



# Analysis of long-term thermal water abstraction and its impact on low-temperature intergranular geothermal aquifers in the Mura-Zala basin, NE Slovenia



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## ABSTRACT

The already exploited geothermal resources in the Mura-Zala basin are planned to be further developed. In this study I investigated thermal water abstraction and its impact on both the fissured basement aquifers and the intergranular Neogene siliciclastic aquifers. Total abstraction of thermal water in north-east Slovenia summed to 3.1 million m<sup>3</sup> in 2011, with very limited artificial recharge supplied through a single reinjection well. This exploitation has resulted in depletion of the aquifers, with decline in aquifer pressure, piezometric groundwater levels and discharge rates, as well as chemistry variation, being evident in many wells. A research monitoring network has been established in 2009 and has been taking hourly measurements in eight wells. These wells are up to 2 km deep and tap aquifers in the Upper Miocene sandy Mura Formation. Daily, seasonal and annual trends were interpreted, and the measured overall regionally declining static groundwater levels are alarming, reaching 0.53 m per year. Despite the changes in conditions in the aquifers, no change of production temperature has so far been perceived.

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## 1. Introduction

Low-temperature geothermal aquifers in sedimentary basins are widely exploited for direct use (Lund et al., 2011). Typical examples of such sand and sandstone geothermal reservoirs occur in France, Hungary and China, as well as in the system discussed here, namely the Slovene part of the Mura-Zala basin. Despite the fact that these resources have been exploited for many decades, observation of their performance has been focused predominately on energy efficiency. Systematic country reports on direct use are updated every five years; however, they do not include any data on the response of geothermal aquifers to their exploitation. Since economically viable abstraction of a geothermal fluid from a geothermal reservoir usually causes its depletion (Axelsson and Gunnlaugsson, 2000; Rybach, 2003), sustainability of ground and/or thermal water abstraction should be followed in order to ensure long-term resource availability. The sustainability of exploitation can be evaluated by various approaches (Sophocleous, 2000; Axelsson, 2010; O'Sullivan et al., 2010; Duan et al., 2011), but reliable datasets on production and reservoir behavior parameters are required for all of them. Several studies were carried out when issues with respect to water or energy availability were indicated. A decrease of artesian pressure in the Paris basin in France

was successfully mitigated by the use of geothermal doublets. Variation in sulfide was used as a chemical breakthrough tracer, and no thermal breakthrough was evident (Lopez et al., 2010). Much more noticeable hydraulic and chemical changes were observed in Hungary due to low reinjection rates (Ottlik, 1990; Tóth, 2009; Szanyi and Kovács, 2010). Total groundwater level drawdown at geothermal fields in Szeged, Szentes and Hajdúszoboszló was measured to be as much as 90 m, but no temperature variations were reported (Szita, 1995; Szanyi and Kovács, 2010). In the Tanggu and Tianjin reservoirs in China, the average drawdown rate was from 3 to 9 m per year, and no temperature or chemical changes were published (Axelsson and Dong, 1998; Kun, 2005; Lei and Zhu, 2013). For the current study area in Slovenia, hydraulic and chemical changes in the Mura-Zala basin have often been discussed at a local level (Pezdič, 1991; Kralj, 1993; Kralj and Kralj, 2000a, 2012; Kralj et al., 2009b), and a few overview studies have also been carried out (Rman et al., 2011; Nádor et al., 2012).

The Mura-Zala basin spreads mainly over northeastern Slovenia and southwestern Hungary. Thinning of the lithosphere has resulted in an elevated heat flow of above 100 mW/m<sup>2</sup> (Rajver et al., 2012). Porous Neogene siliciclastic deposits have formed very important regional geothermal aquifers there, and these may be affected by enhanced use of geothermal energy in Slovenia in the near future, as increased exploitation is foreseen, according to the National Renewable Energy Action Plan, in the period from 2010 to 2020 (Urbaničič et al., 2011). The Miocene, Pannonian and Pontian Mura Formation sandy geothermal aquifer shows the most

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favorable geothermal conditions in the country, and also significant transboundary characteristics (Nádor et al., 2012; Szöcs et al., 2013). Besides, the data indicate a high risk of overexploitation, and therefore identification of its current state is extremely important for developing sustainable exploitation strategies. The present study was initiated because of the insufficient regional management of geothermal resources in Slovenia (Vižintin et al., 2008; Rman et al., 2011). Its purpose is to investigate the influence of thermal water withdrawal on the quantitative and qualitative state of geothermal aquifers in the Mura-Zala basin. Several hypotheses are tested:

- (1) The physical state of the geothermal aquifers has changed due to exploitation,
- (2) The chemical composition of the thermal water has changed due to exploitation, and
- (3) The current rate of thermal water abstraction is unsustainable.

The study reviews not only the historic thermal water abstraction from different aquifers and their physical and chemical state since 1960, but it also presents the results from a research monitoring network, established in 2009, in eight geothermal wells tapping the most exploited Mura Formation. Exploitation data are supplemented by information on hourly and overall trends of piezometric groundwater levels and water temperatures. The results enable quantification of the regional state of the monitored aquifer, evaluation of the sustainability of its current rate of exploitation, and a comparison with similar geothermal sites in the world.

## 2. Study area

### 2.1. Hydrogeological settings

This article focuses on the Slovenian part of the Mura-Zala sedimentary basin, which is one of the western sub-basins of the Pannonian basin. It developed as a result of the Lower to Middle Miocene back-arc style extension in the Central Paratethys (Royden and Horváth, 1988) and it is characterized by fast and heterogeneous Neogene sedimentation (Fodor et al., 2002; Martona et al., 2002). Topographically, the Slovenske gorice and Goričko hills, with elevations of above 300 m, dominate the lower flatlands of the Mura and Drava River plains (Fig. 1).

The Paleozoic metamorphic rocks are dissected into several structural units forming the horst-graben structure that controlled the Neogene sedimentation (Fig. 2). These basement rocks contain little thermal water; however, some fissured basement aquifers have been developed in permeable fault zones, and are captured at Benedikt and Maribor (Fig. 1). Mesozoic carbonate basement aquifers were tested at a few locations, but are not exploited. This sequence is covered by stratified Neogene siliciclastic deposits (Žlebnik, 1978). Geothermal aquifers in the Carpathian to Lower Pannonian sandstone of the Haloze and Špilje Formations (Jelen and Rifelj, 2011) were previously identified as the Murska Sobota Formation (Turk, 1993; Kralj and Kralj, 2000b), and are tapped at Radenci and Moravske Toplice. The Middle and Upper Pannonian sandstone of the Lendava Formation has similar hydrogeological properties to the aforementioned rocks, where low porosity and permeability are only locally enhanced by fissures and fractures. These isolated aquifers evolved in rather thin turbiditic sandstone, and often show abundant occurrences of oil and gas. Thermo-mineral water, unique to the Lendava Formation, is tapped only in Banovci; however, over 10 wells at other sites produce a fraction of their output in this zone. Also, a marine depositional environment is characteristic of the Mura Formation sand and loose sandstone of the Pannonian to Pontian age (Jelen and Rifelj, 2011). The

hydraulically connected sand lenses are deposited in a delta front environment and are often poorly lithified. This most important regional geothermal aquifer is separated from under- and overlying aquifers by thick layers of clay and marl, which are characteristic also of the Mura Formation delta plain sediments. Thermal water from the Mura Formation is currently produced at geothermal sites in Banovci, Dobrovnik, Lendava, Moravci in Slovenske gorice, Moravske Toplice, Murska Sobota, Petišovci, Ptuj and Renkovci. The term Mura Formation was previously attributed to all Pannonian and younger deposits (Turk, 1993), and a commonly used name for geothermal aquifers located in these sediments is Thermal 1 (Kralj, 2004). The most recent litho-stratigraphic classification distinguishes between the deltaic Mura Formation sediments and the younger Pontian to Pliocene fluvial Ptuj–Grad Formation (Jelen and Rifelj, 2011). The latter has similar favorable hydrogeological characteristics, but contains predominately lukewarm water, which is currently exploited only in Ptuj. Fresh water aquifers occur in the Plio-Quaternary and Quaternary gravel, and are hydraulically connected to the Mura or Drava Rivers.

A hierarchically nested gravitational flow system (Tóth, 2009) evolved in the two low-enthalpy warm water geothermal systems in the Mura-Zala basin, in the sedimentary basin aquifers and in its basement. The general groundwater flow direction is approximately from west (Slovenia) to east (Hungary). Natural outflows of mineral water have been identified in Radenci and Nuskova (Pezdič et al., 1995), while thermal water discharges as a slow and hidden seepage into the fresh water Pliocene and Quaternary aquifers. In the case of the Mura Formation aquifer, a part of the water discharges into the Hévíz Lake in Hungary (Nádor et al., 2012).

### 2.2. Hydro-geochemical settings

The vertical stratification of aquifers is reflected in groundwater hydro-geochemical zonation. Young meteoric fresh water of the Ca-Mg-HCO<sub>3</sub> type is stored in the Quaternary and shallower parts of the Ptuj–Grad and Mura Formations (Žlebnik, 1975, 1978; Pezdič et al., 1995; Žlebnik and Drobne, 1999; Szöcs et al., 2013). The composition of the groundwater evolves along the regional flow path into one of the Na-HCO<sub>3</sub> type, and the process is being governed by cation exchange. Lukewarm and thermal water of the Ptuj–Grad Formation has mineralization of below 0.5 g/l, while thermal water of the Mura Formation has mineralization of up to 1.2 g/l. These paleo-meteoric waters were recharged in the Pleistocene (Szöcs et al., 2013). The same retention time is assumed for thermo-mineral water stored in the Lendava Formation, where intense water-rock–gas interactions in the presence of gas and oil result in high mineralization, up to 20 g/l. Thermo-mineral water stored in the Haloze and Špilje Formations is a diluted brine of the Na-Cl and Na-HCO<sub>3</sub>-Cl types, and is probably the oldest water in the basin; however, its chemical signature has been greatly altered by various geochemical processes (Kralj, 2001). Thermo-mineral water in the Mesozoic carbonate and Paleozoic metamorphic rocks has moderate mineralization and an Na-HCO<sub>3</sub> character (Kralj et al., 2009a). The most common gas controlling the composition of thermal water is CO<sub>2</sub>, which is emitted in large quantities along the Raba fault zone (Kralj and Kralj, 2000b; Lapanje, 2006).

Over a few hundred meters length, many geothermal wells are open and they capture several aquifers simultaneously (Table 1, Fig. 3). This is not only in conflict with the Water Framework Incentives (EC, 2000), but also enables artificial in-well flow between aquifers. The researchers attributed variations in chemical composition of thermal waters to two processes: either to natural mixing along permeable structures, such as faults, or to artificial mixing in multiple-screened wells (Kralj and Kralj, 2012; Rman et al., 2012).

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