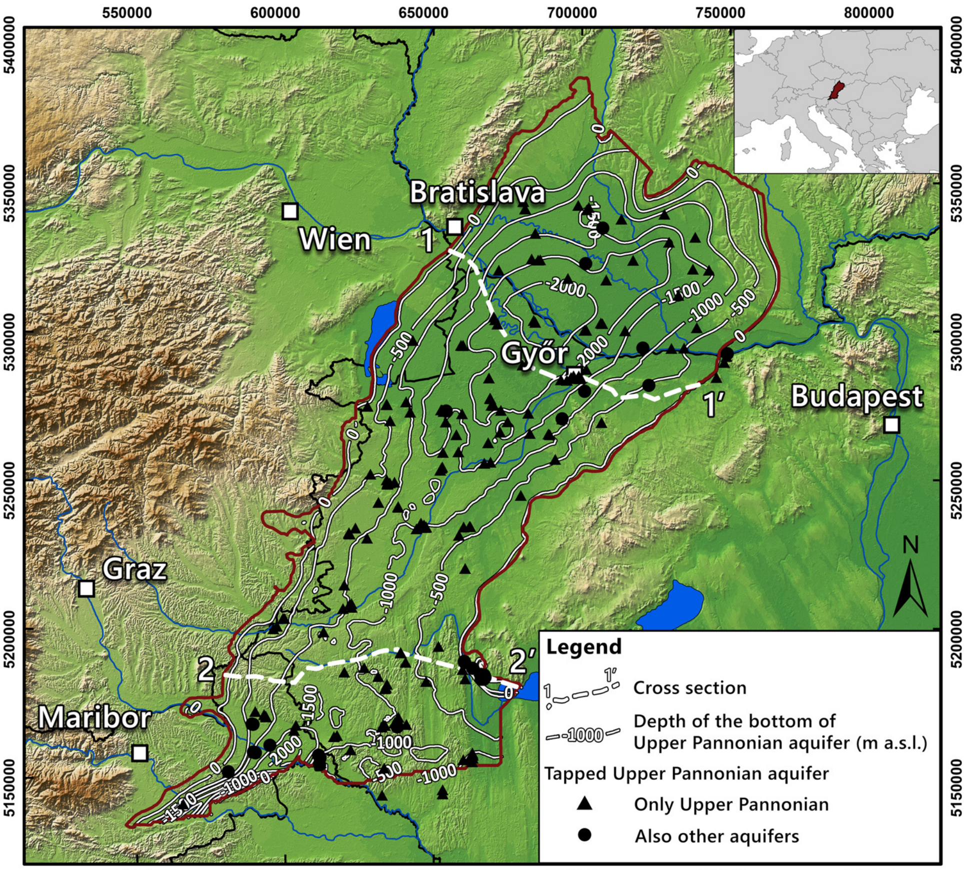

Fig. 1. Regional setting and delineation of the Upper Pannonian Transboundary Thermal Aquifer (UPTTA) with production wells and tapped aquifers.

Table 1
Comparison of European water management and energy policies (after Nádor et al., 2013a).

Compared topic	Water policy (2000/60/EC)	Renewable Energy Policy (2009/28/EC)
target	groundwater within aquifer, groundwater body	heat energy stored in the subsurface space
objective	achieving and/or maintaining good (quality and quantity) status of groundwater	increase the proportion of RES/geothermal usage
framework	Water Framework Directive, national River Basin Management Plans (groundwater body delineation and status assessment, monitoring)	National Renewable Energy Strategy and NREAP (programmes of actions and incentives)
responsible governmental bodies	ministries for environment and water	ministries for energy and economics
time frame	2009–2015 – 2021–2027 – onward	2010–2020 – 2030

Resources of Slovenia, Austria, Hungary and Slovakia (TRANSENERGY) project within the Central European programme (Nádor et al., 2013a). The delineated Upper Pannonian Transboundary Thermal Aquifer (UPTTA) is one out of the 199 aquifers incorporated into the comparative assessment of transboundary aquifers within the continuation of the Transboundary Waters Assessment Programme (TWAP). This work was not part of the Internationally Shared Aquifer Resources Management (ISARM) initiative, a UNESCO and IAH led multi-agency programme, aimed at improving the understanding of scientific, socio-economic, legal, institutional and environmental issues related to the management of transboundary aquifers, but follows its main concepts. This paper presents the results of the joint work related to the Upper Pannonian multi-layered thermal aquifer.

1.1. Policies related to the use of aquifers in the involved countries and their consequences

Beside national legislation, the exploitation of aquifers in the European Union has to be carried out in the context of two main policies, the Water policy and the Energy policy. Although they both deal with issues related to aquifers, they have competing interests. The European framework of the water policy is in line with the WFD and targets the groundwater within the aquifer, focusing on the protection of the resource. The energy policy (2009/28/EC on Renewable Energy Directive) focuses on the maximum utilisation of resources by using the heat energy stored in the subsurface space, in line with the target numbers of the National Renewable Energy Action Plans (NREAP). While the water policy's objective was to achieve and maintain the good qualitative and quantitative status of (ground)water by 2015, or under some required conditions in the second or third management cycle in 2021 or 2027 respectively, the energy policy aims to increase to the proportion of the renewable energy source, namely geothermal energy, within the energy portfolio. Not only the objectives, but also the measures and the time-frames of achieving these objectives are different (Table 1).

A review of legislation in the four countries (Lapanje and Prestor, 2011) shows the following:

- geothermal resources are owned by the state, except in Austria, where they belong to the land-owner;
- geothermal resource management is divided between ministries of environment and water dealing with abstraction of thermal groundwater, and ministries of energy/industry/economics/national development controlling the geothermal energy utilization without groundwater production or dealing just with the heat extraction of thermal water (e.g. geothermal doublets);
- the most permissive regulatory framework is in Austria, where even the energy content of the thermal water is not acknowledged in the legislation, while the most integrated legislation exists in Slovakia controlled by the Geological Act;
- abstraction of thermal water is based on a water license in all four countries. However, there is currently an initiative (April 2017) for the modification of the Hungarian Water Management Law (57/1995) which if accepted would allow groundwater abstraction without any licencing and even any reporting of the abstraction up to a depth of 80 m below surface in the case of household supplies. In Hungary, a geothermal concession is needed for deep geothermal energy usage (more than 2500 m below surface). These areas are closed for geothermal energy exploitation and such an exploitation request cannot be directly submitted to the authority, but the investor can initiate a request at the Hungarian Office for Mining and Geology in order for a concession to be prepared. If the ministry accepts that the area can be used for exploitation, than the investors can apply for a concession based on an open tendering.
- re-injection of the abstracted thermal water for energy use is compulsory in Slovakia, Slovenia and Austria, however this is mostly defined in individual water permits. While compulsory for Slovenia, it is not actually achieved in practise at existing energy use sites (e.g. greenhouses). The Hungarian legislation was changed from requested re-injection to a non-compulsory approach in 2013. Since then, used thermal water can be re-injected, also defined on a case-by-case basis, which means there is no re-injection in most cases. In Slovenia, the use of doublets is obligatory if granted a licence by the Mining Act, but, since 2015, the re-injection provides lower concession fees also for new licences granted according to the Water Act.
- temperature and chemical thresholds for emitting used thermal water into surface water or aquifers are strictly regulated in all four countries;
- monitoring of inspected wells is carried out in all four countries. However the extent, the measured parameters and their frequency, and the organisations responsible for the monitoring and reporting, are very different. In accordance with the WFD in Hungary, there are also wells operating specially for (thermal) groundwater body monitoring.

1.2. Financial supporting schemes

A review of available financial support (Nádor et al., 2013b) revealed that there are a number of options to obtain subsidies, funds and loans from the World Bank, the European Investment Bank, and various international banks. These can be used mainly for funding the drilling of exploration/production wells, or activities such as establishing and running district heating facilities. In some cases the Danube Transnational Programme and state budgets are also available.

Tax incentives are currently not available for producers of green electricity from geothermal sources, except for Slovakia. Geothermal energy in theory would benefit from this exemption if there were any geothermal power plants. The Hungarian and Slovakian NREAP-s foresee geothermal-based electricity in production by 2020 (Slovenia does not), so feed-in-tariffs may become relevant.

The current Austrian feed-in-tariff for geothermally produced electricity is too low to promote any further investment. Geothermal energy as currently produced is mostly suitable for direct heat utilization such as district heating. Indirect support schemes for renewable energy-related operative programmes in Hungary, Slovakia and Slovenia, have been financed by the Structural and Cohesion Funds. These EU funds have provided an average of 50% up to 85% financing of geothermal projects, with a total support in the range of 100 million €. The beneficiaries were typically SME-s, larger companies, non-profit organizations, private companies, and municipalities. Risk insurance as one of the most important supporting instrument for geothermal energy is not available in any of the four countries.

2. Geographical and geological description of the Upper Pannonian Transboundary Thermal Aquifer

The Upper Pannonian Transboundary Thermal Aquifer (UPTTA) extends from NE Slovenia to SW Slovakia, over an area of approximately 20,300 km^2. The entire area is located in the Danube River drainage basin, within the Pannonian Basin. Lowlands of the Mura-Zala, Styrian, Vienna and Danube basins rarely extend to elevations of 300 m a.s.l. and the landscape is rural with only a few middle-sized cities, (population mostly between 60,000 and 130,000) present. The humid, temperate climate results in a decrease in precipitation from about 1500 mm in the south-west to 500 mm in the north-west, with some local variations related to topography.

The basement of the Pannonian Basin consists of Paleozoic and Mesozoic crystalline rocks and carbonates. Paleogene siliciclastic and andesitic rocks, and Neogene and Quaternary sediments were deposited on it. Displayed in the Neogene sequence, the processes connected with the infilling of the huge inland Lake Pannon resulted in the formation of the UPTTA. The lake was formed approximately 12 million years ago and deepened until 9.8 million years ago. Sub-basins were filled rapidly by huge siliciclastic deltaic systems of the Alpine and the Carpathian rivers (Magyar et al., 1999). The bottom of the UPTTA is mostly formed by the turbiditic silt and argillaceous marl that were deposited on basin slopes. Simultaneously, the delta front environment evolved into a prograding shelf resulting in deposition of thick sand bodies. The UPTTA was delineated based on lithostratigraphy and is formed by the Upper Pannonian delta front sand and poorly-lithified sandstone which generally extends to depths between 500 and 2000 m (Fig. 1). The sand prone units are mostly composed internally of individual delta lobes of few tens of meters in thickness and separated by pelitic layers (Nádor et al., 2012). The UPTTA is overlain by fine-grained Pontian and Quaternary delta and alluvial plain sediments, representing the latest stages of the sub-basin filling.

3. Hydrogeological description of the Upper Pannonian Transboundary Thermal Aquifer

The Upper Pannonian multi-layered delta front sediments reach a total thickness of more than 2000 m, averaging about 800 m. The effective aquifer thickness, which comprises the sandy sequence, is estimated to be about 300 m if intercalated fine-grained sediments are excluded as aquitards. The UPTTA sands are heterogeneous and anisotropic. The horizontal hydraulic conductivity varies between approximately 4.0E–06 and 5.0E–05 m/s while the vertical hydraulic conductivity varies between approximately 6.0E–10 and 7.0E–08 m/s. The effective porosity is estimated to up to 30%.

The regional groundwater flow system has evolved in these sands and locally, especially along faults, density and heat-driven flows may interfere with gravitational flows. However, no convection cells are yet discovered in this porous geothermal aquifer. A clear distinction between this regional flow system and the shallower intermediate flow system in the Upper Pannonian delta plain and deeper Quaternary sediments can be made, also based on hydrogeochemistry. The stratification of groundwater shows that moderately mineralized (up to 2000 mg/l TDS) water of Na-HCO_3 type is stored in the UPTTA. This infiltrated during the Pleistocene (Szőcs et al., 2013; Rman, 2016), probably during the last interglacial period.

Meteoric water which recharges the aquifer infiltrates through outcrops at the sub-basin margins, and percolates through overlying layers. However, it can be shown that the recharge is very slow and limited, based on hydrogeological investigations which fail to show any significant annual difference in terms of volume and frequency of recharge (Tóth et al., 2016) with groundwater residence time of several ten thousand years.

The regional, natural groundwater flow in the natural state occurs in two main directions (Figs. 2, 4 and 5). In the south of the UPTTA the infiltrated water percolates along the strata approximately from west to east, so from Slovenia and Austria towards the discharge area of the Hévíz and Balaton Lakes in Hungary. In its northern part, the prevalent flow direction occurs from the north-east to south-west, from Slovakia to Hungary with discharge along the Danube River.

Since the Pannonian Basin is located above a positive geothermal anomaly with an average heat flow of 100 mW/m^2 (Hurter and Haenel, 2002; Lenkey et al., 2002), elevated groundwater temperatures up to 100 °C are recorded in the deepest part of the UPTTA.

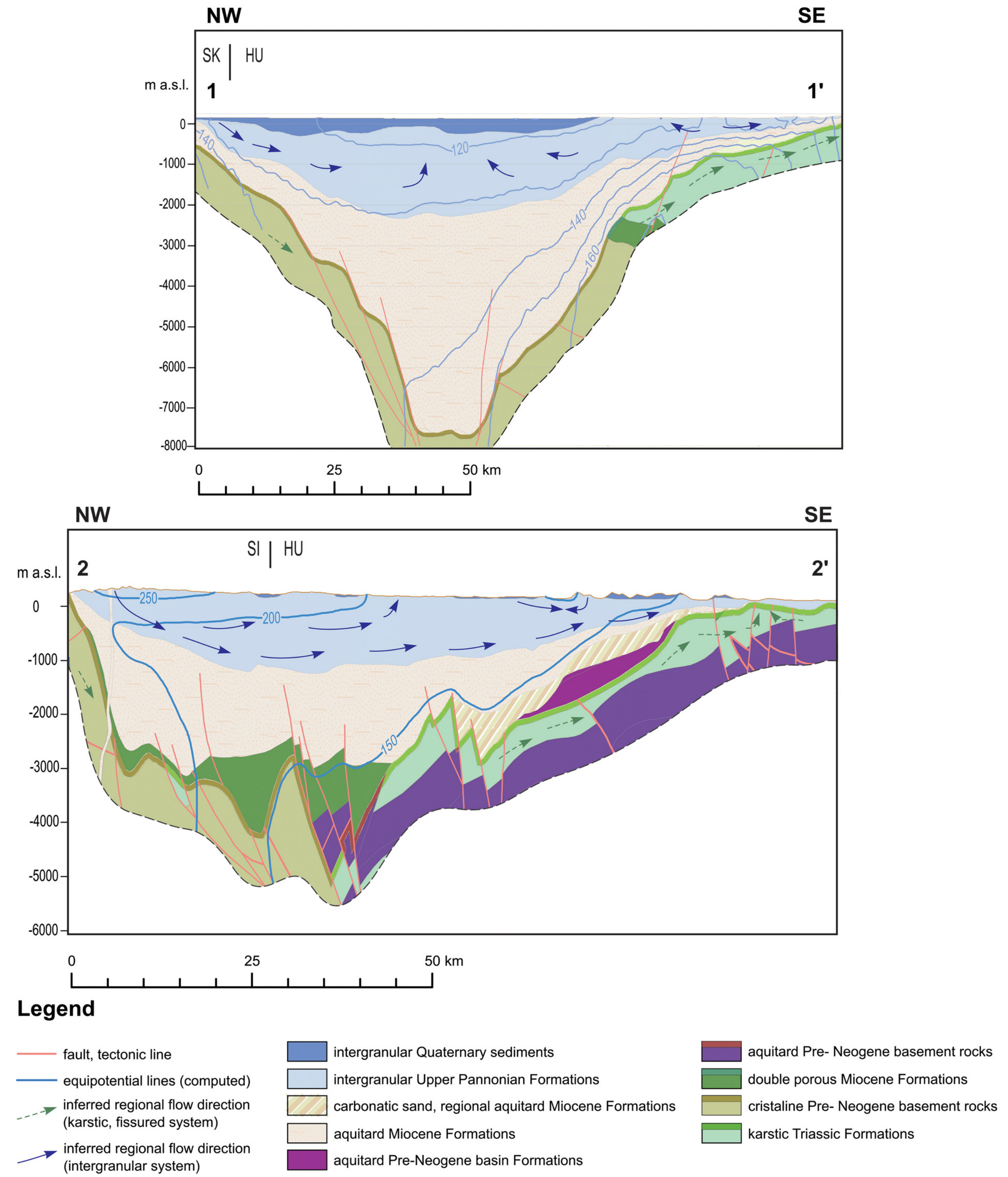

Fig. 2. Transboundary, hydrogeological cross sections (1–1′; 2–2′) of the UPTTA. Position of the cross section is shown in Fig. 1.

The average heat flow in the part of the Pannonian Basin under investigation is 75–80 mW/m^2 (Goetzl et al., 2012). Temperatures below 80 °C prevail in most of the aquifer and thermal water only rarely exceeds 60 °C at the wellhead (Fig. 3).

As many as 225 geothermal wells were identified in the area (Fig. 1), having screen intervals up to about 2400 m below surface. Mostly they tap only the UPTTA (Fig. 1), but 13% of wells terminate in the aquifer below due to a need for higher water temperatures or more mineralized water. The hydraulic conditions result in an observation that 13% of wells, almost exclusively in Slovakia, are still producing without submersible pumps (Fig. 3), while at least 70% of the total needs pumps. Of the 225 wells, about 64% were

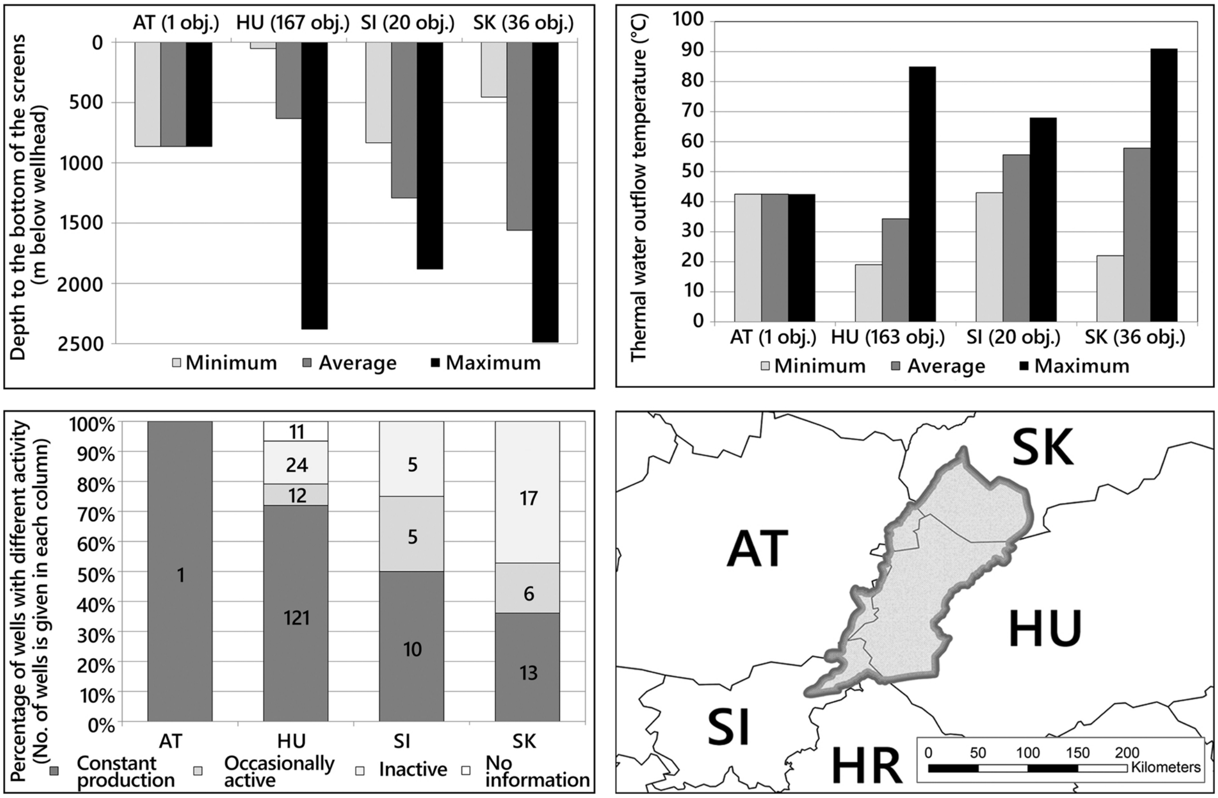

Fig. 3. Thermal water outflow temperature, depth to bottom of screen and percentage of wells according to their activity in the four countries of the UPTTA.

constantly in production (Fig. 3), an additional 10% occasionally produced, while no information was available for the remaining wells. Only three re-injection wells were identified in the region (Fig. 3), one in each country except Austria. However, only the one used for a district heating system in Lendava in Slovenia was active at the time of this investigation.

4. 3D hydrodynamic modelling to help understanding the flow systems

In order to better characterise and quantify the cross-border flows in the studied aquifer system and to evaluate the potential effects of current and future groundwater abstractions, a 3D hydrodynamic model was set up using the USGS MODFLOW v.2011 code. The model has an aerial extent of 283 km x 314 km and extends to a depth of 8 km, having a 1 km × 1 km cell size. It took account of the heterogeneity and anisotropy of the seven hydrostratigraphic units which were introduced into the numerical model as 11 layers. These units are: Quaternary unconfined aquifers, deeper Quaternary confined freshwater aquifers, Upper Pannonian confined freshwater and thermal aquifers, Lower Miocene to Lower Pannonian aquitards, weathered and/or karstified basement containing thermal aquifers, and low permeability, unweathered basement rocks.

The UPTTA was represented as layer No. 6, the Upper Pannonian confined geothermal aquifers. Three steady state model scenarios were prepared, starting from the natural state in the 1960s with no groundwater production (see Fig. 4), to application of the average annual production rate based on the production from 2007 to 2009, to a five times increased production rate for a forecast model (Fig. 5). No freshwater production was included in the model. Both production scenarios were further subdivided into five sub-scenarios to evaluate the effects of production by each country, and combined. The natural state model was not calibrated as it was developed by deducting the thermal water abstraction rates from the calibrated steady state production model with applied average 2007–2009 production rates. Previous research and hydrodynamic modelling provided cross-border information on the extent of use of the Upper Pannonian thermal aquifer between Hungary and Slovenia (Nádor et al., 2012), but this was a very new, regional wide approach. The results of modelling were used to evaluate the present and potential future aquifer depletion as one of the most important factors in long term sustainable use of thermal water and geothermal systems (Rybach, 2003; Rman et al., 2016). A detailed description of the setup of the hydrodynamic model and the results of the modelling is presented by Tóth et al. (2016).

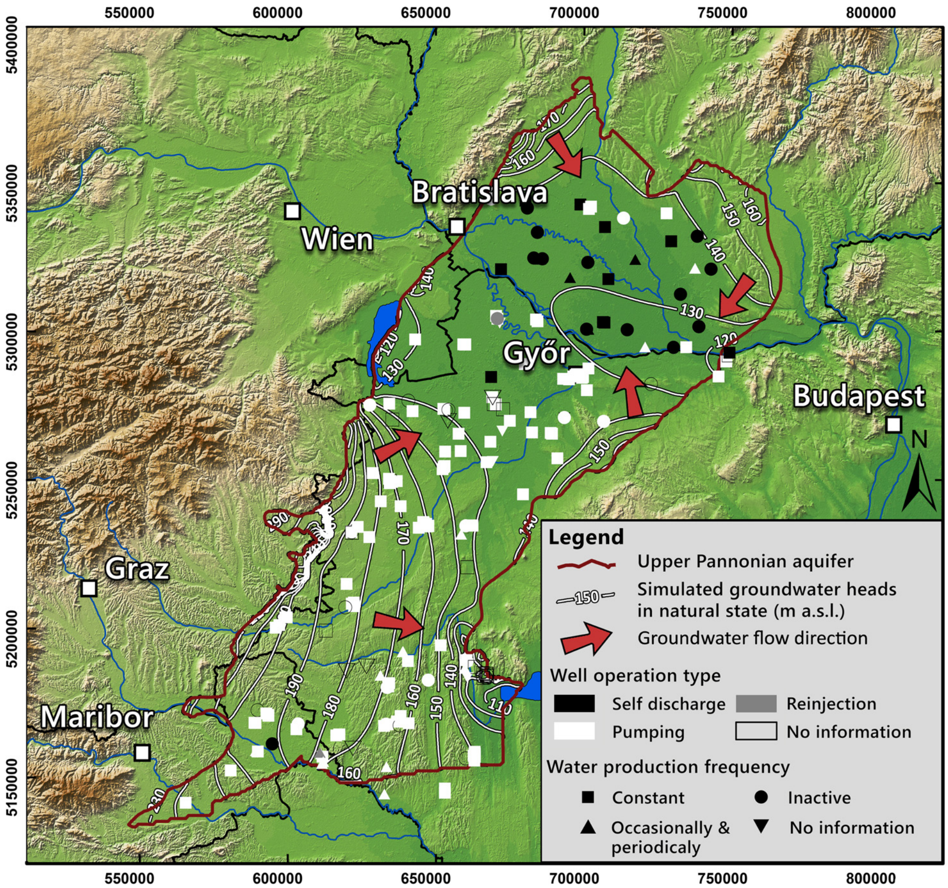

Fig. 4. Simulated steady-state hydraulic head distribution in the Upper Pannonian thermal water aquifer in the natural state (no thermal water production). Information about the well operation type and production frequency is also given.

4.1. Results of scenario modelling

4.1.1. Model scenario 1: natural (1960s) steady state situation

In the pre-production state the regional thermal water flow direction was from west to east in the southern part of the UPTTA (Fig. 4), from SW to NE in the southern part of the Danube basin, and from NE to SW in its northern part. The hydraulic heads ranged from approximately 220–110 m a.s.l. Major discharges occurred west of Lake Balaton and near Győr (HU), and south east of Lake Neusiedl (AT) (Tóth et al., 2016).

4.1.2. Model scenario 2: average annual production rate based on abstraction in the period 2007–2009

The average production is the following: 4628 $m^3 day^{-1}$ for 21wells in south–west Hungary, 5854 $m^3 day^{-1}$ for 19 wells in north–west Hungary, 5336 $m^3 day^{-1}$ for 17 wells in Slovenia, 0 $m^3 day^{-1}$ for Austria having no geothermal wells, and 7726 $m^3 day^{-1}$ for 27 wells in Slovakia.

Thermal water production simulated extensive drawdowns around major production sites, with values exceeding 20 m at production wells. The total regional drawdown is modelled to be between 2 and 10 m respectively (Fig. 5) across the cross-border region of the UPTTA. The drawdown cone, exceeding 0.5 m extends as far as about 60 km in the neighbouring countries. The simulated cross-border drawdowns are different at different locations (Fig. 5). The Slovenian production causes a drawdown of approximately 6 m at the SI-HU border, the production in SW Hungary causes a drawdown of approximately 2 m at the SI-HU and AT-HU borders, the production in NE Hungary causes a drawdown of 2.5 m at the SK-HU border and about 2 m at the AT-HU border, while the Slovakian production causes a drawdown less than 1.5 m at the AT-SK border and 3 m at the SK-HU one. The most affected areas are the Mura-Zala and the Danube basins with total simulated drawdown of about 10 m and 6 m, respectively. If freshwater production was taken into account, the drawdown is expected to be at least a few meters more. It should be mentioned that thermal water production increased in the last years compared to this 2007–2009 period.

4.1.3. Model scenario 3: forward modelling based on 5-fold increase in production compared to 2007–2009

A five-fold increase in total production would cause the drawdowns to increase to over 40 m at the SI-HU border, 20 m at the

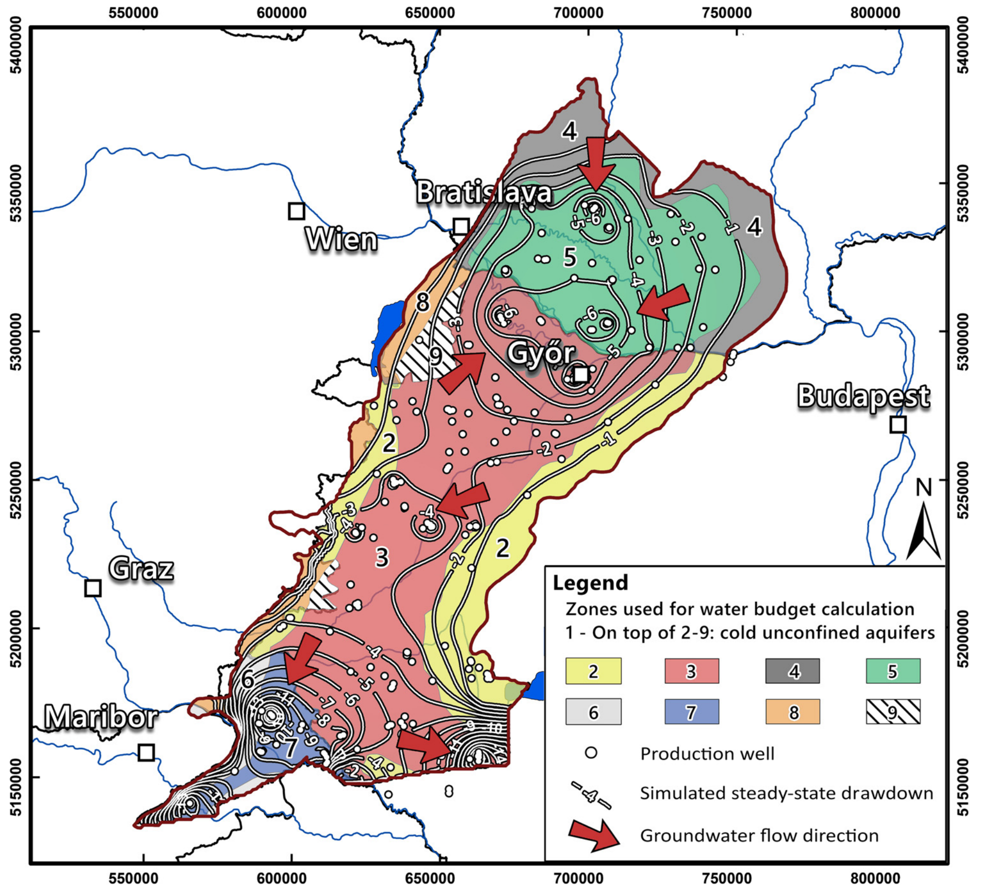

Fig. 5. Simulated steady state groundwater drawdown in the Upper Pannonian thermal aquifer caused by the average thermal water production in the period 2007–2009 in all countries together. Zones used for water budget calculation, locations of production wells and measured outflow temperature are also shown.

southern AT-HU border, 15 m along the AT-HU border to the north, and 30 m at the HU-SK border. It would also open new flow paths between Hungary and Slovakia and lead to a severely increased flow from Austria to Hungary.

The whole UPTTA is covered by the Quaternary unconfined freshwater aquifers (e.g. zone 1 in Fig. 5). Additionally, fresh and thermal water aquifers were distinguished in each country in order to interpret the changes in the water budget due to the regional thermal water production. Simulation shows that thermal aquifers received 86,910 m^3/day recharge in the pre-exploitation state (Table 2). Production has induced recharge from shallow confined aquifers to the thermal aquifers by 13,060 m^3/day and decreased thermal water discharge to unconfined ones by 170 m^3/day, while between thermal aquifers there is a recharge of 24,980 m^3/day (Table 3).

Cross-border flows have been changed due to thermal water production in several ways, generally leading to a reduction in the flows (Table 2). The natural thermal water budget was positive for Austria regarding Hungary, but production has decreased the surplus to only 60 m^3/day. A five-fold increase in production could reverse the flow direction (Tóth et al., 2016). Existing production has resulted in establishment of a new flow connection – discharge from the Slovakian thermal water into the Austrian confined freshwater aquifer has occurred at 6 m^3/day and can increase with higher production rates, e.g. five-fold increase in rates. The thermal water budget between Slovenia and Hungary was strongly positive in the direction of Hungary (3930 m^3/day) in the natural state. Thermal water production has reduced both the freshwater flow rate to Hungary by 8% and the thermal water flow rate by 24%, to about 2980 m^3/day. Increased production would actually change the flow direction towards Slovenia for fresh and thermal waters. The natural thermal water budget from Slovakia to Hungary was about 6000 m^3/day in the pre-production period. Thermal water production has caused a reversal of transboundary flow, which based on the average abstractions between 2007 and 2009 leads to a surplus of 2140 m^3/day for Slovakia. This volume would increase if production increases.

5. Benchmarking – a tool for thermal aquifer assessment and management

In order to ensure a long term sustainable management of transboundary or even national (geothermal) aquifers, an easy to apply and objective method is required which can uniformly be applied in the neighbouring countries. In addition to this the method has to

Table 2
Water budgets of the Upper Pannonian transboundary thermal aquifers according to the pre-exploitation model scenario l. (taken from Tóth et al., 2016).

From → To [m^3/d]	Quaternary freshwater unconfined (1)	HU freshwater confined (2)	HU thermal (3)	SK freshwater confined (4)	SK thermal (5)	SI freshwater confined (6)	SI thermal (7)	AT freshwater confined (8)	AT thermal n (9)
Quaternary freshwater unconfined (1)	–	101,410	0	63,250	0	15,330	/	24,180	/
HU freshwater confined (2)	144,660	–	30,470	3410	60	9170	1	6570	90
HU thermal (3)	330	36,700	–	170	2560	550	2720	170	2690
SK freshwater confined (4)	73,620	610	100	–	16,960	/	/	150	/
SK thermal (5)	180	130	8560	20,510	–	/	/	0	/
SI freshwater confined (6)	14,540	9800	440	/	/	–	11,690	460	/
SI thermal (7)	/	0	6650	/	/	8360	–	/	/
AT freshwater confined (8)	10,840	22,320	390	390	2	910	/	–	1570
AT thermal (9)	/	60	1960	/	/	/	/	2480	–

Names of the countries are abbreviated as following: HU – Hungary, SK – Slovakia, SI – Slovenia, AT – Austria. Slash stands for no connection between aquifers. Numbers in brackets denote zones in Fig. 5.

Table 3
Change in the water budget due to production based on the average production between 2007 and 2009. (taken from Tóth et al., 2016).

From → To [%]	Quaternary freshwater unconfined (1)	HU freshw. confined (2)	HU thermal (3)	SK freshw. confined (4)	SK thermal (5)	SI freshw. confined (6)	SI thermal (7)	AT freshw. confined (8)	AT thermal (9)	Thermal wells [m^3/d]
Quaternary freshwater unconfined (1)		9	0	4	0	12	/	9	/	0
HU freshwater confined (2)	-12		18	2	17	-1	100	-2	0	495
HU thermal (3)	-33	-26		-12	30	-31	-3	-12	-4	9,981
SK freshwater confined (4)	-9	-5	10		20	/	/	40	/	237
SK thermal (5)	-33	-23	-86	-26		/	/	>>100	/	7,488
SI freshwater confined (6)	-18	-1	-11	/	/		24	0	/	88
SI thermal (7)	/	0	-15	/	/	-22		/	/	5,038
AT freshwater confined (8)	-19	3	41	31	-100	20	/		18	0
AT thermal (9)	/	-33	28	/	/	/	/	-32		0

Names of the countries are abbreviated as following: HU – Hungary, SK – Slovakia, SI – Slovenia, AT – Austria. Applied production rates are listed in the last column. Slash stands for not connected aquifers. The value of > > 100% stands for a change in flow rates which were 0 m^3/day in the pre-exploitation scenario. Numbers in brackets denote zones in Fig. 5.

be capable of quantifying and evaluating the relevant parameters related to transboundary or even national aquifer exploitation by multiple users.

A comprehensive draft "Guidelines for Multidisciplinary Assessment of Transboundary Aquifers" was published by the International Groundwater Resource Assessment Centre (IGRAC) in 2015 (IGRAC and UNESCO-IHP, 2015) with the aim of providing a methodology for assessment of aquifers and guidelines for its implementation. Transboundary aquifers are in general cold water aquifers, and these guidelines aim specifically to tackle these aquifers. However in some cases thermal groundwater resources are also shared by different countries which parallel to its geological-hydrogeological assessment and a regular monitoring also requires the assessment of certain specific parameters for sustainable thermal water resource development and management.

In order to achieve a rapid, semi-quantitative evaluation of thermal groundwater resources, whether transboundary or not, a pre-existing scheme developed by Lachavanne and Juge, (2009) for managing the region around Lake Geneva in Switzerland was reworked and modified as a key action in the TRANSENERGY project. Nine indicators based on data evaluation, information availability and relevance were defined (Prestor et al., 2015). The indicators are assigned numerical values based on a calculation method (Eq. (1)–(9)) using detailed information such as status, monitoring and operation, taken from different wells. This leads to a grouping within five categories (bad, weak, medium, good and very good) which allows a fast comparison of different aquifers in different regions to be made. How these indicators are calculated, and what information is used, is shown below.

The nine benchmarking indicators are the following:

1. Monitoring setup
2. Best available technology
3. Thermal efficiency
4. Utilisation efficiency
5. Re-injection rate
6. Quality of discharged thermal water,
7. Over-abstraction,
8. Status of water balance
9. Public awareness

The **monitoring setup** indicator is linked to the choice of parameters to be recorded at a site. This can be simple (eg. only water level) varying up to complex, where numerous parameters are recorded both at the production and monitoring wells. Importantly this indicator also shows whether the monitoring at a given level (local, regional) is carried out in a unified, integrated way, and also indicates the degree of groundwater abstraction monitoring. Regional evaluation of the resources of (thermal) aquifers depends on an optimally functioning monitoring system and provides a basis for issuing new water abstraction permits. The monitoring setup criteria and related points are shown in Table 4.

The indicator calculation formula (Eq. (1)) and corresponding classification/scoring are:

Table 4
Monitoring setup criteria and related points.

Monitoring setup criteria	Yes/No	Points
Active monitoring carried out by water producers: Continuous measurement of abstracted water, piezometric level, temperature and regular chemical water analysis	Yes	5
	No	0
Yearly report of active monitoring results submitted by concessionaire/licenser and approved by granting authority	Yes	3
	No	0
Passive monitoring in observation well: Regular measurements of piezometric level	Yes	1
	No	0
Passive monitoring in observation well: Temporarily sampling of groundwater for chemical/isotopic analysis	Yes	1
	No	0
Sporadic observations	Yes	0

$$I_{MON} = \frac{\sum_{i=1}^{n} P_i}{N_{tot}} \quad \begin{array}{ll} \text{Verygood:} & I_{MON} > 8 \\ \text{Good:} & 6 < I_{MON} \le 8 \\ \text{Medium:} & 4 < I_{MON} \le 6 \\ \text{Weak:} & 2 < I_{MON} \le 4 \\ \text{Bad:} & I_{MON} \le 2 \end{array} \tag{1}$$

Abbreviations; for this and all other equations are explained at the beginning of the paper.

The **best available technology** (BAT) indicator shows whether appropriate technical parameters exist at well installations, whether cascade use is applied, how efficiently the water usage is implemented and it also describes the overall status of documentation. If good BAT is being implemented this will lead to a reduced operational cost, safer operation and usage efficiency. At the same time any environmental pollution will be reduced. The BAT use criteria and related points are shown in Table 5.

The indicator calculation formula (Eq. (2)) and corresponding classification/scoring are:

$$I_{BAT} = \frac{\sum_{i=1}^{n} I_i \cdot Q_i}{\sum_{i=1}^{n} Q_i} \quad \begin{array}{ll} \text{Verygood:} & I_{BAT} = 0 \\ \text{Good:} & 0 < I_{BAT} \le 1 \\ \text{Medium:} & 1 < I_{BAT} \le 2 \\ \text{Weak:} & 2 < I_{BAT} \le 3 \\ \text{Bad:} & I_{BAT} > 3 \end{array} \tag{2}$$

T**hermal efficiency** is determined from the ratio between the used and the available annual heat energy. The mean annual air temperature is used as a reference. Lowering the temperature of the waste thermal water through the use of e.g. cascade systems will increase the thermal efficiency. This also leads to a reduction in the total amount of abstracted thermal groundwater, and reduces the threat of thermal and chemical pollution of surface waters coming from discharge of waste thermal waters.

The indicator calculation formula (Eq. (3.1)–(3.3)) and corresponding classification/scoring are:

$$TE = \frac{\sum_{i=1}^{n} \eta_i \cdot Q_i}{\sum_{i=1}^{n} Q_i} [\%] \quad \begin{array}{ll} \text{Verygood:} & TE > 70 \\ \text{Good:} & 60 < TE \le 70 \\ \text{Medium:} & 40 < TE \le 60 \\ \text{Weak:} & 30 < TE \le 40 \\ \text{Bad:} & TE \le 30 \end{array} \tag{3.1}$$

Where:

Table 5
BAT use criteria and related points.

BAT use criteria	Yes/No	Points
Well-maintained wellheads which are isolated and protected from unfavourable 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. 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
The amount of produced water precisely and continuously follows the water demand. If pumping is required computer-managed frequency pumps are used	Yes	0
	No	1
Thermal water is used based on the principles of a cascade system, with both computerized 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

$$\eta_i = \frac{T_{whd} - T_{out}}{T_{whd} - T_o} \tag{3.2}$$

In case of re-injection:

$$\eta_{ri} = \frac{Q_i(T_{whd} - T_{out})}{Q_i(T_{whd} - T_{out}) + Q_{wwi}(T_{out} - T_o)} \tag{3.3}$$

The ratio of the average annual water production to the maximum water quantity that could theoretically be produced gives the **utilization efficiency**. A maximum value for production is simply taken from the installed pump capacity. A more realistic approximation is calculated on the basis of the maximum yield and conditions as stated in the water permits. The TRANSENERGY project evaluated this approach in detail. This indicator cannot be calculated for naturally discharged thermal waters (e.g. from springs), which enter the ecosystems.

The indicator calculation formula (Eq. (4)) and corresponding classification/scoring are:

$$F_u = \frac{\sum_{i=1}^{n} Q_i}{\sum_{i=1}^{n} Q_{capi}} \cdot 100[\%] \quad \begin{array}{ll} \text{Verygood:} & Fu > 30 \\ \text{Good:} & 25 < Fu \le 30 \\ \text{Medium:} & 20 < Fu \le 25 \\ \text{Weak:} & 15 < Fu \le 20 \\ \text{Bad:} & Fu \le 15 \end{array} \tag{4}$$

An important indicator is the **re-injection rate** as it can be used as a test for sustainable thermal water exploitation. Re-injection is permitted only for non-treated and uncontaminated thermal water (i.e. used only for its heat energy). It is calculated based on the ratio of the volume of re-injected and abstracted thermal water used for geothermal energy production. This indicator shows whether re-injection is taking place or not. It does not monitor where re-injection is taking place (i.e. in the same aquifer from where the thermal water is abstracted). Unfortunately if re-injection takes place, it is often applied to shallower aquifers. This is in direct contradiction with the guidelines of the Water Framework Directive, since shallow re-injection can lead to the introduction of higher organic matter and/or trace element content into these aquifers. A new parameter to be included in the indicator calculation will be a check if the re-injection depth is the same as the abstraction depth.

The indicator calculation formula (Eq. (5)) and corresponding classification/scoring are:

$$RI_Q = \sum_{1}^{n} \frac{Q_{reinji}}{Q_{absi}}[\%] \quad \begin{array}{ll} \text{Verygood:} & RI_Q > 60 \\ \text{Good:} & 40 < RI_Q \le 60 \\ \text{Medium:} & 20 < RI_Q \le 40 \\ \text{Weak:} & 0 < RI_Q \le 20 \\ \text{Bad:} & RI_Q = 0 \end{array} \tag{5}$$

An indicator for the **quality of discharged thermal waste water** shows if an operating well does or does not pose a chemical or thermal threat to surface waters or other parts of the environment. It also shows how many wells comply with the local or international legislative standards for thermal wastewater emissions.

The indicator calculation formula (Eq. (6.1) and Eq. (6.2)) and corresponding classification/scoring are:

$$I_{Qualww} = \frac{\sum_{i=1}^{n} I_{Qualwwi} \cdot Q_i}{\sum_{i=1}^{n} Q_i}[\%] \quad \begin{array}{ll} \text{Verygood:} & I_{Qual\,ww} > 95 \\ \text{Good:} & 90 < I_{Qual\,ww} \le 95 \\ \text{Medium:} & 80 < I_{Qual\,ww} \le 90 \\ \text{Weak:} & 70 < I_{Qual\,ww} \le 80 \\ \text{Bad:} & I_{Qual\,ww} \le 70 \end{array} \tag{6.1}$$

Where:

$$I_{Qualwwi} = \frac{N_{positivei}}{N_{toti}} \cdot 100[\%] \tag{6.2}$$

Exploitation of thermal water can clearly have an impact on the aquifer being exploited. For this reason an **over-abstraction** indicator has been developed to characterise the status of the aquifer. Potential impacts include piezometric level, water temperature, groundwater availability, water quality change, the groundwater dependent ecosystem and subsidence, and so these are included in the calculation and evaluated. The over-abstraction criteria and related points are shown in Table 6.

The indicator calculation formula (Eq. (7)) and corresponding classification/scoring are:

$$I_{OE} = \frac{\sum_{i=1}^{n} I_i \cdot Q_i}{\sum_{i=1}^{n} Q_i} \quad \begin{array}{ll} \text{Very good:} & I_{OE} = 0 \\ \text{Good:} & 0 < I_{OE} \le 1 \\ \text{Medium:} & 1 < I_{OE} \le 2 \\ \text{Weak:} & 2 < I_{OE} \le 3 \\ \text{Bad:} & I_{OE} > 3 \end{array} \tag{7}$$

Table 6
Over-abstraction criteria and related points.

Over-abstraction criteria	Yes/No	Points
Significant decreasing of piezometric level shows 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

The **status of water balance assessment** is a measure of the level of the depth and reliability of information on the water quantity status of an aquifer. Reliable, good quality, regional hydrogeological data is needed in order to make an estimate on the natural recharge of a thermal aquifer. If there is an ongoing national monitoring programme, and data interpretation can be combined with data from users' 'active' monitoring, then more accurate estimates can be calculated. It is proposed that every 3–6 years the annual data for water balance assessment and regional hydrogeological evaluation should be assessed and evaluated since only after this period will any trends become evident (Goldbrunner et al., 2007). The status of water balance assessment criteria and related points are shown in Table 7.Only one criteria can be allocated to one well.

The indicator calculation formula (Eq. (8)) and corresponding classification/scoring are:

$$I_{wba} = \frac{P_i}{N_{tot}} \cdot 100[\%] \quad \begin{array}{ll} \text{Very good:} & I_{wba} > 95 \\ \text{Good:} & 75 < I_{wba} \leq 95 \\ \text{Medium:} & 50 < I_{wba} \leq 75 \\ \text{Weak:} & 25 < I_{wba} \leq 50 \\ \text{Bad:} & I_{wba} \leq 25 \end{array} \tag{8}$$

Public engagement is considered an important aspect of the exploitation of any natural resource, including thermal waters. For this reason a **public awareness** indicator has been developed based on a range of data which can allow the public to make an informed decision. Relevant parameters in the calculation include open-access on information about monitoring, BAT, the quantity status of aquifers, the quality of discharged thermal waste water, and thermal efficiency. The public awareness criteria and related points are shown in Table 8.

The indicator calculation formula (Eq. (9)) and corresponding classification/scoring are:

$$I_{inf} = \frac{\sum_{i=1}^{n} P_i}{N_{tot}} \quad \begin{array}{ll} \text{Very good:} & I_{inf} > 8 \\ \text{Good:} & 6 < I_{inf} \leq 8 \\ \text{Medium:} & 4 < I_{inf} \leq 6 \\ \text{Weak:} & 2 < I_{inf} \leq 4 \\ \text{Bad:} & I_{inf} \leq 2 \end{array} \tag{9}$$

BAT: best available technology, DTWW: discharged thermal waste water, WBA: water balance assessment

Major changes in the piezometric levels and water budgets in the transboundary zones of the Upper Pannonian aquifer, as discussed in Section 4, were identified between Slovenia and Hungary, and between Hungary and Slovakia. The benchmark indicators presented above for these two regions are summarised in Fig. 6 based on data covering the period 2009 (Slovakia) and 2011 (Slovenia, Hungary).

Table 7
Status of water balance assessment criteria and related points.

Status of water balance assessment criteria	Yes/No	Points
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.	Yes	1
	No	0
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	Yes	0.75
	No	0
Critical level point is defined (based on average yearly minimum level value from previous years at the location)	Yes	0.5
	No	0
Critical level point is defined (not based upon measurements on the location but from other available data/locations)	Yes	0.25
	No	0
Not assessed	Yes	0

Table 8
Public awareness criteria and related points.

Information about	Yes/No	Points
Monitoring	Yes	1
	No	0
BAT use	Yes	1
	No	0
Quantitative status (over-exploitation)	Yes	3
	No	0
Quality of discharged thermal waste water	Yes	3
	No	0
Thermal efficiency	Yes	2
	No	0

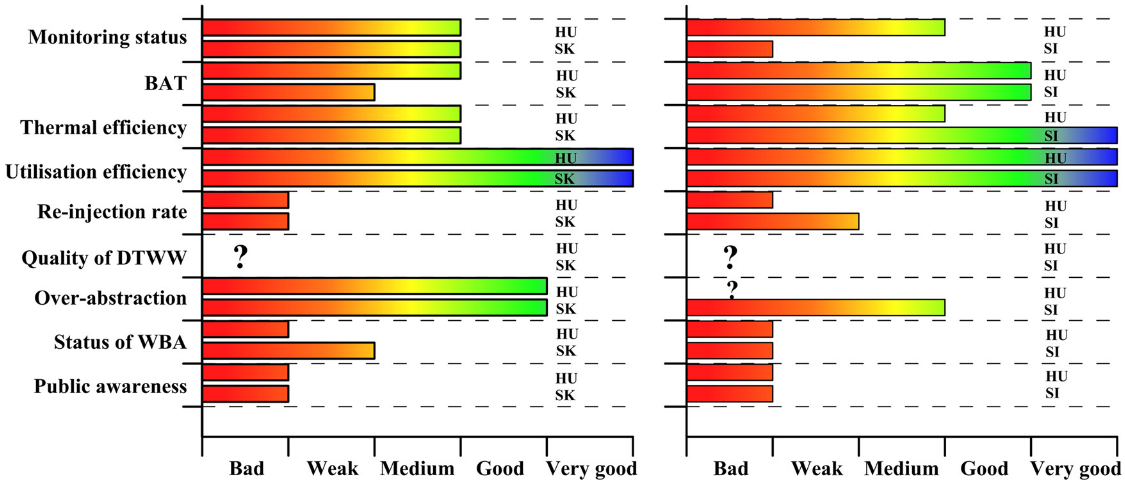

Fig. 6. Application of benchmarking indicators for two transboundary areas: the Danube basin between Hungary and Slovakia (left) and the Mura-Zala basin between Slovenia and Hungary (right).

5.1. Hungarian-Slovakian border region – Danube basin

The benchmarking comparison carried out in this study clearly shows that the general management of the geothermal aquifers under investigation has to be improved significantly in both countries. The results of this comparison, together with the main issues which should be improved first (Nádor et al., 2013a) are:

- Currently the monitoring indicator for the active thermal water wells is only medium. Monitoring of geothermal aquifers relies on reported abstraction (yield and temperature) on an annual basis, with monthly reported values in both countries. All water users have a legal obligation under the Slovakian Water Act to report these values annually, relative to limits stated in the Water Act. Groundwater users also have to report yearly their abstractions in Hungary to the Water Authorities. Only active wells are used for benchmarking in the monitoring evaluation. There is no independent monitoring of the geothermal aquifer (e.g. through monitoring wells constructed exclusively for this purpose) in any of the countries.
- The exploitation of thermal water is not always done using the best available technologies. Sometimes wellheads are poorly maintained and there may be gas or water leaks in the system. Pumps with frequency converters are occasionally installed. Cascade usage of thermal water is not applied in Hungary.
- There is a clear lack of use of efficient thermal systems such as cascade configurations. For this reason there is only a medium thermal effectivity. It is likely that this is a result of a lack of investment by the organisation exploiting the thermal water, and shows also that there is limited or no support from the government or banks in this environmentally acceptable technology. Thermal efficiency needs improving in both countries.
- There are no re-injection wells operating in the studied region of the Upper Pannonian Transboundary Thermal Aquifer. There has been only one test to evaluate the re-injection rate in the intergranular environment in a well in Horna Poton (Slovakia), which shows very complicated conditions for re-injection into such a geological environment. Nowadays this well is used as an abstraction well. The only re-injection is applied to the karst – fissure environment (Mesozoic formation) at the Podhájska site.
- Several studies have been carried out in Slovakia, to evaluate the regional conditions for thermal water flow and related water regime, as part of wider studies into recharge of geothermal water. Unfortunately there are no periodic updates from monitored data in the geothermal aquifer. Water balance calculations on the Hungarian side of the study region cannot be considered

representative. Nevertheless the amount of abstraction has been defined for most of the wells and is stated in the abstraction permit.
- There is a deterioration in the quantity status of this geothermal aquifer, which is reflected in the over-abstraction indicators. However more work is needed to better define the parameters of this indicator.
- Since no information on the quality of discharged thermal waste water was collected during this study, so it was not possible to evaluate this parameter.
- Concerning public awareness information about the reported yield (thermal water usage), chemical composition and temperature of thermal water is partly available on some websites, but is archived mainly in institutions responsible for data storage. The general public does not have access to data on monitoring, BAT, quantity status of the aquifers, quality of discharged thermal waste water or energy efficiency of thermal water exploitation. In specific cases these have not been even monitored.

5.2. Slovenian-Hungarian border region – Mura-Zala basin

- Fig. 5 shows that utilisation efficiency, energy efficiency and best available technology are mostly good or very good in the Mura-Zala basin, while monitoring and over-abstraction practice could be improved. The lack of designated monitoring wells in the Slovenian side resulted in a bad indicator value but the situation has much improved after 2015. Reliable over-abstraction calculations on the Hungarian side could not be carried out due to lack of representative data.
- Re-injection is bad in Hungary with no operating re-injection wells (there is one re-injection well, but out of usage), while the one re-injection well in Slovenia still only results in a weak indicator value. It has been concluded that re-injection will play a crucial part in the long term sustainable use of thermal waters, not just in the Mura-Zala basin, but in the whole Upper Pannonian Transboundary Thermal Aquifer.
- There is a lot of progress to be made concerning the knowledge on the degree and reliability of information on the quantity status of the aquifer. The situation in Slovenia has much improved after 2015 as holders of the newly granted concession permits are obliged to set up a continuous monitoring system of groundwater levels, temperatures and discharge rates and annually check the chemical composition of waters. So in the next few years we expect to have a reliable evaluation of the aquifers state.
- In both countries public awareness indicator results should be increased and stakeholders better informed about the current use and the need to improve it.

6. Transboundary agreements

In Hungary groundwater governance has been organised through the Ministry of Interior since 2014. The groundwater management is coordinated by the General Directorate of Water Management under the supervision of Ministry of Interior. This also includes the drafting of the River Basin Management Plan. Under the supervision of the Ministry of National Development the Geological and Geophysical Institute of Hungary (which from July 2017 has been merged into the Mining and Geological Survey of Hungary) supports the national level groundwater status assessment and strategic planning. It is also tasked with groundwater monitoring together with the regional water directorates and environmental authorities and assists the groundwater delineation on both national and bilateral levels and provides scientific support for transboundary groundwater management.

There are 11 aggregated transboundary groundwater bodies in the Danube River Basin, and seven affect Hungary. At international level, under the Danube River Protection Convention (signed on June 29, 1994 in Sofia; Bulgaria) the activity of the Groundwater Task Group within the International Commission for Protection of Danube River (ICPDR) is therefore relevant and important for Hungary. The work of the ICPDR is supported by seven bilateral water commissions, (each of them based on bilateral agreement on Government level) of which 4 are active in groundwater governance.

The Geological Survey of Slovenia provides professional support for the implementation of the national River Basin Management Plan where it concerns groundwater, with the plan being coordinated by the Ministry of the Environment and the Spatial Planning. The Ministry also manages bilateral water commissions and their activities. The Survey provides professional support to the Ministry regarding groundwater and in the last years the Mura-Zala Transboundary Thermal Groundwater Body has often been discusses in the Permanent Slovenian-Hungarian Commission on Water Management.

7. Conclusions and perspectives

Although long term groundwater management has been practiced in the Pannonian Basin, and transboundary bilateral agreements existed before ISARM, due to the hydrogeological conditions (eg. regional transboundary groundwater flow over large distances) and existing and planned abstraction plans, further steps for transboundary aquifer management are needed. These should be in line with ISARM, UNGA/RES/63/124 (UNGA, 2008), the principles given by the UN Water Convention (UNWC, 2014), the EU Water Framework Directive and the Danube River Basin Management Plans of ICPDR. In addition to supporting environmental goals, it also has to follow the aims of sustainable utilization of renewable energy resources. The resolution on Transboundary Aquifers prepared by the United Nations General Assembly should be considered for adoption by the four countries sharing the UPTTA.

The delineated UPTTA is a good example of how aquifers are shared and used by multiple countries. Lessons learnt from the surveys carried out and the results of the indicator system can be summarised as follows.

The system of licensing for thermal water abstraction and exploitation of geothermal resources is not efficiently regulated in general. i.e. it is complicated, both under and at the same time over regulated, rather slow, and expensive, thus it does not help to develop national geothermal sectors.

We propose that the indicators defined previously (Prestor et al., 2015) have to be measured and evaluated both when water permits are issued or concessions on thermal water use are granted and when they are renewed. Future refinement and/or modification of some indicators especially focusing on the assessment of sustainable use of energy and thus thermal water exploitation can also be expected.

Legislation and groundwater/aquifer vary greatly across the region. In order to overcome cross boarder differences, a harmonised approach must be developed by the relevant institutes and authorities using common thinking and unified objectives.

The results of the benchmarking action highlight that there is a long tradition of using thermal water for balneological purposes. In addition it can be seen that in the whole western part of the Pannonian Basin there is a very good utilization efficiency in this sector.

Other indicators such as the re-injection rate and public awareness have very low scores, indicating that a major effort is needed to improve the management of the geothermal resources in all four countries. This study looked only to see if re-injection had been applied or not. In a proper governance setting it will be necessary to differentiate between re-injection into the aquifer from which water is being abstracted and re-injection into other aquifers or at different depths of the same aquifer.

With the exception of Austria, the monitoring indicator for the active thermal water wells is mostly medium or bad. Effective monitoring of the geothermal aquifer should be prioritised in all countries, which requires implementation of viable monitoring policies which should be taken care of by the relevant Ministries and Authorities dealing with resource management and environment protection.

Data on the quality of emitted thermal waste water was not collected during this study and therefore it was not possible to accurately assess this parameter.

The indicator values for the best available technology vary between bad and good. It has become apparent that the good values may be due to a lack of reliable information.

So far the thermal aquifers are not being 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.

The thermal efficiency indicator generally shows a bad or very bad status, so we recommend that the exploitation of annual heat energy of operating wells should be increased rather than focusing on the exploitation of new wells. The thermal efficiency indicator does not correctly reflect the efficiency of the well, in the case of low (less than about 35 °C) wellhead temperatures.

The status of water balance assessment is also bad or very bad in Hungary, Slovenia and Slovakia, so there is much to be achieved 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 successful cooperation established among the geological surveys of the four countries of UPTTA, with a harmonised evaluation of transboundary hydrogeothermal resources, is continued within the DARLINGe project (EU INTERREG Danube Transnational Programme; http://www.interreg-danube.eu/approved-projects/darlinge). The project area covers the central and southeastern part of the Danube Region, and involves 15 partners from Hungary, Slovenia, Croatia, Serbia, Bosnia and Herzegovina and Romania. They work together to promote sustainable utilization of the existing, but still largely untapped deep geothermal resources for the heating sector. This will clearly involve a greater cooperation on transboundary thermal aquifers and governance.

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