Analysis of thermal water abstraction from a low enthalpy geothermal system in the Mura-Zala sedimentary basin, NE Slovenia

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ABSTRACT

Low enthalpy geothermal aquifers in sedimentary basins are predominately exploited for direct use and this is characteristic also for the Slovenian part of the Neogene Mura-Zala basin (NE Slovenia), which is one of the western sub-basins of the Pannonian basin with very favourable geothermal conditions. The Pliocene Ptuj-Grad Fm. contains lukewarm water, while the most important regional and transboundary geothermal aquifer is formed by the Pannonian to Pontian delta front sands of the Mura Fm. The turbidites of the Pannonian Lendava Fm. as well as the Sarmatian to Carpathian Špilje and Haloze Fms. often form rather limited aquifers with thermomineral water rich in gases or organic compounds. Over-exploitation of these Neogene aquifers was assumed for some time, being attributed to inadequate monitoring and lack of management strategies.

The preserved geoscientific and production information was interpreted by the time-series trend analyses on the basis of a linear regression method. The results clearly indicate that not much systematic hydraulic measurements were done in the last 15 years. Also, the water composition was analysed unsystematically and only for about half of the 43 identified production wells. The chemical trends were estimated on basic chemistry datasets from eleven wells. New hourly datasets of piezometric groundwater levels, air pressure, water temperatures and daily abstraction rates have been acquired from a research monitoring network of 9 geothermal wells in the Mura Fm. It has been in operation since May 2009 and is managed by the Geological Survey of Slovenia.

The total amount of abstracted thermal water from the Neogene aquifers in the period 1960-2011 is estimated to 64.9 million m^3, of which 1% appertains to the Lendava Fm., 13% to the Ptuj-Grad Fm., 19% to the Špilje Fm. and 67% to the Mura Fm. Constantly increasing production reached 3.0 million m^3 in total in 2011. The existent data on aquifer pressure decrease, yield and water mineralization indicate that the current abstraction from all geothermal aquifers exceeds their natural recharge rate. Moreover, the 14 active abstraction wells tapping the Mura Fm. caused its over-exploitation, which is locally mitigated by a reinjection well operating since 2009 in Lendava. Hydraulic, chemical and isotopic changes are evident, indicating induced recharge of less mineralized Pleistocene paleo-meteoric water. Daily, seasonal and annual groundwater level and temperature trends were confirmed in the observation wells Do-1 in Dobrovnik, V-66 in Petanjci and Fi-5 in Renkovci, plus in the abstraction wells Mt-6, Mt-7 and Mt-8g in Moravske Toplice and Sob-2 in Murska Sobota. The regional trend of decreasing water levels is app. -0.53 m annually, while near the abstraction wells a few meters drops are observed.

The results imply a strong need for long-term feasible management strategies. The most important measures include: enhanced thermal efficiency simultaneously with reduced abstraction rates, reinjection wells in areas with the greatest thermal water withdrawal, establishment of a sound regional monitoring network and well-specific application of operational monitoring system.

1. INTRODUCTION

Exploitation of low enthalpy geothermal systems has increased worldwide but the economical abstraction of fluids from these geothermal reservoirs usually exceeds their natural discharge. If thermal water is not naturally or artificially replenished, the resources become depleted (Rybach, 2003). Geothermal mining might result in deterioration of thermodynamic and hydrodynamic conditions with changes manifested as fluctuations in pressure, discharge rate, fluid temperature and/or chemistry (Axelsson and Gunnlaugsson, 2000). Environmental indicators related to sustainability of the liquid-dominated geothermal aquifers in sedimentary basin in the Slovenian part of the transboundary Mura-Zala basin will be discussed in the following text.

This sedimentary basin is one of the Pannonian basin sub-basins and spreads between NE Slovenia, N Croatia, SW Hungary and SE Austria. After the healing effects of »black oil water« were recognized in the early 1960s, many health and spa resorts developed in Slovenia. Individual space heating, greenhouse heating, sanitary water and district heating systems plus swimming and balneology are widely applied now in the region. Quantity of the abstracted thermal water is rather high and there has been only one reinjection well operating in Lendava since 2009 (Rajver et al. 2012; Rman et al. 2012).

Over-exploitation has been studied only in Murska Sobota (Kralj and Kralj, 2000, 2012). Based on the existing studies, four hypotheses were set: a) the hydraulic, b) thermal and c) chemical state of the Neogene geothermal aquifers has changed due to exploitation, and d) the current thermal water abstraction exceeds natural recharge of the aquifers.

2. SETTINGS

The Mura-Zala sedimentary basin is positioned in the western Pannonian basin, where it developed as a result of the Lower to Middle Miocene extension in the Central Paratethys (Royden and Horváth, 1988). Topographically, the hilly parts of Slovenske gorice, Dravinjske gorice, Goričko, Lendavske gorice and Haloze rise above the River Mura and Drava lowlands by approximately 200 m in elevation (Fig. 2).

The metamorphic or carbonate basement rocks are cut into several structural units forming horst-graben-like structures which controlled the heterogeneous Neogene sedimentation that started in confined depressions and later spread to the unified basin. The Ptuj-Grad, Mura, Lendava, Špilje and Haloze Formations are identified (Fig. 1), overlying the basement rocks (Fodor et al. 2011; Jelen and Rifelj, 2011; Maros et al. 2012).

NE Slovenia is heated by an elevated heat flow due to thinner lithosphere which reaches 80-120 mW/m^2 on average (Rajver and Ravnik, 2002). It heats up thin turbiditic sandstone layers of the Badenian and Sarmatian age (Špilje Formation) and of the Lower Pannonian age (Lendava Formation), which represent rather isolated geothermal aquifers with thermomineral water ar up to 75 °C, but oil and gas are abundant there also. Lower part of the more than a kilometre thick Pannonian-Pontian Mura Formation is identified as the most important and exploited geothermal aquifer in the region and abroad (Nádor et al. 2012), producing water at maximum 66 °C (Kralj and Kralj. 2000). The Pontian and Pliocene fluvial deposits of the Ptuj-Grad Fm. yield thermal water below 40 °C.

Chemical and hydrogeological characteristics of this geothermal system have been described by many (Pezdič, 1991; Kralj and Kralj, 2000; Kralj, 2001; Lapanje, 2006; Szőcs et al. 2012). Active gravitational groundwater flow has evolved in the Upper Miocene, and thermal water composition has been modified along the flow path due to water-rock-gas interaction, mixing, geothermal effects, organic matter evolution and degradation, presence of evaporites, etc. Thermal water in the Ptuj-Grad Fm. shows low mineralization, while the one in the Mura Fm. is higher mineralized, but both are of Na-HCO_3 type. In shallower depths (<300 m) up to thousand year old groundwater is perceived, while the Mura Fm. water in depths 0.5 to 2 km is a few ten thousand years old / Pleistocene paleo-meteoric water with a characteristic stable isotope shift (Pezdič, 1991; Szőcs et al. 2012). Rather stagnant thermomineral water of Na-Cl-HCO_3 type stored in the Lendava Fm. has a similar retention time, while the Špilje Fm. and the basement rocks stored water is often diluted brine with strong isotopic evaporative effect.

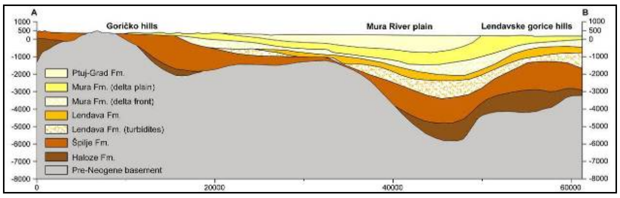

Fig. 1. Geological cross-section of the Slovenian part of the Mura-Zala basin in NW-SE direction, adapted after (Maros et al. 2012).

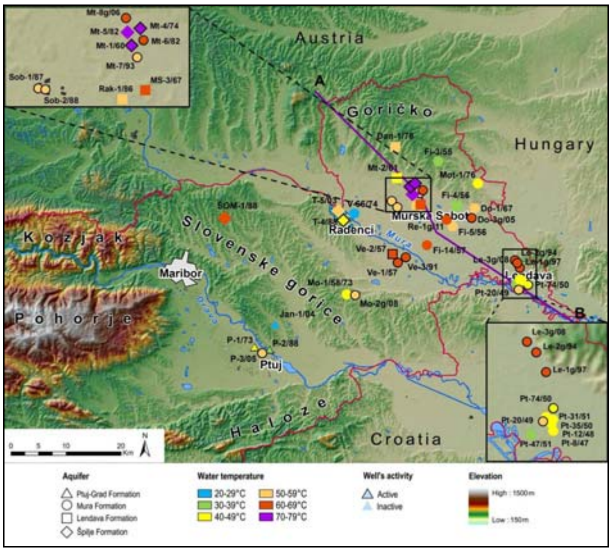

Fig. 2. Geothermal wells tapping the Neogene aquifers and classified by activity and outflow temperature. Mt-8g is classified as Mura Fm. but thermal water from Lendava and Špilje Fms. is also produced from it.

3. METHODOLOGY

First, a historical geothermal development was investigated, plus technical, hydrogeological, chemical, geothermal and production information was organized into a database. Over 900 measurements of hydrogeological parameters (porosity, permeability etc.) were stored along with 238 chemical and 55 isotope analyses performed in the period 1962 to 2012. Information on wells that produce or are capable of producing thermal water was extracted and presented by MS Office Excel, ArcGIS, Surfer, Statistica and AquaChem software. A conceptual model of this geothermal system in the sedimentary basin was developed by interpretation of these data and improved by the results of the EU T-JAM and Transenergy projects (Nádor et al. 2012, Nádor et al. 2013).

Sparse and unsystematic archival chemical and isotopic data did enable some statistical trend estimation, assuming that the analyses are comparable, regardless different laboratories and techniques used as only the detection limit has lowered. Another very important fact for interpretation of hydraulic and chemical trends is that many geothermal wells are perforated over a few hundred meters and often produce water from more aquifers. Consequently, the variations have to be carefully interpreted and they will have to be confirmed by additional analyses and hydraulic testing in future. The »static« groundwater level, pressure, temperature etc. denominations in the text refer to the measured values when the well was not discharging, while »dynamic« values were acquired during thermal water abstraction, and »pre-exploitation« values are gained before any relevant historical thermal water production started.

Graphical methods included visual inspection of scatterplots, triangular plots such as the Piper diagram, Box & Whisker diagrams and time-series or depth diagrams. A linear correlation was calculated for various hydraulic and chemical parameters and linear regression models were applied where possible. Statistically significant trends were denoted from the Student t-test at a significance level of 0.95.

New hydraulic datasets were acquired from a research monitoring network established in the most exploited Mura Fm. aquifer and operating since May 2009, because the national monitoring of geothermal aquifers is yet not operational. Due to limited funds, the monitoring was based on 8 existing wells (Table 1) in the area of the greatest thermal water withdrawal, between towns Radenci, Moravske Toplice and Dobrovnik, but one more well (Fi-3) was added later as an exchange for Sob-1 (Fig. 2).

Table 1. Position of the monitored wells

Well	Location	Z_{SI} (m a.s.l.)	Free depth (m)	Status
Do-1	Dobrovnik	173.50	1913	Inactive
Fi-3	Fokovci	330.00	1755	Inactive
Fi-5	Renkovci	174.50	1326	Inactive
Mt-6	Moravske Toplice	185.90	987	Active (pump)
Mt-7	Moravske Toplice	186.15	991	Active (pump)
Mt-8g	Moravske Toplice	191.84	1257	Active (pump)
Sob-1	Murska Sobota	189.20	870	Active (pump)
Sob-2	Murska Sobota	189.16	887	Active (pump)
V-66	Petanjci	196.12	205	Inactive

Down-hole Siemens pressure and temperature sensors were incorporated into PPI200 transducers produced by the ELTRATEC Ltd. and used in all monitored wells for hourly measurements of groundwater levels and temperatures. Air pressure was recorded simultaneously by a DMT210 transducer at the Mt-7 wellhead. Data were daily transmitted via a GSM/GPRS modem to the GeoZS server and stored electronically in the database. The cumulative daily thermal water abstraction was collected manually from various types of water-gauges by the very helpful maintenance staff. Not all records were continuous, mainly due to technical failures because induced by high gas content, high temperature or electromagnetic fields.

4. RESULTS AND DISCUSSION

4.1 Historical thermal water abstraction from the Neogene geothermal aquifers

The historical thermal water withdrawal is only informative before 1995. Systematic overviews of geothermal energy use are made every 5 years since then, providing more reliable data (Rajver et al. 2010). Almost all users measure daily and annual thermal water abstraction now and therefore these quantities are quite accurate.

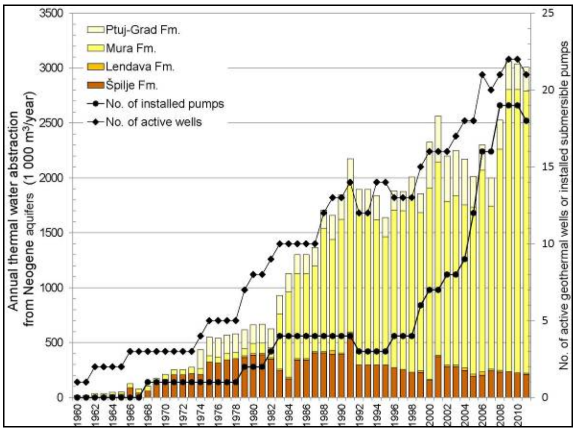

Fig. 3. Annual thermal water abstraction from the Neogene aquifers and the numbers of active abstraction wells and installed submersible pumps in the period 1960-2011, including one reinjection well active since 2009.

The number of active geothermal wells tapping the Neogene aquifers has been steadily increasing since 1960 (Fig. 3) with four new wells activated every ten years on average. The maximum of 21 production and one reinjection wells was reached in 2009 and 2010. Many new wells were started up in Moravci, Moravske Toplice and Banovci in the early 1980s, used for bathing and swimming mainly. Additional wells were drilled at existing sites in the early 1990s and later at new locations in Radenci and Murska Sobota. Quite a lot of new drillings occurred during the last 10 years at new locations, focused especially on geothermal heat exploitation. Spatial distribution, prevailing producing geothermal aquifer, activity and discharged water temperature of geothermal wells as identified in 2012 are shown in Fig. 2. Altogether, 43 geothermal wells are identified, but almost half of them are inactive (Table 2). Thermal water from the

Lendava and Špilje Fms. is rarely captured despite having the highest temperature, as high carbonate scaling potential and gas content make it difficult to use. Most geothermal wells intercept the very productive Mura Fm. Half are active and one reinjection well has been operating during the colder months of the year in Lendava. The Ptuj-Grad Fm. was tapped more than 20 years ago by two wells in Ptuj, which still produce thermal water. However, a new well from 2004 is yet not developed.

Table 2. Active and inactive geothermal wells classified by the main geothermal aquifer

Aquifer Fm.	Active wells		Inactive wells	*Total*
	Abstraction	Reinjection		
Ptuj-Grad.	2	0	1	***3***
Mura	14	1	13	***28***
Lendava	1	0	5	***6***
Špilje	3	0	3	***6***
Total	***20***	***1***	***22***	***43***

Total regional withdrawal of thermal water in the period 1960-2011 is estimated to be 64.889 million m^3. The majority of production comes from the Mura Fm. (67%), with almost 70% of it produced in Moravske Toplice and Murska Sobota due to the high abstraction rates needed for geothermal heat utilization systems. The reinjection well in Lendava may locally improve the state of this aquifer but less than 3% of the total abstraction from the Mura Fm. is returned. 19% of all thermal water was produced from the Špilje Fm. during the 50-years of its exploitation. A little lower fraction, 13%, comes from the Ptuj-Grad Fm. Its productivity is restricted by lower temperatures and therefore lower usability. Only 1% comes from the Lendava Fm., however, if production from wells which tap both, the Mura and Lendava Fms., is considered this share would be a little higher.

4.2 Archival datasets analysis

Alterations of abstraction rate, GWL or aquifer pressure and water temperature often give the first indications of hydraulic changes. Only sparse and unsystematic measurements were available from the archives because hydraulic measurements were made either after (re-)drilling or when some issues occurred, and only half wells have records available. A variety of chemical datasets is available but only 11 wells had at least 4 chemical analyses performed on different years and were included in the investigation (Fig. 4).

Wells Mt-1, Mt-4, Mt-5 and T-4 tapping the Špilje Fm. are still producing without submersible pumps. Their reservoir pressure was approximately constant until the late 1980s. Despite the fact that the annual thermal water withdrawal reduced after the 1990s, being 6-7 l/s on average, the aquifer pressure has decreased as well as the discharge. Chemical and isotopic water sampling was not systematically performed. Trends indicate that an oil-field brine of marine character, which was produced at the beginning of exploitation in Moravske Toplice, was no longer discharged by the late 1970s, and the diluted brine has been produced from then on (Fig. 5). The latter shows a clear dilution trend with a statistically significant decrease in sodium and chloride concentrations, indicating continuous depletion of this component nowadays. Because the bicarbonate concentration has been rising and the isotopic shift indicates different waters being accessed than previously, an induced aquifer recharge is assumed.

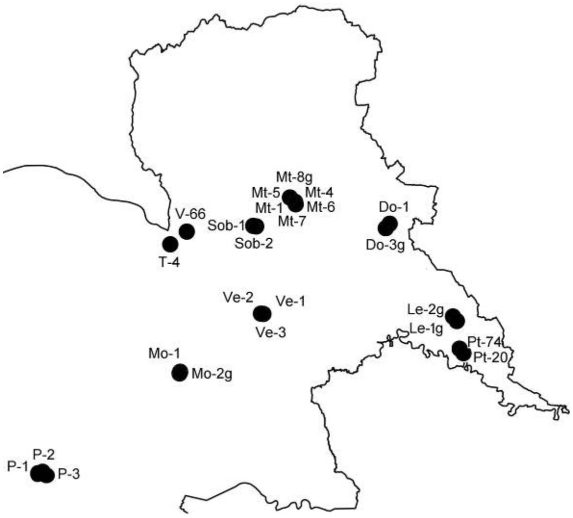

Fig. 4. Location of geothermal wells included into interpretation of chemical trends

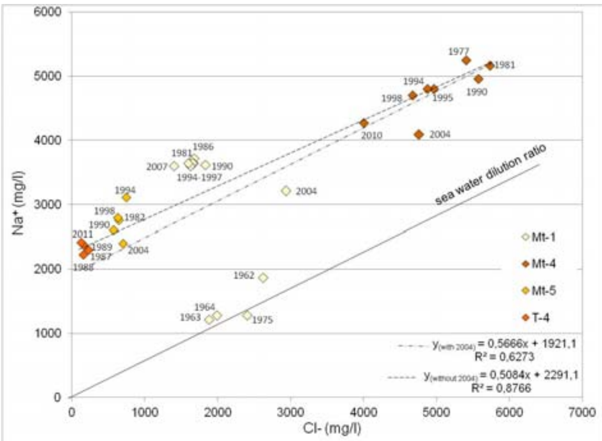

Fig. 5. Variation of the sodium-chloride ratio in thermomineral water from the Špilje Fm. (Mt-4 and T-4) and the Špilje & Lendava Fms. (Mt-1 and Mt-5) over years of exploitation. Dashed trend lines indicate a dilution trend in Mt-4, statistically significant at p<0.05. A distinction is made due to outliers from 2004. The analytical error of the 2010 analysis is ±2%.

There are no aquifer pressure measurements available for the Mura Fm. aquifer after 2000. Previous do show decreasing trends in GWL and discharge rate, and this information is supplemented with changes in chemistry and isotopes. Many wells which capture water from both the Mura and Lendava Fms. simultaneously may have unclear chemical changes but very clear isotopic alterations (Mt-6, Mt-7, P-1, Sob-1, Sob-2, Ve-1). At the beginning of geothermal development, the wells produced lots of water from the Lendava Fm. and therefore the mixture was highly mineralized and gaseous. As the replenishment of these layers is poor and their pressure decreased significantly, less mineralized thermal water became predominant. A sodium-chloride concentration decrease is observed in Moravske Toplice, while thermal water in Lendava has undergone different geochemical processes and therefore its chloride concentration is not characteristic. There, a significant ($p<0.03$) decrease in sodium and bicarbonate concentrations marks the same depletion process. Regionally, the bicarbonate concentration is decreasing but exceptions are noticed. According to the stable isotopic shift towards the heavier and more meteoric water component, an induced recharge of less mineralized Pleistocene water is observed in most wells. However, no simple explanation can be applied to the observed isotopic alterations. As the retention time of the originally produced water was not determined by carbon-14 method, for instance, it is impossible to say whether the observed recharge is older or younger than the originally produced water. Leakage of bicarbonate pore water is also a possibility but it has to be checked separately by interpretation of trace and rare earth elements as described already by (Kralj and Kralj, 2009), continuous studies of stable isotopes and carbon-14 variations. Regarding the Ptuj-Grad Fm., not many data are available and therefore the status assessment is not reliable. A significant chloride decrease ($p<0.003$) and a bicarbonate increase ($p<0.05$) plus surprisingly light stable isotopes indicate the possibility of older bicarbonate pore water leakage caused by an almost constant but very long-term abstraction of 7 l/s of thermal water in Ptuj.

4.3 Interpretation of the research monitoring results

Useless data was gained in Sob-1 as this well encounters pressure, temperature and chemical fluctuations and has unpredictable CO_2 blowouts. The Sob-2 well has reliable measurements only till the beginning of 2011, while the probe had to be removed from Fi-5 in December 2011 due to reinjection testing in a double with Re-1g. Nevertheless, seasonal variation in water withdrawal is noticeable for the three wells in Moravske Toplice, where the highest abstraction is applied in February and the lowest in July. This variation is directly connected to thermal water demand which is the highest in cold season when the resorts and nearby buildings are heated by geothermal energy. The timetable of changing production rates is rather synchronized between the wells however their amplitude varies significantly. The highest abstraction is reported for Mt-6, exceeding max. 2,000 m^3 daily. Mt-7 has a max. of 1,400 m^3, while Mt-8g app. 1,000 m^3. The summer minimums are similar, 300-500 m^3 daily. The daily measurements for Mt-8g were available only for 2010 and therefore this abstraction was not included into the daily regional abstraction as shown in Fig. 6. Sob-2 exhibits a more constant abstraction rate, close to 500 m^3 daily, while production from Sob-1 is 20% higher in summer.

The temperature in observation wells was perceived to be constant or within the range of measurement error over the whole investigated period and around the average annual air temperature of 11 °C. However, abstraction wells Mt-6, Mt-7, Mt-8g and Sob-2 show daily, seasonal and annual temperature trends. Daily variations are positively correlated to the abstracted water quantity and pumping frequency, where the fluctuations reach up to 4 °C and are usually higher in the summer when less water is abstracted. The seasonal trend is positively correlated to daily water withdrawal as the higher withdrawal results in higher water temperatures. These fluctuations are around 1 °C, except in Sob-2 where up to 4 °C was measured and is probably connected to gas eruptions. The annual thermal water temperature was not observed to change significantly in the observed 3.5 year time interval in the producing wells.

Table 3. Statistics of the observed GWLs in the period 1/5/2009 to 1/11/2012.

Well	No. of data	Mean (m a.s.l.)	Max. (m a.s.l.)	Std. dev. (m a.s.l.)
Do-1	29,232	168.46	170.57	0.90
Fi-5	29,233	195.06	195.84	0.43
V-66	29,234	196.35	197.22	0.52
Mt-6	22,725	175.45	190.21	6.53
Mt-7	24,655	173.68	189.00	11.14
Mt-8g	26,002	190.58	211.52	9.74
Sob-2	8,623	189.33	194.80	2.74

Table 4. Linear regression trends of the hourly GWLs in the period 1/5/2009 to 1/11/2012.

Well	R^2	r	Linear regression trend
Do-1	0.31	-0.56	169.34 – 5.72E-05*x
Fi-5	0.97	-0.98	195.87 – 6.74E-05*x
V-66	0.94	-0.97	197.24 – 5.79E-05*x
Mt-6	0.01	0.07	174.50 + 5.86E-05*x
Mt-7	0.01	-0.10	175.69 – 1.29E-04*x
Mt-8g	0.20	-0.44	198.89 – 4.99E-04*x
Sob-2	0.84	-0.92	193.36 – 4.87E-04*x

On the contrary, groundwater levels decreased significantly (Tables 3, 4), depending on spatial distribution, activity and production history of the wells. Distant observation wells V-66 and Fi-5, positioned approximately 8 km away from the abstraction sites in Moravske Toplice and Murska Sobota, are very appropriate for long-term regional trends observation, because the daily amplitude of about 5 cm and with phase change every 12 hours was observed. These observation wells show a synchronous negative correlation between the regional abstraction rate and GWLs which sharply decline from January to August and remain quite constant from then to the next January (Fig. 6). A hydraulic time-lag of 5 to 6 months can be deduced from these observations. Despite long recovery period, no relevant increase in piezometric GWL was noticed in the two wells in the observed interval even though the total annual abstraction from the Mura Fm. aquifer was stable. After the statistically significant GWL linear trend was removed (Table 4), the average seasonal amplitude was in a range of 8 to 15 cm. The average annual regional decrease rate is calculated to -0.53 m. GWL fluctuations in Do-1 are much influenced by the nearby abstraction well Do-3g and show almost no time-lag with lower abstraction and fast recovery in the summer months.

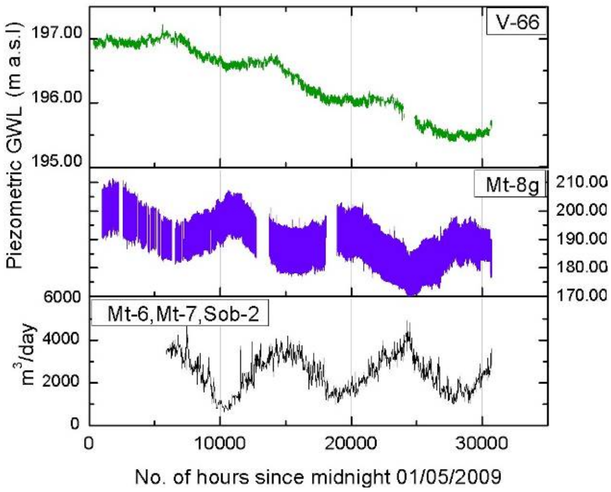

Fig. 6. Piezometric GWLs in V-66 and Mt-8g in the period May 2009 to Nov 2012. The daily sum of thermal water withdrawal from Mt-6, Mt-7 and Sob-2 is presented. X-axis corresponds to dates: 0 = 1/5/2009; 10,000 = 21/6/2010; 20,000 = 12/8/2011; 30,000 = 01/10/2012.

Daily dynamic GWL fluctuations in abstraction wells depend on the abstraction rate and vary from 2 to 12 m in Sob-2, 9 to 15 m in Mt-6, 15 to 20 m in Mt-7 and around 18 m in Mt-8g (Fig. 6). Seasonal fluctuations of the maximum dynamic GWL lay in a range of 7 (Mt-7) to 16 m (Mt-6). The three monitored abstraction wells confirm the aforementioned long-term GWL decline trend (Table 4), while the Mt-6 contradicts to this with an indication of a slight increase in the average GWL (+0.5 m annually). However, its maximum dynamic GWL has been constantly decreasing, with a calculated downward trend of approximately -0.4 m per year. Even though this well has the highest annual abstraction it obviously receives high recharge and has very good technical characteristics. The fastest dynamic GWL decrease rate of -4.4 m per year is observed in Mt-8g, which is probably not yet hydraulically equilibrated as the production started only few years ago. It is followed by Sob-2, where the annual dynamic GWL decrease of -4.3 m is calculated. This well has been producing for over 20 years and over-exploitation has been proved in the area (Kralj and Kralj, 2000). The decrease rate of -1.1 m is determined for Mt-7.

The available abstraction rate, which remains after the legislative and environmental etc. restrictions are considered, is called the »sustainable yield« and is significantly lower than the natural recharge but it can be elevated by applying artificial recharge where feasible (Sophocleous, 2010). If a comparison between the regional static piezometric GWLs in observation wells is done for the pre-exploitation time and the year 2012, the total regional decrease is calculated to be approximately -15 m. This is below the critical regional piezometric GWL decrease point of 30 m, which should limit the sustainable transboundary geothermal energy resources in the Mura-Zala basin according to Nádor et al. (2012). However, this limit has been reached or exceeded in the inspected abstraction wells, indicating the critical areas locally. Because the regional static piezometric GWLs have been constantly decreasing and the maximum GWLs do not return to the previous-year values, it can be concluded that the current regional average annual abstraction of little more than 80 l/s exceeds the sustainable yield of the Mura Fm.

5. CONCLUSIONS

Three of the four hypotheses postulated in the introduction can be accepted as the observed Neogene clastic geothermal aquifers in the Mura-Zala sedimentary basin have hydraulically (a) and chemically (c) responded to the historical thermal water abstraction, but no thermal water wellhead temperature alterations have been determined (reject b). Diverse rates of change are noticed for individual wells and aquifers dependent on their hydrogeological settings and development stage. The continuously declining regional static piezometric GWL trend indicates that current thermal water abstraction exceeds the recharge rate in all inspected geothermal aquifers developed in the Ptuj-Grad, Mura and Špilje Formations, which confirms the (d) hypothesis.

Over-exploitation may arise from poor hydrogeological understanding of the system but inadequate monitoring and lack of common management strategies importantly contribute to the problem in Slovenia (Vižintin et al. 2008; Rman et al. 2011). This research prompts the need to raise awareness of thermal water users and managers in order to enhance rational abstraction and efficient use. Since it shows that geothermal aquifers highly stressed, a fast and efficient strategy on future exploitation and artificial recharge should be carried out in order to mitigate their further deterioration. Both, physical and chemical monitoring of geothermal aquifers are essential to be established if relevant processes have to be observed and interpreted. The abstraction scenarios should be adjusted accordingly in order to enable a continuous and long-term sustainable exploitation of these low enthalpy geothermal aquifers.

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