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Effects of Regional Production of Thermal Water on Low-Temperature Geothermal Aquifers in North-East Slovenia

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ABSTRACT

Low-temperature geothermal aquifers in the Neogene Mura-Zala sedimentary basin in northeastern Slovenia have been exploited for direct use for over 40 years. This basin is one of the western sub-basins of the large Pannonian basin with very favorable geothermal conditions. Here, the most important geothermal aquifer is the Pannonian to Pontian delta front sand of the Mura Formation. Its over-exploitation due to regional thermal water abstraction has been assumed and three hypotheses were set: a) hydraulic and b) chemical state of this aquifer has changed due to exploitation, plus c) current thermal water abstraction exceeds its recharge. The hypotheses were tested by interpreting time-series of archive chemical analyses and new hydraulic datasets acquired from a research monitoring network of 11 geothermal wells which is being constantly upgraded since 2009. The results point out that the current exploitation is not sustainable because hydraulic and chemical state of the aquifer has been continuously deteriorating; however, no temperature changes have been measured at the wellheads. The regional drawdown rate in observation wells is approximately 0.5 m annually, while very rough average value for abstraction wells is 3.1 m per year. This rate is twice as high locally. Total regional drawdown caused by 40 years of abstraction is above 15 m and even higher in the vicinity of the abstraction sites. The numerical model set up in the AUTOUGH2 code confirmed the analytical results. Both research approaches imply that current abstraction of thermal water from the Mura Fm. (75.5 l/s) and hydraulically connected Ptuj-Grad Fm. (7.0 l/s) geothermal aquifers severely exceeds the recharge rate. Based on the modelling scenarios we have estimated that the available groundwater resources sum up to approximately 41 l/s, which do enable sustainable exploitation. We expect that these findings will affect the concession granting process in Slovenia by improving optimization of exploitation and implementation of reinjection. The experience gained by establishing the research monitoring system will be used to develop a harmonized transboundary monitoring of the sharing 'Transboundary Thermal Groundwater Body Mura-Zala' between Slovenia and Hungary.

1. INTRODUCTION

The use of thermal water in Slovenia follows two national strategic goals. Implement of the Directive on the promotion of the use of energy from renewable sources (2009/28/EC) foresees an increase of the proportion of renewables by 20% by 2020. In the National Renewable Energy Action Plan we aim at 3-3.5 times increase of geothermal heat production from 2010 to 2020 (from 1.11 to 3.42 PJ) (Urbančič et al., 2011), which is mostly based on the promising geothermal potential of the Pannonian basin. The Mura-Zala basin, which spreads between NE Slovenia, N Croatia, SW Hungary and SE Austria, lies in its west part. Exploitation of thermal water in Pomurje region in NE Slovenia started in the 1960's by using 'black oil water' from the Miocene sandstones and about a decade later much more favorable 'white water' with temperatures up to 65°C was first produced from Mura Formation aquifer. Nowadays, the transboundary (Nádor et al., 2012; Szőcs et al., 2013) geothermal aquifer in the Upper Pannonian Mura Fm. sands yields most of thermal water, which is utilized for direct use (Rajver et al., 2012; Rman et al., 2012).

Now, the second national strategic goal emerges. Aims of implementation of the Water Framework Directive (2000/60/EC) into national legislation are reaching and maintaining good quantitative and qualitative state of groundwater bodies. In Slovenia, geothermal energy is extracted by using geothermal doublets only in one location, in Lendava, and most of waste thermal water is emitted to surface waters. By current practice, we may reach the energetic goal but we will fail from reaching the groundwater protection goal at the same time it optimization of exploitation and implementation of reinjection are not applied sufficiently.

Exploitation of low-temperature geothermal aquifers is usually economical only when abstraction of fluids is very high and therefore depletion poses a serious risk (Axelsson & Gunnlaugsson, 2000; Rybach, 2003). Over-exploitation of the Mura Fm. geothermal aquifer in the Slovene part of the Mura-Zala basin was first studied in Murska Sobota (Kralj & Kralj 2000a, 2012). Since very few water concessions have been granted in this region by 2014 and the established production monitoring systems are poor (Rman et al., 2011), it is difficult to provide a reliable information on actual production of thermal water or hydrodynamic conditions of the aquifer. However, quite some new information has been successfully provided by a research monitoring network, operating since 2009, and numerical modelling studies. Because first results indicated that this groundwater body is at risk, a Decree on the river basin management plan for the Danube Basin and the Adriatic Sea Basin was declared, forbidding granting new thermal water concessions until groundwater levels in the Mura-Zala basin are declining (Anonymous, 2011, 2012). This was supposed to be a tool preventing new exploitation sites until all water concessions are granted and appropriate monitoring operated.

The most recent results of the regional research monitoring network are presented in this paper and three hypotheses were tested based on the available datasets: a) hydraulic and b) chemical state of the Mura Fm. aquifer has changed due to exploitation, and c) current thermal water abstraction exceeds its recharge.

2. SETTINGS

The Pannonian basin is an Alpine-Carpathian fore-deep and intramontane basin which spreads from Austria to Ukraine. Its sub-basin, the Mura-Zala basin, developed as a result of Lower to Middle Miocene extension in the Central Paratethys (Royden & Horváth, 1988) and is divided among Austria, Croatia, Hungary and Slovenia. Metamorphic and carbonate Basement rocks are cut into several structural units forming horst-graben-like structures, which controlled the Neogene sedimentation. The Neogene siliciclastic deposits contain several permeable water-bearing layers. The hierarchically nestled gravitational flow system is probably the main driving force for groundwater flow (Lapanje, 2007; Tóth, 2009; Rman, 2014).

The Carpathian to Upper Pannonian Špilje and Lendava Fms. geothermal aquifers have low porosity and permeability (Kralj and Kralj, 2000b). These confined and often stratigraphically isolated aquifers evolved in rather thin turbiditic sandstone sequences in the Radgona-Vas and Ptuj-Ljutomer-Budafa sub-basins of the Mura-Zala basin. In the latter, especially near Ptuj, the layers are additionally isolated due to their subvertical position along the Ljutomer fault (Žlebnik, 1978).

Hydraulically connected coarse-grained loose sand lenses of the Mura Fm. delta front sequence form an important regional and transboundary confined geothermal aquifer (Kralj, 2004; Nádor et al., 2012). The extent of this Upper Pannonian sand is estimated to 22,175 km^2 altogether in Austria, Croatia, Hungary, Slovakia and Slovenia, of which only 1,766 km^2 is located in Slovenia (Tóth et al., 2012). The water-bearing layers are relatively undisturbed with most recharge in the west (Slovenia) and discharge in the east (Hungary). Thermal water discharges into the Lake Hévíz, with an estimated flow rate of 20 l/s, but a hidden underground discharge into shallow fresh water aquifers is assumed elsewhere (Tóth, 2009). The Mura Fm. thermal water is used in Banovci, Dobrovnik, Lendava, Moravci in Slovenske gorice, Moravske Toplice, Murska Sobota, Petišovci, Ptuj and Renkovci. The covering delta plains fine-grained sediments are much less favorable for thermal water production.

The Pontian to Pliocene Ptuj-Grad Fm. aquifer contains predominately fresh water due to the shallower depths but some lukewarm thermal water is produced in Ptuj. Layers outcrop or are in contact with the unconfined Quaternary gravely aquifers on the River Drava and Ptuj plains, where they receive some recharge, while in the Slovenske gorice hills overlying clays control the recharge (Žlebnik, 1978). Many drinking water wells tap this aquifer also (Figure 1).

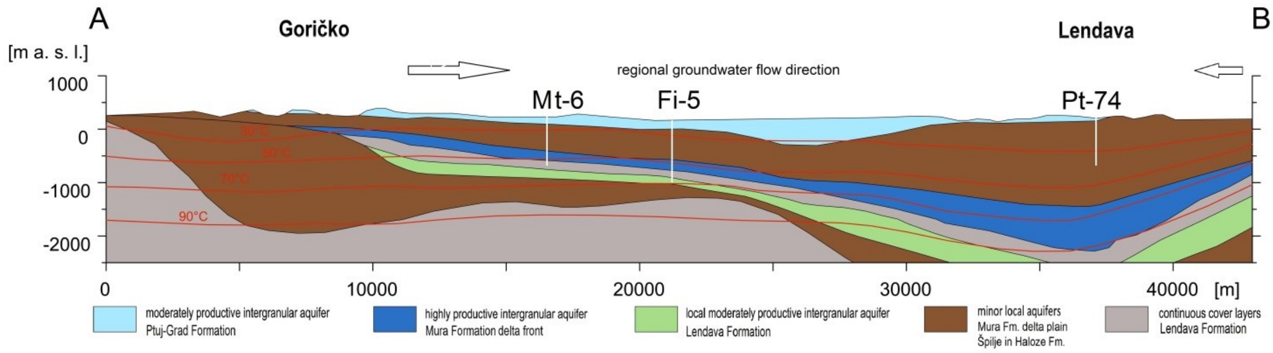

Figure 1: Hydrogeological cross-section of the Slovene part of the Mura-Zala basin, approximate direction NW-SE.

Conductive heat transfer is predominant in the Neogene sediments and the area has been studied in detail within few EU projects, such as Transthermal (Lapanje et al., 2007), T-JAM (Nádor et al., 2012) and TRANSENERGY (Goetzl et al., 2012) in recent years. High heat flow is explained by the Middle Miocene extension and thinning of the lithosphere (Lenkey et al., 2002), and is locally reduced to 30% due to rapid Neogene sedimentation, or cold water infiltration (Ravnik et al., 1995). The average temperature gradient is 5.8 °C/100 m but it can be much higher in some places (Pezdič et al., 1995). Temperatures above 100°C are expected below two kilometers depth but shallower near the Murska Sobota and Lendava towns (Rajver et al., 2012).

3. METHODOLOGY

3.1 Analysis of archive chemical data

At first, the archive data on groundwater levels, temperatures, discharges of wells and chemical composition of thermal water were collected to evaluate the amount of available data and identify possible trends. Details on this information are presented in a PhD thesis (Rman, 2013) and a research article (Rman, 2014) and will not be repeated here. However, we were able to supplement these data with new chemical analyses of thermal water from the Mura Fm. geothermal aquifer in the last two years and this information in reported here. We used Statistica and Aquachem software to interpret changes in chemical composition of thermal water from few wells where at least five analyses from different years were available. Analytical method comprised of linear correlation and regression analyses. Since the amount of chemical analyses is rather small for an individual well, Pearson's correlation coefficient (r) and nonparametric statistics with Spearman's rank correlation coefficient (R) were calculated. The statistically significant correlation coefficients were denoted from the Student's *t* test at a significance level of 0.95.

3.2 Research monitoring network of geothermal wells

The first research monitoring network of eight geothermal wells which tap the Mura Fm. geothermal aquifer in NE Slovenia was established in 2009 (Table 1). The network changed little over the following years and now there are five active wells and four observation wells continuously monitored. The changes are attributed to many reasons: some wells are no longer monitored by the Geological Survey (Sob-1), some are observed by the users themselves and the information is available to us (P-3; Fi-5 after a short discontinuity due to testing of the well) or some were included into the system only in the last years (Fi-3, Fi-14) (Figure 2).

Identical down-hole Siemens pressure and temperature sensors are incorporated into the PPI200 transducers produced by ELTRATEC Ltd. and lowered approximately 50 m below the wellheads in most cases. However, the depths vary from 150 m below the wellhead (Fi-3) to zero - at the wellheads (Fi-14) in reality. These transducers record height of the water column above the probes and the water temperature hourly and the air pressure at the Mt-7 wellhead as the measured pressures are automatically corrected for air pressure variations. All transducers are connected to electronic data loggers (GSR 301 or GSR 310) which are equipped with GPRS modem and therewith the measured data are daily transmitted to database of the Geological Survey. Besides, the cumulative daily water abstraction has been collected manually by the users since 1st January 2010 for the wells Mt-6, Mt-7 and Sob-2, while very poor production data is available for other wells.

Measurements are imported to MS Office Excel where outliers and duplicates are manually removed. Since the temperature data has already been identified as not providing enough relevant information for the investigated time period (Rman, 2014), it is not presented in this paper. We focused only on the piezometric groundwater levels, for which basic statistics (minimum, maximum, mean, standard deviation) and the total annual change were calculated for each well with a sufficiently long sequence of information and for each year separately. Linear correlation and regression analyses were also performed and the linear determination coefficient (R^2) and Pearson's correlation coefficient (r) were calculated (Helsel & Hirsch, 2002). The statistically significant correlation coefficients were denoted from the Student's *t* test at a significance level of 0.95.

Due to constant technical failures of the probes, the sparse datasets of wells Sob-1 and Sob-2 are not evaluated. For wells Fi-3 and Fi-14 there is yet not enough information as we started to monitor them only in the last years, while Mt-7 is not presented here as it is positioned very near the wells Mt-6 and Mt-8g.

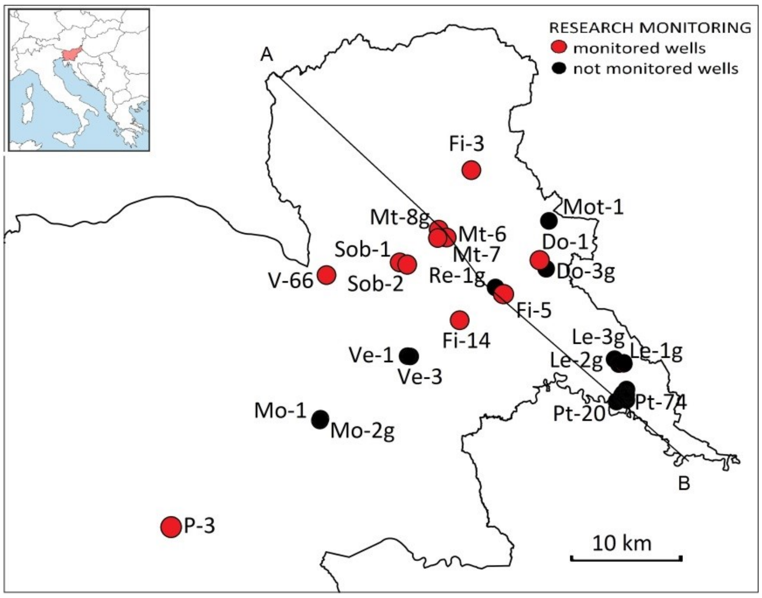

Figure 2: Location of geothermal wells tapping the Mura Fm. in NE Slovenia. Red dots stand for wells which are included into the research monitoring network. Line A-B marks the location of cross-section as shown on Figure 1.

Table 1: Location (UTM WGS84 33N, referenced to the Adriatic sea level) and properties of monitored geothermal wells.

Well	Location	X	Y	Z	Open interval top (m below wellhead)	Open interval bottom (m below wellhead)	Period of continuous observation
Mt-6[a]	Moravske Toplice	593457	5170643	187	720	974	since 23.5.2009
Mt-7[a]		593520	5170377	186	751	985	since 20.5.2009
Mt-8g[a]		592881	5171124	190	651	906	since 10.6.2009
P-3[a]	Ptuj	565615	5141034	221	1195	1572	since 26.11.2010
Sob-1[a]	Murska Sobota	588837	5168000	199	550	870	18.6.2009 - 17.5.2012
Sob-2[a]		589164	5167944	189	601	848	since 3.6.2009
Do-1[o]	Dobrovnik	603560	5167592	173	931	1874	since 20.5.2009
Fi-3[o]	Fokovci	596932	5176250	311	570	1315	since 5.7.2012
Fi-5[o]	Renkovci	598475	5165454	175	1175	1300	10.6.2009 - 12.2.2012; since 2014
Fi-14[o]	Beltinci	594882	5160834	176	1046	1881	since 24.4.2013
V-66[o]	Radenci	582416	5166285	196	164	204	since 13.5.2009

[o] – observation well; [a] – abstraction well

3.3 Numerical simulation

Modelling was done with the AUTOUGH2 simulator (O'Sullivan et al., 2001; Pruess et al., 1999; Yeh et al., 2012). The mesh was generated with rmaview 3.8.5.8 and PyTOUGH (Croucher, 2012) codes. The pure water equations of state (EOS1) were used in this 3D coupled mass and heat transfer numerical model and all blocks are prescribed to be saturated.

The numerical model of the Mura Fm. geothermal aquifer is a partial model, according to a basin-scale approach. The irregular grid covered an area of approximately 3,430 km^2 between the latitude 512,621 to 5,195,100 m north and the longitude 529,590 to 624,570 m east in the UTM WGS84 33N coordinate system, and elevations from 300 m a.s.l. to 2,500 m b.s.l. The grid was oriented at 32° counter clockwise, according to the subsurface basement topography. There were 3211 square and 1864 triangular blocks in each slicing and 21 layers defined in total, including the atmosphere. The local grid refinement was used and the layers were set to be 50 m thin at the main production zones and up to 650 m thick at the bottom of the model. The grid is refined horizontally between and around the wells because the geometry of regional pressure drawdown had to be inspected. Dimension of the block sides changes from 2,000 to 125 m in the vicinity of wells.

The calibrated and locally adjusted fresh water heads of the T-JAM regional model (Tóth et al., 2011) were used as a surface (Dirichlet) hydraulic boundary condition. The top model boundary was open to the atmosphere, with an average mean air temperature set at 11°C and pressure at 1.021 bars. The 3D geological model follows the geometry of the Neogene sedimentary fill (Table 2) which was adjusted from the previous projects T-JAM (Fodor et al., 2011) and TRANSENRGY (Maros et al., 2012). The model was closed by sides except for its south-eastern lateral boundary where it was open for discharge. The open constant heat flux (Neumann) boundary condition was assigned to the bottom with value of 100 mW/m^2. Specific heat of rock types was assigned as 1,000 J/kgK to all cells. The abstracted and reinjected mass flows of 32 geothermal wells tapping the Ptuj-Grad and Mura Fm. were prescribed in the history matching process as well as for the scenario modelling.

Table 2: Assigned physical properties of five different rock types used in the numerical model.

Rock type	Rock density (kg/m^3)	Porosity	Horizontal permeability (mD)	Vertical permeability (mD)	Thermal conductivity (W/mK)
Ptuj-Grad Fm.	2,600	0.2	5	0.01	2
Mura Fm. delta plain	2,600	0.1	10	0.01	2
Mura Fm. delta front	2,600	0.2	200	10	2
Lendava, Špilje or Haloze Fms.	2,600	0.1	1	0.1	2
Metamorphic basement	2,700	0.01	0.01	0.01	4

The model was properly calibrated and validated, and details are presented in Rman, 2013. It showed that heat flow at the bottom, thermal conductivity, vertical permeability of shallower layers and anisotropy control the temperature field, while anisotropy and discharge coefficient at the open lateral boundary control the regional groundwater fluxes. The gravitational groundwater flow was confirmed by the simulation of the natural state. The regional drawdown in the Mura Fm. geothermal aquifer is controlled mainly by the horizontal permeability of sand, but also by its anisotropy and porosity as it was shown by simulation of thermal water production in the period 1960-2012.

3.3.1 Determination of available groundwater resources of the Mura Fm. aquifer

The latest calibrated production model was taken as an initial state for 17 steady-state forecast scenarios which simulated various production and reinjection of thermal water in the period 2013-2050. The scenarios were (Table 3): no abstraction or reinjection (A000), abstraction and reinjection as in 2012 (T100), reduced abstraction of 2012 for 10% (T090), 20% (T080), 30% (T070), 40% (T060) and 50% (T050), triple the production in 2012 (T300), abstraction rates as defined in water concession applications (K000), the latter amount reduced for 30% (K070), 50% (K050) and 70% (K030), maximum possible production from inactive wells also (K100), plus four reinjection scenarios: partial reinjection in Lendava and Murska Sobota (R001), total reinjection in Lendava and Murska Sobota (R002), partial reinjection in Lendava, Murska Sobota and Moravske Toplice (R003) and partial reinjection in Lendava, Dobrovnik and Renkovci (R004).

This was done in order to estimate the effects of thermal water withdrawal on the proposed sites of national monitoring of geothermal wells (P-1, P-3, Mo-2g, V-66, DOK-1, Mt-6, Fi-5, Fi-4, Do-1, DV-1, Le-2g, Mg-4), and to determine the available groundwater resources which enable sustainable use of the aquifer without noticeable regional drawdown in groundwater levels.

Table 3: Total regional abstraction rate of thermal water in the 17 simulated forecast scenarios.

Scenario	A000	T100	T090	T080	T070	T060	T050	T300	K000	K100	K070	K050	K030	R001	R002	R003	R004
Regional abstraction rate (kg/s)	0	-81	-73	-65	-57	-49	-41	-244	-159	-185	-130	-93	-56	-73	-70	-58	-75

3.3.2 Selection of best sites for reinjection

Selection of sites where reinjection can be applied most cost and time efficiently was performed based on a few assumptions:

- If used thermal water is not previously treated to remove microbiological pollution (when used for bathing), only the one which is used for geothermal heat production can be reinjected. Therefore the reinjection rate is lower than the abstraction rate in some cases. The water from wells Le-1g and Pt-20 in Lendava, Sob-2 in Murska Sobota, plus Mt-6, Mt-7 and Mt-8g in Moravske Toplice is used for both, bathing and heating. Since shares of thermal water used for bathing and heating are not known for any of the investigated sites, we assumed that 30 % of the abstracted quantity is used for bathing and therefore cannot be reinjected. Thermal water from wells Do-3g in Dobrovnik, Le-2g in Lendava, Sob-1 in Murska Sobota and Re-1g in Renkovci is used only for heat production and therefore total reinjection is possible.

- The most effective are targeted reinjection wells, while re-design of older wells is usually less successful.
- The distance between production and reinjection wells should be less than 2 km (deviated wells should be considered).
- Due to high density of wells and abstraction rates the most critical area is between Lendava, Murska Sobota and Moravske Toplice.
- Since thermal resorts in Ptuj (P-3), Mala Nedelja (Mo-1, Mo-2g) and Banovci (Ve-1 to Ve-3) are distant from the critical area and use thermal water for bathing mostly, these sites are not of the first priority to establish regional reinjection.

Based on these assumptions we suggest the following reinjection sites with total average available reinjection rate of 47.1 l/s:

a) Well Le-3g in Lendava: Total reinjection from Le-2g and 70 % return from Le-1g and Pt-20. Total reinjection rate would be 10.1 l/s.
b) Well Sob-4g in Murska Sobota: Total reinjection from Sob-1 and 70 % return from Sob-2. Total reinjection rate would be 10.4 l/s.
c) New reinjection well between Renkovci and Dobrovnik: Total reinjection from Do-3g and Re-1g. Total reinjection rate would be 6.1 l/s.
d) New reinjection well in Moravske Toplice: 70 % return from Mt-6, Mt-7 and Mt-8g. Total reinjection rate would be 20.5 l/s.
e) If the average regional abstraction rate (which was 75.5 l/s in 2012) increases in future, the number of reinjection wells or their reinjection rate should increase proportionally.

The time sequence of the proposed reinjection scenario is given in Figure 3. Effects of this implementation onto the regional hydraulic conditions of the Mura Fm. aquifer were investigated by two forecast numerical models: the system is properly set up in the period of 2015-2018 (fast implementation, scenario R00A) and little slower implementation in years 2015- 2021 (scenario R00B). These models can be used only for regional evaluation of thermal and hydraulic changes in the aquifer while more detailed models are needed for investigation of local interferences between production and reinjection wells.

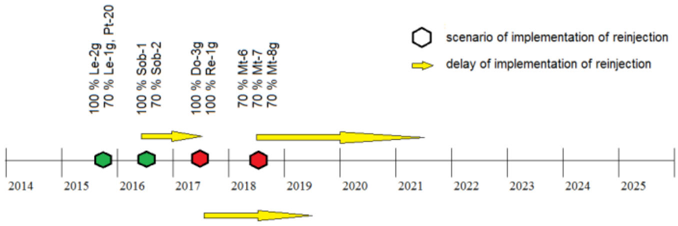

Figure 3: Fast and slow scenarios of implementation of regional reinjection into the Mura Fm. geothermal aquifer.

4. RESULTS AND DISCUSSION

4.1 Analysis of thermal water abstraction

The overview showed that 53.3 million m^3 of thermal water was abstracted in total in the period 1960-2012 (Figure 4). Approximately 8.774 million m^3 (16.5 %) appertains to the Ptuj-Grad Fm. and 91 % of this amount was abstracted from the P-1 well in Ptuj. The majority of production (44.560 million m^3 or 83.5%) comes from the Mura Fm. In this case the Mt-6 well in Moravske Toplice has produced 39 % of the quantity, while its neighbor Mt-7 has had a share of 8 %. The two wells in Murska Sobota (Sob-1 and Sob-2) have produced approximately 21 % of this quantity.

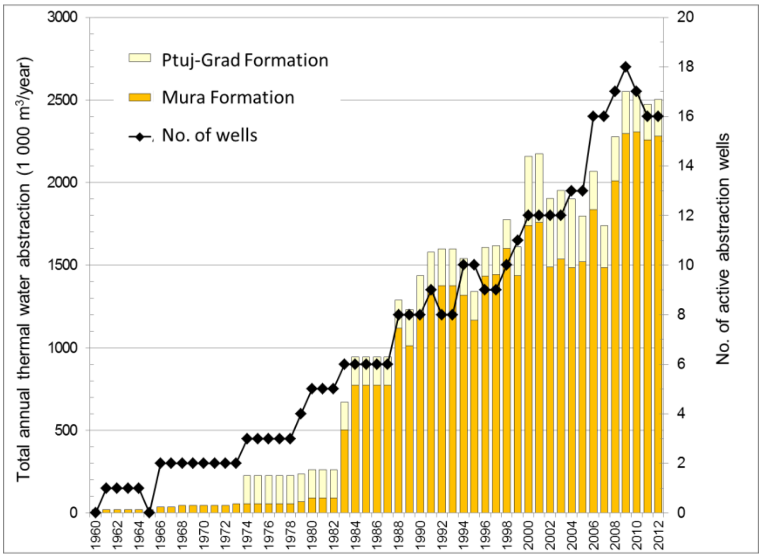

Figure 4: Annual thermal water abstraction from Ptuj-Grad and Mura Formation in the period 1960-2012.

In 2012, there were 16 abstraction wells and one reinjection well active in the Ptuj-Grad and Mura Fm. Approximately 0.220 million m^3 (6.98 l/s) was pumped from the first aquifer and approximately 2.380 million m^3 (75.46 l/s) from the second. This sums to 2.6 million m^3 (82.45 l/s). There is only one reinjection well active in the Mura Fm., but less than 3% of the regional production is reinjected.

The forecast indicates a severe increase in production according to the amounts applied for in the water concession applications (Table 4). Abstraction from the Ptuj-Grad Fm. should increase for three times, to 0.662 million m^3 per year, while from the Mura Fm. the production is expected to double, to 5.092 million m^3 per year.

Table 4: Status of wells, and current and forecasted annual thermal water abstraction.

Formation aquifer	No. of wells		Abstraction (m^3/year)	Estimated abstraction from (m^3/year)		
	inactive	active	in 2012	active wells with concession[1,2]	inactive wells with concession [1,2]	inactive wells without concession [3]
Ptuj-Grad	1	2	220,056	441,504	220,752	0
Mura	15	14+1[4]	2,379,765	3,710,356	719,792	835,700
Sum	16	17	2,599,821	4,151,860	940,544	835,700

[1] - quantities, applied in the water concession applications
[2] - quantities, defined in granted water concessions of wells Jan-1, P-1, P-2, P-3, Le-2g and Le-3g
[3] - quantities are estimated as the water concession have yet not been applied for
[4] - reinjection well (reinjected quantity has been applied in the calculation)

4.2 Changes of chemical composition of thermal waters

New chemical analyses of thermal water from the Mura Fm. geothermal aquifer were used to interpret changes in chemical composition of thermal water from three wells, Mt-6 and Mt-7 from Moravske Toplice and P-3 from Ptuj, which are predominately of Na-HCO_3(-Cl) water type. Analyses from 2004 are not included in interpretation because they are identified as outliers. For others, there were only little analyses available for the last 5 years.

Table 5: Chemical analyses of thermal water used for chemical trends evaluation.

Well	Year	Water Type	Lab.	Ref.	Temp (°C)	pH	$TDS_{measured}$ (mg/l)	EC (uS/cm)	K^+ (mg/l)	Na^+ (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Fe (mg/l)	NH_4^+ (mg/l)	Mn (mg/l)	Cl^- (mg/l)	SO_4^{2-} (mg/l)	HCO_3^- (mg/l)	NO_3^- (mg/l)	SiO_2 (mg/l)	Ion Balance Error (%)
Mt-6	1983	Na-HCO_3-Cl	4	2	60.3	7.80	1231	1700	6.6	321	3.4	1.3	0.8	3.2	0.0	130	1	716			-3
Mt-6	1990	Na-HCO_3-Cl		4	60.0	8.93			9.0	330	6.3	2.1	0.3	1.6	0.0	132	2	699	-0.1		0
Mt-6	1992	Na-HCO_3-Cl	3	2	59.0	7.84	1165	1400	8.0	322	5.7	1.9	0.0	2.7	-0.1[1]	138	-5	683	0.2		-1
Mt-6	1993	Na-HCO_3-Cl	3	2	58.0	7.53	1198		5.0	340	5.7	1.7	0.1	2.7	-0.1	133	-5	708	0.2		0
Mt-6	1994	Na-HCO_3-Cl	3	2	59.0	7.93	1176		5.0	335	5.7	1.0	0.1	1.9	-0.1	131	-5	689	0.3		0
Mt-6	1995	Na-HCO_3-Cl	3	2	59.0	8.07	1259		7.0	350	5.6	0.9	0.0	2.7	0.1	128	-5	711	0.9		2
Mt-6	1996	Na-HCO_3-Cl	3	2	59.1	7.98	1118		10.0	310	5.7	0.6	0.1	2.4		119	-5	665			0
Mt-6	1997	Na-HCO_3-Cl		4	58.1	8.04	1137		10.0	310	4.7	1.5	0.1	2.6	0.0	116	10	682	0.0		-2
Mt-6	1998	Na-HCO_3-Cl	1	1	59.0	7.80		1190	5.6	350	5.7	1.7	0.3	4.0	0.1	124	2	677	-0.5		5
Mt-6	2004	Na-HCO_3-Cl		1	57.9	7.50		1310	5.0	240	6.0	-1.0	0.7	2.4	0.0	108	45	700	-2.2	37.0	-14
Mt-6	2007	Na-HCO_3		4	54.7	7.70		1163	5.6	310	7.6	13.0	-0.1	2.9	0.1	89	-1	670	-2.2		6
Mt-6	2012	Na-HCO_3-Cl	5	4	56.6	8		1100		290	5.7	-1.0	-0.1		0.0	110	-1	670	-2.2		-4
Mt-6	2013	Na-HCO_3-Cl	5	4	56.6	7.9		1100		310	5.4	-1.0	-0.1	2.6	0.0	100	-1	640	-2.2		2
Mt-7	1993	Na-HCO_3-Cl	3	3	53.0	7.90	1162	1200	7.0	310	7.1	3.4	1.3	2.2	0.0	107	2	687	-0.1	24.3	1
Mt-7	1998	Na-HCO_3-Cl	1	1	56.0	7.80		1130	5.5	320	5.7	2.6	0.1	8.9	0.1	103	2	671	-0.5		4
Mt-7	2004	Na-HCO_3-Cl		1	55.7	7.30		1360	3.3	260	6.0	-1.0	0.3	2.2	0.0	110	45	730	-2.2	35.0	-15
Mt-7	2007	Na-HCO_3-Cl	5	4	54.7	7.6		1281	6.3	330	6.1	11.0	0.2	2.4	0.0	120	-1	730	-2.2		-1
Mt-7	2010	Na-HCO_3	2	5	55.7	7.25	1160	1364	5.5	314	5.8	1.1	0.2	1.5	0.0	100	1	702	-0.1	20.8	0
P-3	2005	Na-HCO_3		6	50.8	7.5	795	743	7.0	200	7.0	2.0		1.0		4.7	0.4	570		35.0	0
P-3	2010	Na-HCO_3		6	52.7	7.3	795	813	3.5	194	6.4	1.6	0.2	1.1		0.4	0.4	559		21.1	-1
P-3	2012	Na-HCO_3	5	4	54	8				200	5.5	-1	0.2			2.1	-1	520	-2.2		3
P-3	2013	Na-HCO_3	5	4	51.4	7.9				200	5.0	-1	0.6	1.3		1.4	-1	600	-2.2		-5
P-3	2014	Na-HCO_3	5	4	52.2	7.5	821	722	4.0	200	5.3	2.0	0.2	1.2	0.0	2.0	-1	560	-2.2	36.1	0
Analytical Error (%)								2	13	15	12	20		18		15	9	10		18	

[1] minus (-) stands at the detection limit value

Lab.	Laboratory
1	Center za razvoj in znanstveno raziskovanje mineralnih vod, Maribor, Slovenia
2	Geological Institute of Hungary, Budapest, Hungary
3	Razvojni laboratorij Radenske, Radenci, Slovenia
4	Zavod za fizikalnu medicinu i rehabilitaciju medicìskog fakulteta, Zagreb, Croatia
5	Zavod za zdravstveno varstvo, Maribor, Slovenia

Ref.	Reference
1	Gerič, N. 2006
2	Kralj, P. 2001
3	Lapanje, A. 2006
4	Š. Smodiš (personal communication)
5	T-JAM borehole database (available at http://akvamarin.geo-zs.si/t-jam_boreholes/)
6	Archive of the Geological Survey of Slovenia

First, we compared concentrations of the main ions to the first measured value and to the analytical error (Table 5) and only a few parameters gave some clues on chemical trends. Conductivity of thermal water has decreased only in Mt-6, for 35% which is much above the analytical error. Parameters where variations in concentrations were noticed are sodium, chloride and bicarbonate. The analytical error of sodium measurements is 15% and slight decrease in Mt-6 and increase in Mt-7 are within this value. Changes in chloride concentration are also evident in both these wells. A decrease of 23% is obvious in Mt-6 being well above the analytical error of 15%, while decrease in Mt-7 is within this error; however, the calculated water type has changed from Na-HCO_3-Cl to Na-HCO_3 lately. Variations of chloride in P-3 are very high but without noticeable trend. The bicarbonate ion is the main anion in these thermal waters and it shows a decrease of 10% in Mt-6, which is exactly the analytical error, and an increase of 6% in Mt-7.

Linear correlation and regression analyses show that there are no significant trends in sodium, chloride or bicarbonate ions of thermal water in P-3 (N = 5, r < 0.50 and p > 0.20); R < 0.35, p > 0.55). No statistically significant trends are also evident in Mt-7 (N = 4) despite good correlation of sodium (r = 0.45, p < 0.55; R = 0.40, p < 0.60) and bicarbonate ions (r = 0.67, p <0.33; R = 0.60, p < 0.40) which indicate their increase. All three parameters decrease in Mt-6 (N = 12), which is evident by sodium (r = -0.54, p < 0.07; R = -0.47, p < 0.12) and statistically significant decrease in bicarbonate (r = -0.81, p < 0.001; R = -0.82, p < 0.00) and chloride concentrations (r = -0.82, p < 0.001; R = -0.87, p < 0.00).

The results indicate that changes in chemical composition of thermal water from the Mura Fm. aquifer do occur but only locally. The well with the highest total production, Mt-6 as given in Section 4.2, shows statistically significant depletion of the original higher mineralized water. Other two investigated wells do not show statistically significant variations. The number of all analyses is small and hopefully new monthly analyses of thermal water which will be performed in 2014-2015 will give more information.

4.3 Changes of groundwater levels in geothermal wells

Despite the fact that the total regional abstraction from the Mura Fm. geothermal aquifer has stayed quite constant over the last few years (Figure 4), a decline of static and dynamic groundwater levels (GWL) was measured in most monitored wells (Figure 5). Basic statistic of observation wells Do-1, Fi-5 and V-66 shows that the average regional drawdown rate was approximately half meter per year in the period 2009-2013, if the Fi-5 data from 2012 are excluded (Table 6). Since a new well Re-1g has started producing in its vicinity then, the drawdown rate is expected to be higher nowadays. All parameters which were evaluated on an annual basis, minimum, mean and maximum GWLs, have been constantly decreasing.

Drawdown rate is even higher in abstraction wells but changes of the dynamic groundwater levels are very diverse, however, an average value of 3.1 m per year was calculated from the available data (Table 6). Linear correlation and regression analyses indicate that Pearson's correlation coefficient is very high for observation wells (0.65 < r < 0.97) but rather low for abstraction wells (0.004 < r < 0.45). This is assigned mostly to large daily variations in dynamic groundwater levels due to pumping, as they vary up from 10 to 30 m in most abstraction wells. Seasonally high abstraction rates in winter and low in summer are also characteristic for thermal water production in NE Slovenia, which is clearly evident from variations of GWLs in Figure 5. Due to large number of total measurements, all correlation coefficients for the monitored wells in Table 6 are statistically significant.

Based on the presented results of this approach we believe that the average regional abstraction rate of 75.5 l/s from the Mura Fm. geothermal aquifer exceeds its recharge.

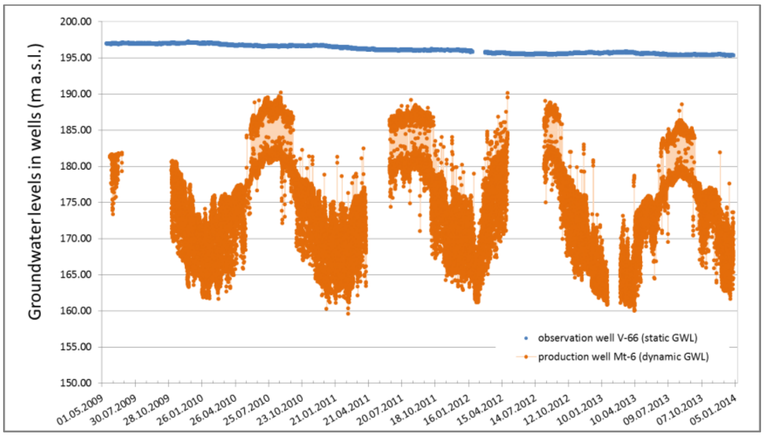

Figure 5: Two examples of measured groundwater levels: observation well V-66 and active production well Mt-6 in the period 2009-2013.

Table 6: Basic statistics of the measured hourly piezometric groundwater levels in the period 2009-2013.

Year		**2009**	**2010**	**2011**	**2012**	**2013**
Observation well Do-1						
No.		5362	8700	7824	8821	8854
Min.	m a.s.l.	168.82	167.59	166.99	166.85	166.41
Max.	m a.s.l.	170.57	169.05	168.18	169.61	168.61
Mean	m a.s.l.	169.87	168.46	167.64	168.13	167.45
St. dev.	m a.s.l.	0.55	0.33	0.29	0.81	0.65
GWL change	m/year	-	-1.41	-0.82	0.49	-0.68
		y = -0.00005*x + 169.3, r = 0.65				
Observation well Fi-5						
No.		4857	8658	8759	1032	
Min.	m a.s.l.	195.46	194.89	192.52	191.57	
Max.	m a.s.l.	195.84	195.68	195.01	193.00	no data
Mean	m a.s.l.	195.64	195.17	194.51	192.41	
St. dev.	m a.s.l.	0.08	0.20	0.43	0.26	
GWL change	m/year	-	-0.46	-0.66	-2.10	
		y = -0.00009*x + 196.1, r = 0.85				

Year		2009	2010	2011	2012	2013
Observation well V-66						
No.		5499	8654	8637	7842	8710
Min.	m a.s.l.	196.83	196.49	195.88	195.39	195.27
Max.	m a.s.l.	197.22	197.12	196.61	196.07	195.84
Mean	m a.s.l.	196.97	196.73	196.15	195.60	195.51
St. dev.	m a.s.l.	0.06	0.16	0.16	0.13	0.14
GWL change	m/year	-	-0.24	-0.59	-0.54	-0.09
		y = -0.00005*x + 197.1, r = 0.97				
Abstraction well P-3						
No.				8741	8779	7252
Min.	m a.s.l.			159.80	154.70	153.80
Max.	m a.s.l.	no data	no data	197.40	193.50	188.50
Mean	m a.s.l.			167.41	160.92	160.63
St. dev.	m a.s.l.			5.36	3.75	4.70
GWL change	m/year			-	-6.48	-0.29
		y = -0.0003x + 167.4, r = 0.45				
Abstraction well Mt-6						
No.		1817	8703	7238	6409	8029
Min.	m a.s.l.	163.28	160.26	159.57	161.16	160.02
Max.	m a.s.l.	181.84	190.21	189.13	190.13	188.51
Mean	m a.s.l.	175.57	175.91	175.06	173.91	172.80
St. dev.	m a.s.l.	4.88	6.84	6.64	6.27	6.05
GWL change	m/year	-	0.34	-0.85	-1.15	-1.11
		y = -0.0001*x + 176.7, r = 0.21				
Abstraction well Mt-8g						
No.		3659	7108	7899	8814	2652
Min.	m a.s.l.	182.14	177.99	173.96	169.41	170.17
Max.	m a.s.l.	211.52	207.21	203.04	198.16	193.81
Mean	m a.s.l.	199.03	193.77	189.31	184.00	177.35
St. dev.	m a.s.l.	8.76	8.19	8.51	8.21	5.78
GWL change	m/year	-	-5.26	-4.46	-5.31	-6.65
		y = -0.0000005*x + 58.4, r = 0.004				

4.4 Renewable quantity of thermal water

Previous analyses imply that the available groundwater resources of the Mura Fm. geothermal aquifer are in a range of 82 l/s (Vižintin, 2010), 60 l/s (Pezdič et al., 2006) and 50 l/s (Nádor et al., 2012). Our results show that these values are probably overestimated. Analysis of groundwater level trends and variation of chemistry has shown that the state of this geothermal aquifer has deteriorated regionally. Chemical trends imply local inflow of less mineralized water. Total drawdown in observation wells was between 1.5 m and 3.2 m in the last five years and between 2.8 m and 21.7 m in abstraction wells. Consequently, submersible pumps are now needed in all abstraction wells and discharge rate has also lowered. This indicates that the hydraulic quasy-equilibrium has not been achieved even though the total regional abstraction even decreased a little. According to the methodology of the Decree on groundwater status (Anonymous, 2009, 2012) both facts indicate that the aquifer's quantitative status has been deteriorating and the long-term regional abstraction rate exceeds the available groundwater resources.

Absolute drawdown of groundwater levels since the beginning of thermal water abstraction is estimated to exceed 15 m in observation wells and 30 m in abstraction wells. According to the regional groundwater drawdown method (Nádor et al., 2012, Prestor et al., 2012) the exploitation should not be considered as unsustainable because the regional drawdown is below the limiting value of 30 m from the pre-exploitation state, and only locally critical areas occur near the abstraction sites. However, due to the identified significant long-term negative trends in groundwater levels the current exploitation of thermal water with the abstraction rate of 75.5 l/s is unsustainable also by this methodology.

There are a few similarities observed in comparison to alike geothermal sites worldwide. No temperature variations were also reported in Hungary even though drawdown in Szeged, Szentes and Hajdúszoboszló was three times higher (Szita, 1995; Szanyi and Kovács, 2010). Similar effects were observed in the Tanggu and Tianjin reservoirs in China but also with higher drawdown rates (Kun, 2005; Lei and Zhu, 2013). The measured effects in the Mura Fm. aquifer probably have lower rates of changes due to a large extent of the aquifer and more favorable hydrogeological settings with some induced recharge and leakage from above.

As already presented in the Methodology, we have evaluated the available groundwater resources by using a numerical model. The scenario modelling shows that immediate termination of production (scenario A000) would increase aquifer's pressure up to 1.6 bars by 2050 and return it near to the pre-exploitation level but similar results would also be achieved if abstraction rate is reduced for 50% (T050). All other scenarios (Table 7), including local and partial reinjection, seems much less effective in reversing the negative trend in pressures/groundwater levels. Based on our analytical and numerical results we assessed that the regionally available groundwater resources of the Mura Fm. geothermal aquifer are approximately 41 l/s or 1.3 million m^3 of thermal water per year.

Table 7: Simulated pressure changes in wells by 17 scenarios of the numerical model.

Well	A000	T100	T090	T080	T070	T060	T050	T300	K000	K100	K070	K050	K030	R001	R002	R003	R004
P-3																	
Mt-6																	
V-66																	
Fi-5																	
Do-1																	

Legend

Pressure drop > 0.5 bar
Pressure drop ≤ 0.5 bar
No change in pressure

W-1 Observation well
W-1 Abstraction well

4.5 Measures to prevent overexploitation

The cheapest and simplest way to prevent further deterioration of the state of the investigated geothermal aquifer is to reduce the regional abstraction of thermal water. Since the production is partly dependent on the installed direct use systems, we estimate that it would not contribute enough to properly improve the regional hydraulic conditions. Moreover, until all water concessions for thermal water use are granted (only two of eleven users in the region have it), the users are also not obliged to accordingly adjust the thermal water production. Due to the Slovene National Renewable Energy Action Plan it is expected that new sites will emerge in NE Slovenia in order to fulfill its goals and to significantly increase geothermal energy extraction from this resource. On the other side, according to the Water Act (Anonymous, 2002) we are obliged to reach good status of the geothermal water body in the following years. With all these facts in mind, we tested two scenarios where the suggested four reinjection wells return 47.1 l/s.

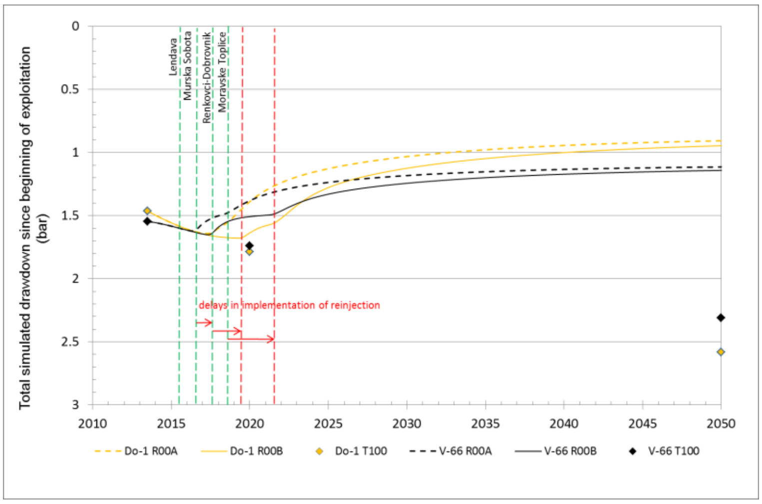

Figure 6: Total drawdown in the aquifer based on the results of two reinjection scenarios (R00A and R00B) in years 2013-2050. Results of the scenario with production as in 2012 (T100) are added for comparison.

Simulation results are exemplified for two observation wells Do-1 and V-66 (Figure 6) and they show that the suggested reinjection would reverse the negative groundwater level trends. It is very important that the reinjection is established as soon as possible (scenario R00A). The longer we wait, the higher the drawdown will be and so the period of recovery would be prolonged (scenario R00B). It is also important that when new geothermal sites occur or the regional abstraction rate increases for any reason, the reinjection rate will be accordingly increased, since the available groundwater resources will stay the same, approximately 41 l/s.

Simultaneously with implementation of regional reinjection of thermal water it is necessary to grant water concessions, so that the users will be obliged to perform operational monitoring of thermal water production and geothermal wells. Additionally, few representative observation wells should be equipped to monitor static pressures and temperatures regionally and therefore included into the national monitoring network of groundwater bodies. The monitoring results should be annually interpreted and implemented into the regional numerical model in order to forecast the effects of thermal water exploitation and evaluate the success of reinjection. Last but not least, benchmarking analysis of geothermal resource management (Prestor et al., these proceedings) is also advised to be performed for each used individually and a comparison between them can be done in order to find out which practices can be further improved to reach more sustainable use of this aquifer.

6. CONCLUSIONS

There is much information available on long-term monitoring of high-temperature geothermal systems (Axelsson & Gunnlaugsson, 2000) but much less publications present practices in low-temperature systems. In case of the Mura-Zala basin in NE Slovenia, the main problem is that thermal water concessions have yet not been granted to most users and therefore the implementation of monitoring systems has been rather vague. We partly overcame this issue by implementing a research monitoring network, financed by PhD and post-doc projects, which have provided continuous information on hydrodynamic state of the aquifer in the last five years. Analysis of gained datasets confirmed all three working hypotheses. The regional drawdown rate is 0.5 m per year in observation wells and 3.1 m per year in abstraction wells (locally even higher). Additionally, chemical changes imply inflow of less mineralized groundwater locally. By using a 3D numerical model of groundwater flow and heat transfer we not only confirmed the problem but also quantified it for the first time. We modelled that the available groundwater reserves sum up to approximately

41 l/s or 1.3 million m^3 of thermal water per year. It was shown that the current thermal water abstraction rate from the Mura Fm. (75.5 l/s) and hydraulically connected Ptuj-Grad Fm. (7.0 l/s) aquifers exceeds their recharge rate and is unsustainable.

Results of this investigation were reported to thermal water users, the Environmental Agency and the Ministry of Agriculture and the Environment of Slovenia, which grant water concessions and manage groundwater resources. They are being implemented into the Water Management Plans and we expect that they will affect the concession granting process. We believe that if current practice continues, we MAY reach the national energetic goals but we will FAIL from reaching the groundwater protection goals at the same time. Since we want to ACHIEVE BOTH GOALS, we suggest that a few measures are taken.

The *first measure* is to (finally) grant the water concessions to all thermal water users in the Mura-Zala basin. Therewith they will be obliged to set up production monitoring, annually evaluate its results (effects of their production onto the aquifer's state) and identify sites with the weakest technological practices. The *second* and probably the most economically feasible measure is optimization of thermal water and heat extraction (use of BAT, increase of energy, utilization and bating efficiency, as described in Prestor in al., these proceedings). The *third* and more time- and money-consuming measure consists of applying geothermal doublets in systems with geothermal heat production. The numerical simulation showed that the proposed regional reinjection of approximately 47 l/s should be sufficient to improve the quantitative state of the aquifer and reach its good status if current abstraction rate does not change. In case that the regional abstraction rate reduces, lower reinjection rates can be applied of course, and the opposite. Implementation of reinjection into intergranular aquifers represents technological and economic challenges, and by simulation we were able to evaluate time-effects of two scenarios of its realization which is not possible with analytical models. Besides, we believe that all new users with solely geothermal heat production should apply geothermal doublets at the beginning of operation in order to use this geothermal resource sustainably. The *fourth* measure is to establish a national monitoring system of representative geothermal wells in the NE Slovenia, so that evaluation of the regional state of the aquifer will be more reliable. *Last but not least*, we hope that the experience gained by establishing the research monitoring system will also be used to develop a harmonized transboundary monitoring at the border region between Slovenia and Hungary, which is expected to be set up in the following years to observe the state of this sharing Mura Fm. geothermal aquifer, named also 'The Transboundary Thermal Groundwater Body Mura-Zala'.

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