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Transboundary geothermal resources of the Mura-Zala basin: a need for joint thermal aquifer management of Slovenia and Hungary

Čezmejni geotermalni viri Mursko-Zalskega bazena: potreba po skupnem upravljanju geotermalnih vodonosnikov Slovenije in Madžarske

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Ključne besede: geotermalna energija, termalna voda, čezmejni vodonosnik, tokovni model, Panonski bazen

Abstract

Large transboundary Upper Miocene geothermal sandy aquifers which are widely utilized by both countries for balneological and direct heat purposes exist in the Slovenian-Hungarian border region. In NE Slovenia the total direct heat use was 382 TJ in 2010, while in SW Hungary it was 648 TJ, including utilization from basement reservoirs. The total installed capacity of the 13 Slovenian users was 38.8 MW_t, while that of the 29 Hungarian users was 70.6 MW_t. Utilisation takes place without harmonized management strategies which might endanger the long-term sustainability of these systems. We aimed to overcome this by delineating a transboundary thermal groundwater body (TTGWB) Mura-Zala with an aerial extent of 4,974 km^2 and with vertical extent between depths 500–2,200 m, which was done based on detailed geological, hydrological, geochemical and geothermal models as well as numerical modelling. The regional groundwater flow in the Mura-Zala TTGWB is from west to east in general, the modeled cross-border flow is approximately 50 l/s. At present, thermal water abstraction rates from the Mura/Újfalu Fm. (61.8 l/s in the Slovenian and 67.3 l/s in the Hungarian part of the TTGWB) does not endanger the good regional quantity status of the water body, and this should be maintained by allowing a maximum increase of thermal water abstraction 3.5 times higher than today. However, to achieve target numbers for an increased proportion of geothermal energy in the total energy mix in both countries, we suggest that increase of thermal efficiency and re-injection should be prioritized apart from the higher thermal water abstraction with setting up limit of the maximum allowable drawdown.

Izvleček

Na mejnem območju med Slovenijo in Madžarsko so razprostranjeni obsežni, prekomejni zgornjemiocenski geotermalni peščeni vodonosniki, ki se v obeh državah uporabljajo predvsem v balneološke namene in za direktno rabo toplote. V severovzhodni Sloveniji je skupna direktna raba toplote v letu 2010 dosegla 382 TJ, v jugovzhodnem delu Madžarske pa 648 TJ, vključno z rabo vodonosnikov v podlagi neogenskih kamnin. Celotna inštalirana kapaciteta 13 slovenskih uporabnikov je znašala 38,8 MW_t, medtem ko je inštalirana kapaciteta pri 29 madžarskih uporabnikih dosegla 70,6 MW_t. Uporaba poteka brez usklajene strategije upravljanja, kar lahko ogrozi dolgoročno vzdržnost teh sistemov. To smo želeli preseči z opredelitvijo prekomejnega Mursko-Zalskega telesa termalne podzemne vode (VTPodV Mura-Zala) s površino 4.974 km^2 in vertikalnim razponom globine 500–2200 m, določenega na podlagi podrobnih geoloških, hidrogeoloških, geokemičnih in geotermalnih modelov, kot tudi numeričnega modela podzemne vode. Tok podzemne vode v VTPodV Mura-Zala je usmerjen pretežno v smeri zahod-vzhod, pri čemer je prekomejni tok ocenjen na približno 50 l/s. Pri trenutni količini odvzema termalne vode (~ 61,8 l/s iz slovenskega ter ~ 67,3 l/s iz madžarskega dela VTPodV Mura-Zala) količinsko stanje telesa ni ogroženo, a njegovo dobro stanje je potrebno ohranjati z omejitvijo maksimalnega povečanja odvzema termalne vode na 3,5-kratnik današnjega odvzema. Da bi dosegli ciljne vrednosti povečanja deleža geotermalne energije v skupni energetski bilanci v obeh državah, namesto povečanega odvzema termalne vode priporočamo povečanje toplotne učinkovitosti, določitev največjega dovoljenega zniževanja tlaka v vodonosniku in vzpostavitev vračanja toplotno izrabljene termalne vode nazaj v vodonosnik.

Introduction

Growing energy demand, restricted reserves of fossil fuels and efforts to reduce greenhouse gases emissions, thus contributing to the mitigation of climate change effects made clear that within 20-30 years a significantly growing proportion of energy has to come from renewables. The integrated climate and energy policy of the EU [COM (2006)848] aims to reduce energy consumption and greenhouse gases emissions by 20 % and increase the proportion of renewables by 20 % by 2020. This ambitious goal is manifested in the 2009/28/EC Directive on the promotion of the use of energy from renewable sources, on the basis of which each country prepared its national renewable energy action plan where they defined the target numbers. In these strategies both Slovenia (Urbančič et al., 2011) and Hungary (Nemzeti Fejlesztési Minisztérium, 2010) aim at 3-3.5 times increase of geothermal heat production from 2010 to 2020 (in Slovenia from 1.11 to 3.42 PJ, in Hungary from 4.23 to 14.95 PJ), which is mostly based on the promising geothermal potential of the Pannonian basin.

Geothermal energy has been widely utilized for more than hundred years in the Pannonian basin by the abstraction of deep circulating thermal groundwater that extracts and transports heat from hot permeable rock volumes in the depth. This classical hydrogeothermal system is governed by convection in zones with higher permeability or faults, and by conduction in less permeable deposits (Tóth & Almási, 2001; Tóth, 2009). Although this large flow system forms one interconnected entity in geological-hydrogeological terms, it is cross-cut by state-borders, and its various parts are shared by neighboring countries in Central Europe. When adjacent countries exploit the same geothermal resource (thermal groundwater aquifer), fluid extraction at a national level without cross-border harmonized management strategies may cause negative impacts (depletion or overexploitation), leading to economic and political tensions between countries. The ICPDR (www.icpdr.org) manages mostly transboundary surface water resources in the Danube River Basin, however a successful management example of thermal karst between Lower Bavaria and Upper Austria (Vollhofer & Samek, 2010) is now also among their assignments.

Interpretation of the geological structure of the Mura-Zala sedimentary basin, situated at the Slovenian-Hungarian border region and positioned in the southwestern part of the Pannonian basin (Fig. 1) (Sachsenhofer et al., 2001; Tomljenović & Csontos, 2001; Fodor et al., 2002; Saftić et al., 2003; Fodor et al., 2005) implied the existence of transboundary geothermal aquifers but only little bilateral scientific cooperation was established before 2009. Due to rather poor monitoring network and scarcity of comparable datasets in NE Slovenia (Rman et al., 2011b) not much overexploitation effects have been observed, therefore no transboundary conflicts of these widely utilized geothermal aquifers have yet emerged. However, to avoid potential conflicts among users in the two countries as well as between different utilization aspects (e.g. balneology and/or direct heat purposes) in future, a harmonized management strategy of identified transboundary geothermal resources is required to ensure their sustainable utilization. Integrated study of potential regional and transboundary geothermal aquifers were the focus of the T-JAM project (Thermal Joint Aquifer Management: Screening of geothermal utilization, evaluation of thermal groundwater bodies and preparation of joint aquifer management plan in the Mura-Zala basin) running between years 2009 and 2011 in the frame of the Slovenia-Hungary Operative Program 2007-2013. A complex geological, hydrogeological, hydrogeochemical and geothermal assessment of the potential geothermal resources in regions of Pomurje and Podravje in NE Slovenia and in Vas and Zala counties in SW Hungary enabled identification and delineation of a transboundary thermal groundwater body Mura-Zala, for which a harmonized management strategy was elaborated. In addition, utilization aspects of the existing geothermal resources were inspected forcasting a rapid increase in thermal water demand (Rman et al., 2011b; Rman et al., 2012), taking also into consideration environmental objectives. As the transboundary groundwater bodies between Slovenia and Hungary are not officially delineated yet (Rman et al., 2011b) there is no common resource management in practice. However the results of this study already provided a firm scientific basis for a discussion on transboundary groundwater resources at the Slovenian-Hungarian Water Management Commission in 2011.

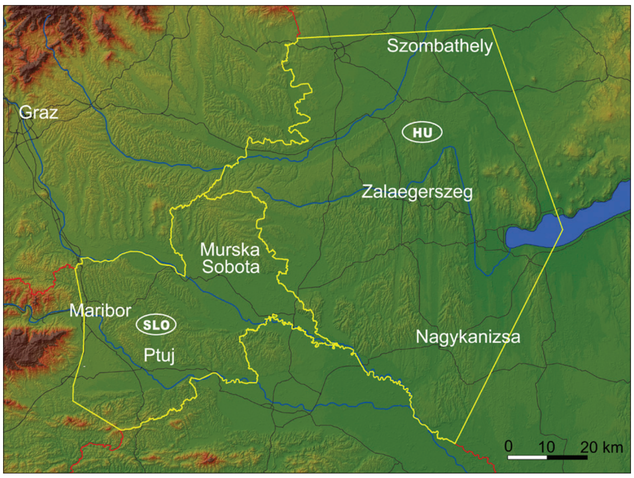


Fig. 1. T-JAM project area

Settings of the investigated Mura-Zala sedimentary basin

The geothermal potential of the Pannonian basin is outstanding in Europe, as it lies on a characteristic positive geothermal anomaly, with heat flow density ranging from 50 to 130 mW/m² with a mean value of 100 mW/m^2 and geothermal gradient of about 45 °C/km (Dövényi & Horváth, 1988; Hurtig, 1992; Lenkey et al., 2002; Rajver & Ravnik, 2002). This increased heat flux is related to the Early-Middle Miocene back-arc style extension of the Pannonian Basin following the ongoing subduction along the Carpathians, when the lithosphere thinned and the hot astenosphere got closer to the surface (Horváth & Royden, 1981). After the closure of marine connections in the area via deep troughs with elevated ridges in the basement (about 12 Ma ago), the continuing post-rift subsidence provided the possibility for the formation of a huge lake (Lake Pannon), which extended and deepened until ca. 9.8 Ma before present (Magyar et al., 1999).

During the Lower Miocene the lake basin started to be infilled rapidly from north-west and north-east by huge deltaic systems of rivers, originating in the surrounding Alpine and Carpathian mountain belts (Bérczi & Phillips, 1985; Juhász, 1994; Jelen et al. 2006), being composed mainly of clays, clayey marls, calcareous sandstones and limestones which crop out on the surface in Slovenia. The prograding delta systems of Lake Pannon reached the area of the Mura-Zala basin about 8-9 Ma ago from the north, with a gradually extending sedimentary shelf behind them (Jelen et al. 2006; Uhrin et al., 2009). The deposited Late Miocene-Pliocene sedimentary succession is up to 2500-3000 m in thickness. A large portion of the coarse sediment reached the basin floor due to turbidity currents forming on the slopes. The slope sediments, built up by silt and argillaceous marl were overlain by the deposits of the shelf, commonly beginning with thick sand-bodies of delta fronts. As the shelf margin prograded basinwards, a delta plain, then an alluvial plain evolved. In the latter two environments, meandering channels built up sandy point bars, while fine-grained sedimentation took place in the inter-channel areas (Fig. 2).

Within this several thousand meters thick sedimentary succession, fluid reservoirs are linked mainly to turbiditic sand bodies; however, their potential is limited by their low connectivity as each of them deposited by a single turbidity current. Much better connectivity can be expected among those large sand bodies which once deposited in the front of the prograding delta-systems (Fig. 2). These 50-300 m thick sand-prone units, composed of individual delta lobes of 10-20 m in thickness, divided by pelitic layers, have an areal extent of 200-2,000 km^2 and are found in a depth interval of about 700-1,400 m in the interior parts of the Pannonian basin, where the temperature ranges from 50 to 70 °C (Žlebnik, 1978; Dövényi & Horváth, 1988; Kralj & Kralj, 2000a) and are considered as the main thermal-water bearing aquifers.

In addition to these porous reservoirs, the karstified zones of the Palaeozoic-Mesozoic carbonates in the basement, as well as fractured zones along main regional tectonic faults in the crystalline rocks are also good thermal water reservoirs. At this depth (on average 2,000 m or more) temperature can exceed 100 °C, reaching 120-140 °C in some areas (Dövényi & Horváth, 1988). The Pre-Tertiary basement of the Mura-Zala basin at the southwestern part of the Pannoninan basin is built up of Palaeozoic low-grade metamorphic crystalline rocks and non-metamorphic Permo-Mesozoic carbonates belonging to various Alpine nappe systems and the Transdanubian structural unit, and is bounded by the Rába Line in the north and the Periadriatic Line in the south (Tari, 1994, Fodor et al., 2003, Haas et al., 2010).

Hydrogeologically speaking, shallow (local), intermediate and regional flow systems are expected to be developed in this sedimentary basin (Kralj, 2001; Tóth and Almási, 2001; Jocháné Edelényi et al., 2005; Lapanje, 2007; Cserny et al., 2009; Tóth, 2009). The first occurs in Quaternary and Plio-Quaternary intergranular aquifers, with groundwater flow following the surface water net. Deeper, intermediate systems encompass the Pliocene multi-level sandy and gravely intergranular aquifers and provide the majority of drinking

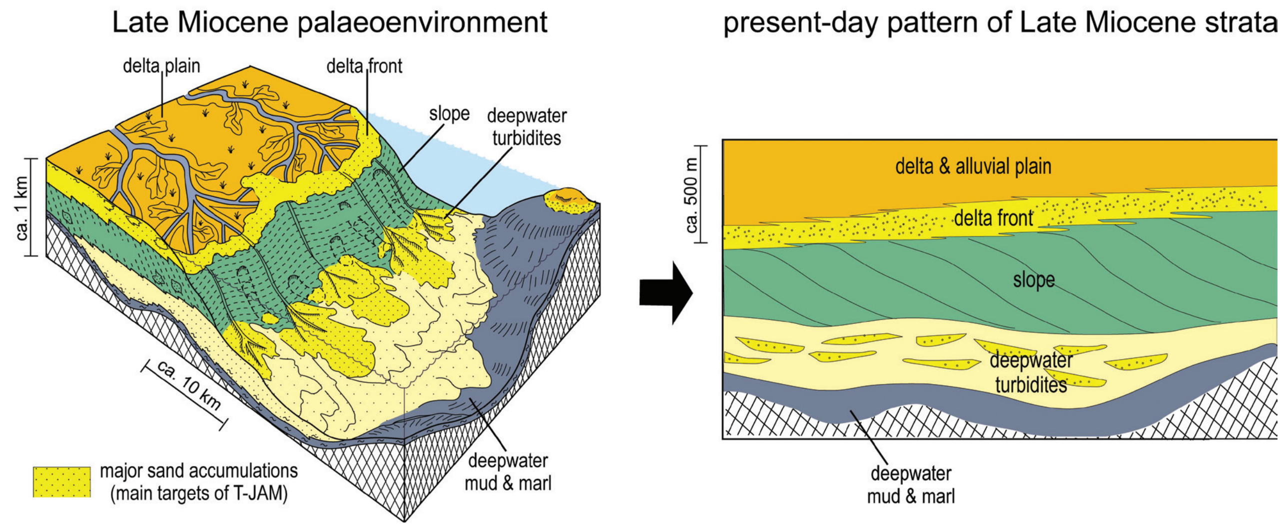


Fig. 2. Depositional model of the Upper Miocene delta systems filling up Lake Pannon (after Juhász, 1994). Most productive thermal water reservoirs are extensive sand bodies of the Mura/Újfalu Fm. which were once deposited on the prograding delta-fronts and were in focus of the T-JAM project.

water in the area as well as the recharge to porous and karstified/fractured basement aquifers. The deepest, regional flow system penetrates till delta-front and delta-plain sands of the Upper Pannonian age. Thermal waters with temperatures (usually much) above 20 °C discharge from this unit. Its main recharge zones are at the hilly parts of the western basin margin, in Slovenia, Austria and Hungary, while discharge is identified in the Croatian and Hungarian part of the Drava valley and partly at the Hévíz Lake, where mixing of thermal water from porous and karst systems occurs.

Geochemical investigations were done in the central and eastern Hungarian part of the Pannonian Basin (Deák et al., 1987; Varsányi et al., 1997, 1999, 2011; Varsányi & Kovács, 2009) as well as in its Slovenian part (Kralj & Kralj, 2000a, 2000b; Kralj, 2001; Kralj et al., 2009; Lapanje, 2006, 2007; Pezdič, 1991, 1999, 2003). However, no cross-border hydrogeochemical studies of the Mura-Zala basin aquifers were known before our research.

Methodology

To understand the hydrogeothermal system of the cross-border region of north-eastern Slovenia and south-western Hungary, geological, hydrogeological and geothermal data were collected first and based on expert consultations, a framework of common understanding was established. Based on the harmonization of nomenclature of various geological formations (Fig. 3) the lithostratigraphy of the studied boreholes was re-evaluated. The most important hydrogeological parameters (porosity, transmissivity and hydraulic conductivity) (Rman et al., 2011c) and geothermal parameters (temperature and temperature gradient, thermal conductivity of rocks with different lithology and calculated heat-flow density) (Tóth et al., 2011a) were also collected from the archives and published literature. They were re-evaluated and interpreted according to the new lithostratigraphical classification. As a result harmonized datasets from 792 Hungarian and 404 Slovenian boreholes were integrated into a joint database (MS Office Access) containing more than 42,000 inputs of which 12,904 are available to public through interactive ArcGIS web-map at http://akvamarin.geo-zs.si/t-jam_boreholes (Rman et al., 2011a).

Based on the harmonized lithostratigraphical classifications of borehole-logs and seismic profiles the spatial distribution of the most important hydrostratigraphic units (rock bodies with similar hydrogeological properties) were determined at a scale 1: 100,000, which was the major output of the geological model (Fodor et al., 2011) and later served as basic inputs for the numerical hydrogeological model.

Hydrogeochemical data from newly sampled thermal and cold waters (12 Hungarian and 12 Slovenian wells) include basic chemistry, trace elements, δD, $\delta^{18}O$, $\delta^{13}C$, ^{14}C, organic compounds, plus noble, free and dissolved gases and provided

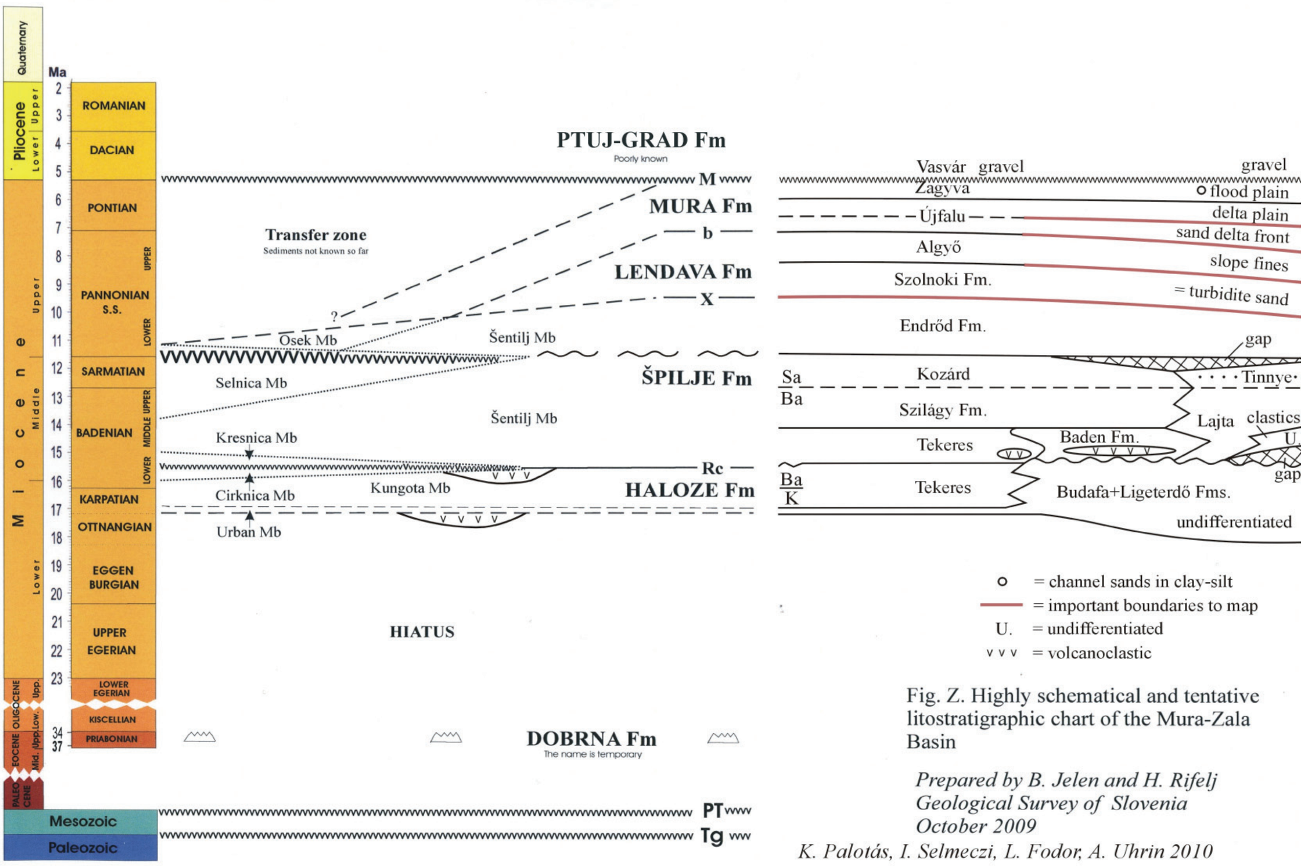


Fig. 3. Correlation of the Neogene formations

important tools for evaluation of cross-border flow, detection of stagnant aquifers and, additionally, for numerical model calibration (Rman et al., 2011d; Szőcs et al. 2012).

The steady-state numerical hydrogeological modeling was performed in Visual MODFLOW. The rectangular model-area was 143 × 122 km, with grid size of 500 × 500 m and a vertical extension of 2 km. Only geothermal aquifers with presumably active groundwater flow were modeled, ranging from Upper Miocene to Quaternary sedimentary succession. In the steady-state numerical flow model (Tóth et al., 2011b) the investigated Upper Miocene, Pliocene and Quaternary sediments, hosting regional, intermediate and shallow groundwater flow systems were divided into 6 model layers. The 6th (deepest) model layer corresponded to the Upper Miocene Mura/Újfalu Fm. delta front sequence (base of the regional thermal flow system), while the 1st model layer was analogous to the shallow unconfined "water-table aquifer". In between them, the Upper Miocene-Pliocene delta plain and alluvial sediments (upper part of the Mura Fm., Ptuj-Grad Fm. in Slovenia and Zagyva, Somló-Tihany Fms. in Hungary) were separated into four model layers. The numerical model made it possible to quantify the hydraulic potentials and therefore to outline groundwater flow direction. Incorporating cold and thermal water annual production data, drawdowns in different aquifers were estimated and also different scenarios were investigated showing depressions caused by production of cold and thermal water separately and together, applying abstraction in each country separately and in both of them simultaneously. The zone budgets were also calculated.

To understand the geothermal conditions, temperature distribution maps were edited for 500, 1,000, 2,000 and 4,000 m below the ground surface from various types of temperature measurements from 154 boreholes on the Slovenian- and 284 boreholes on the Hungarian side of the project area. From temperature data the nearest measured temperature to the given surface was selected, and extrapolation was made by the help of the computed gradient along the same vertical profile (Tóth et al., 2011a).

The evaluation of direct geothermal energy utilization till the first half of 2010 was based on the questionnaire of the International Geothermal Association used for world-wide country assessments performed every five years, which was sent to all direct heat users of geothermal energy in the T-JAM project area (Lapanje et al., 2011).

Based on the integrated interpretation of all above investigations, recommendations have been phrased for a harmonized management system and sustainable utilization of joint geothermal resources in the Mura-Zala basin (Prestor et al., 2011).

Results and discussion

Geological delineation of transboundary formations in the Mura-Zala basin

The geological model was focusing on the edition of boundary horizons of those hydrostratigraphic units that are important for the regional thermal groundwater flow systems. These are the maps showing morphology and geology of the pre-Cenozoic basement, the depth contour map for the base of the Pannonian, bottom and top contour maps of the Pannonian turbiditic Lendava/Szolnok Fm., and the delta front Mura/Újfalu Fm. (Fig. 4), as well as the morphology and geology of the base of the Quaternary sediments. Moreover a surface geological map with an extensive harmonized legend was also edited. All these maps have been edited uniformly for the entire project area, and as such, they show first the results of joint understanding of geology and distribution of certain geological formations on both sides of the state border in the Mura-Zala basin.

For a better understanding of the geological structures nine cross-sections, 3 along the longer axis in SW-NE direction of the Mura-Zala basin and 6 perpendicular were elaborated and described in details (Fig. 5) (Fodor et al., 2011).

Geothermal conditions in the Mura-Zala basin

Earlier studies (Dövényi et al. 1983, Ravnik 1991, Lenkey et al. 2002, Rajver and Ravnik 2002) already proved and described an elevated surface heat flow density (HFD) of the area, which has a value of 60-70 mW/m^2 at Ptuj in the southwest and increases towards the Slovenian-Hungarian border. Elevated HFD of above 120 mW/m^2 characterizes the Murska Sobota high from Lenart to Moravske Toplice and the Pečarovci-Dankovci area, which may be explained by the convection zones in the relatively shallow lying Pre-Neogene basement, as it is proved in Benedikt and is possible beneath Murska Sobota and Moravske Toplice. Smaller anomaly, of above 110 mW/m^2, is located in Lendava. The Hungarian part is characterized by a wider range of surface HFD. The lowest values occur in the southwestern part of the Transdanubian Range (Keszthely Mountains), where the Mesozoic basement carbonates crop out and infiltrating cold karstic waters cool down the environment. Values show a gradual increase towards the southwest and may reach 90-100 mW/m^2 close to the border.

The previously published HFD pattern is conform to the subsurface temperature distribution, which is shown in 4 newly edited maps. At a depth of 1,000 m (Fig. 6) temperatures over 50 °C are expected east of Maribor-Ptuj. The highest anomaly exists in the area from Lenart via Benedikt to Moravske Toplice with values over 65 °C that is so far confirmed with temperature measurements in the boreholes in Benedikt, Murska Sobota and Moravske Toplice. The anomaly in Benedikt, Murska Sobota and Moravske Toplice

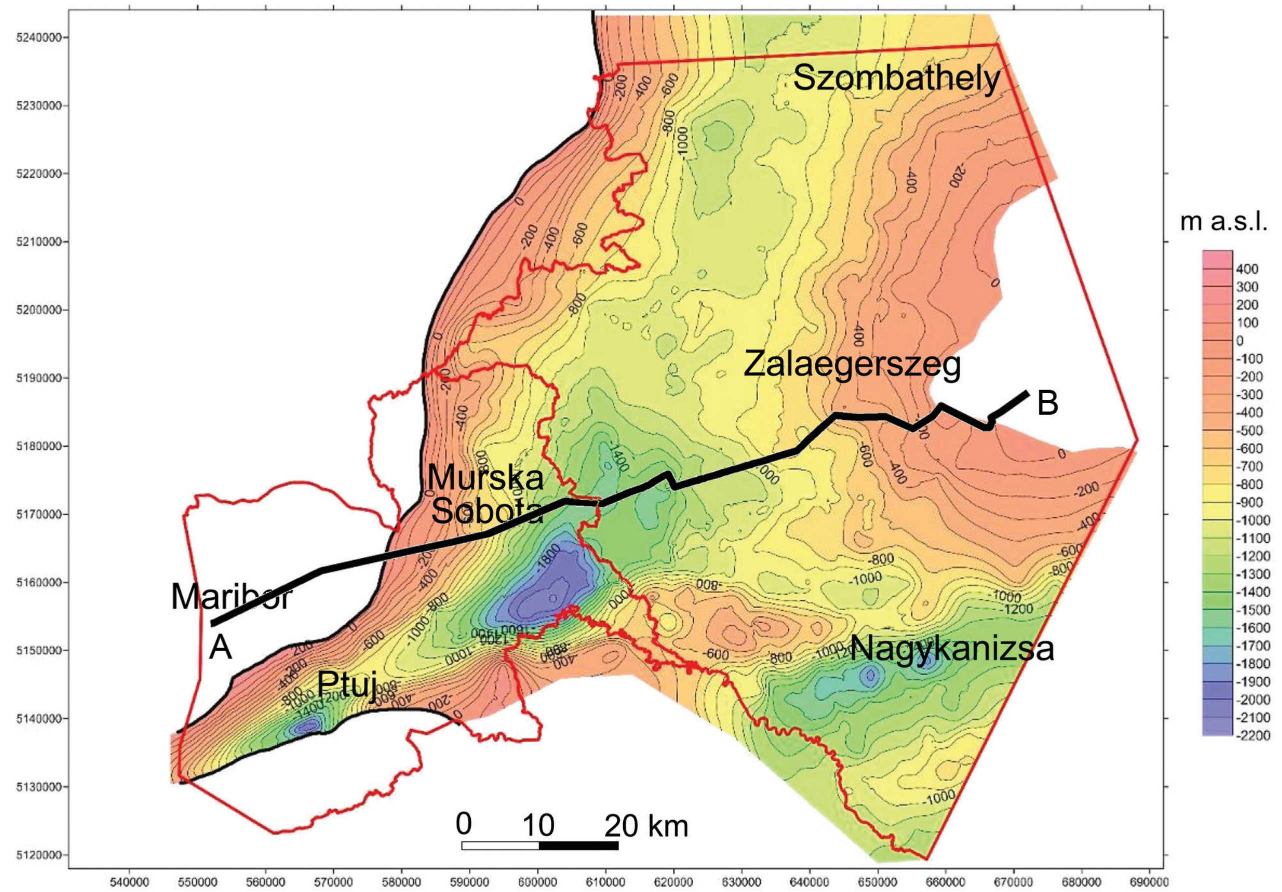


Fig. 4. Depth of the base of delta front sediments (base of the Mura/Újfalu Fm.) in meters a.s.l.

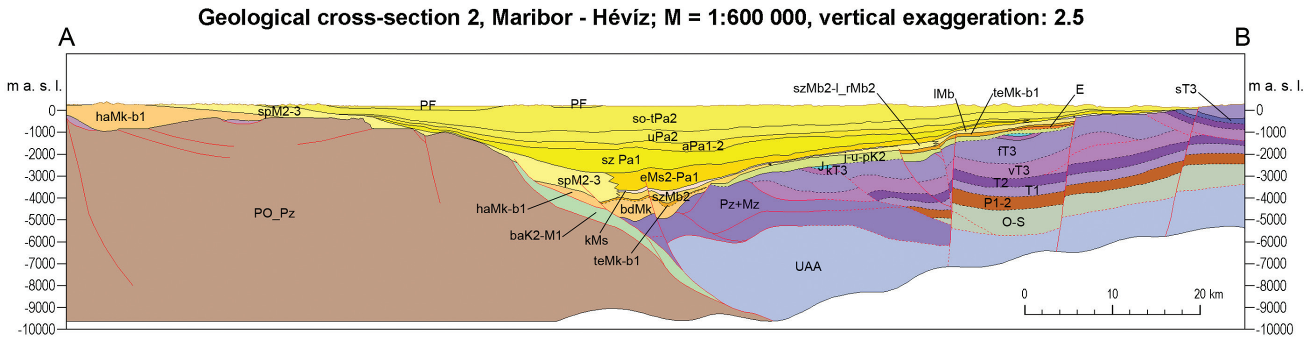


Fig. 5. A simplified cross-section through the basement and Neogene sedimentary deposits

Explanation of labels:

PF: Pliocene gravel, sand, silt (Ptuj-Grad Fm.); **so-tPa2**: Upper Miocene sandstone, siltstone, mudstone, coal (Mura/Újfalu Fm.); **uPa2**: Upper Miocene sandstone, siltstone, mudstone (Mura/Újfalu Fm.); **aPa1-2**: Upper Miocene argillaceous marl (Lendava/Algyő Fm.); **sz Pa1**: Upper Miocene sandstone, siltstone, marl (Lendava/Szolnok Fm.); **eMs2-Pa1**: Upper Miocene marl (Endrőd Fm.); **kMs**: Middle Miocene marl, silt, sandstone (Kozárd Fm.); **spM2-3**: Middle Miocene marl, silt, sandstone (Špilje Fm.); **szMb2**: Middle Miocene marl, argillaceous marl (Szilágy Fm.); **szMb2-l_rMb2**: Middle Miocene marl, argillaceous marl, limestone (Szilágy, Lajta Fm.); **lMb**: Middle Miocene limestone (Lajta Fm.); **teMk-b1**: lower Middle Miocene sandstone, silt (Tekeres Fm.); **haMk-b1**: lower Middle Miocene sandstone, silt (Haloze Fm.); **bdMk**: lower Middle Miocene gravel, sand, conglomerate, sandstone, marl, silt (Budafa Fm.); **E**: Eocene limestone, marl; **baK2-M1**: Upper Cretaceous-Lower Miocene mica schist, gneiss, milonite (Baján Fm.); **j-u-pK2**: Upper Cretaceous limestone, marl (Jáko, Ugod, Polány Fm.); **J**: Jurassic limestone, marlstone; **kT3**: Rhaetian limestone (Kössen Fm.); **fT3**: Upper Carnian-Norian main dolomite; **sT3**: Carnian limestone (Sándorhegy Fm.); **vT3**: Carnian marl (Veszprém Fm.); **T2**: Middle Triassic limestone, dolomite, siliciclastic rocks; **T1**: Lower Triassic sandstone, siltstone, dolomite, limestone; **Pz+Mz**: Paleozoic-Mesozoic clastic and carbonate (meta-)sedimentary and volcanoclastic rocks; **P1-2**: Permian sandstone, siltstone, conglomerate, dolomite; **O-S**: Ordovician-Silurian argillaceous schist, porphyry (Lovas, Alsóörs Fm.); **PO_Pz**: Paleozoic mica schist, gneiss, amphibolite, marble (Pohorje Fm.); **UAA**: Proterozoic-Lower Paleozoic gneiss, mica schist, amphibolite, marble

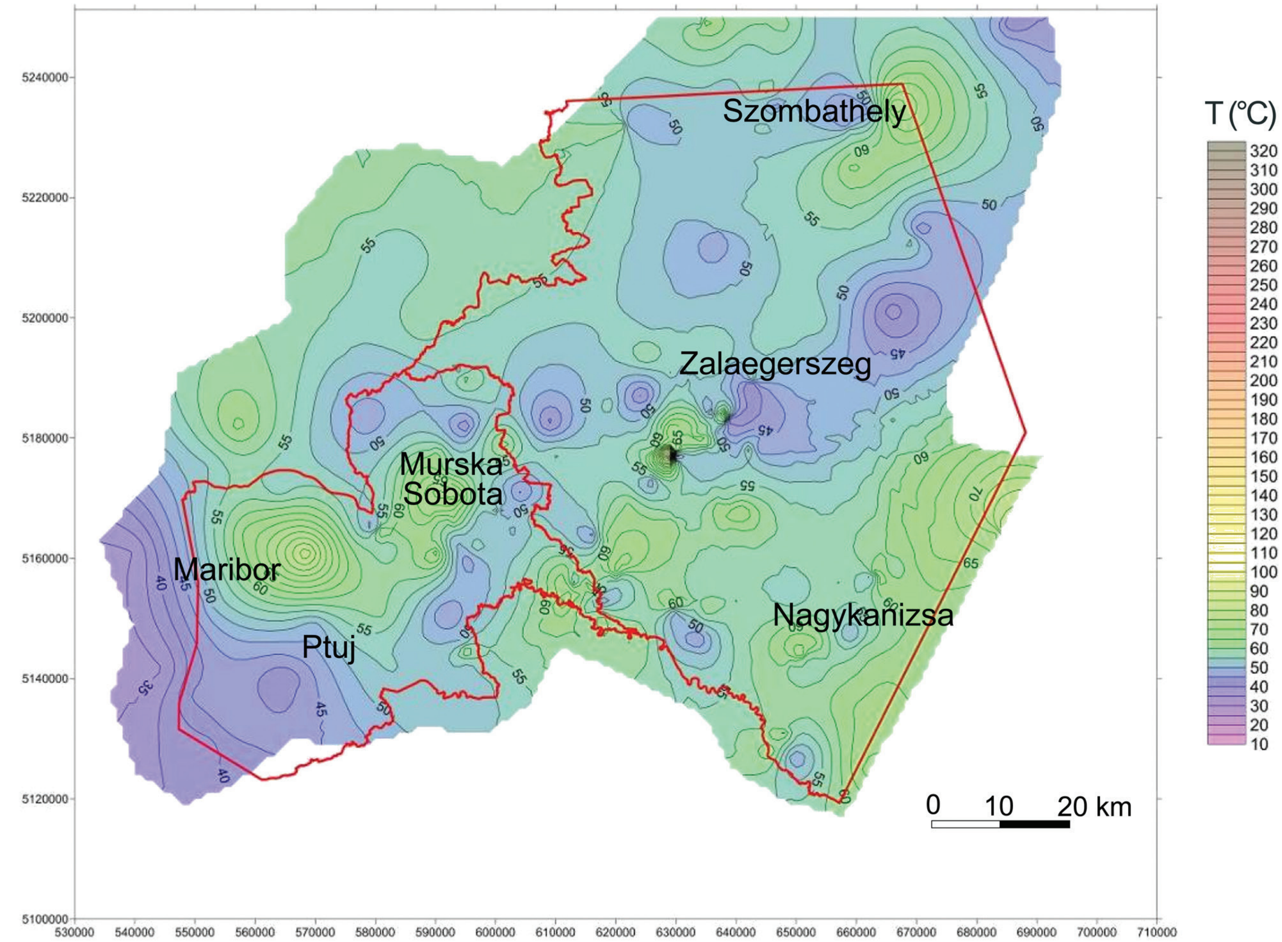


Fig. 6. Temperature distribution at a depth of 1000 m below the surface.

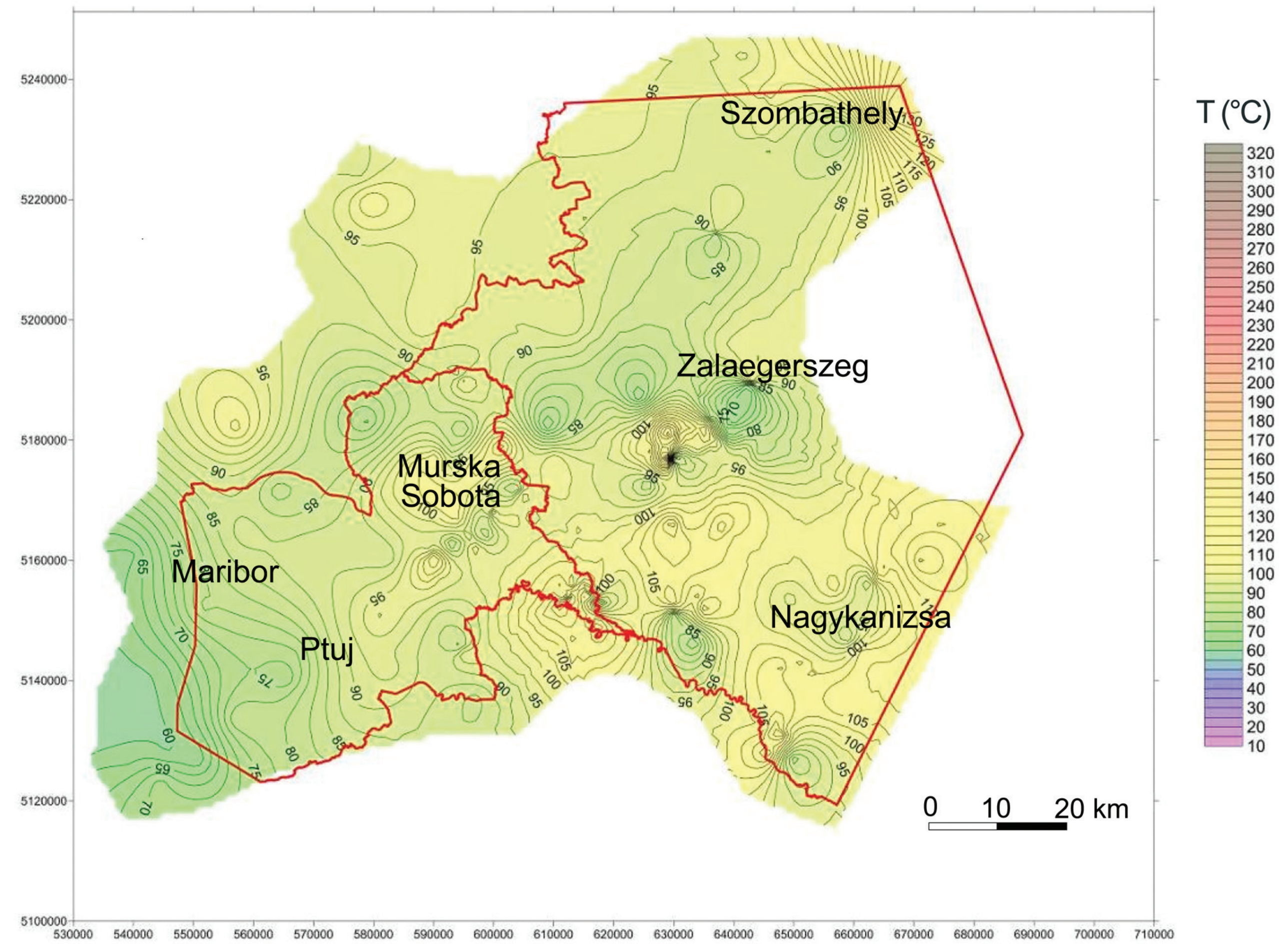


Fig. 7. Temperature distribution at a depth of 2,000 m below the surface.

is most probably due to some deep fracturing in the metamorphic rocks in the basement which enables heat to be transferred by convection from depths towards the Neogene layers. In the Hungarian part, the positive anomalies around Pusztaszentlászló (over 65 °C) are also linked to the basement high. The negative anomalies (below 45 °C) in the western, northern and north-eastern direction can be explained by downward groundwater movement in the deeper karst systems below 1,800 meters.

At a depth of 2,000 m below the surface (Fig. 7) temperatures are higher than 80 °C almost everywhere east of the line Maribor-Ptuj in Slovenia. Over 100 °C may be expected in Murska Sobota and further to the northeast towards the Slovenian-Hungarian border, in Veržej and Lendava. Lower temperatures are found in the Ljutomer-Ptuj depression compared to its surroundings. In Hungary, the positive temperature anomalies (>100 °C) in Nagylengyel-West and Zalaegerszeg-North are the consequences of the upwelling branch of the regional convection in the thermal karst. Similarly, the negative anomalies (< 75 °C) in Zalalövő, and between Nagylengyel and Zalaegerszeg indicate the downward water movement of the convective currents.

Geothermal energy utilization in 2010 in the Mura-Zala basin

The use of geothermal resources from all geothermal aquifers in the Mura-Zala basin, the basement rocks and sedimentary aquifers, was surveyed based on data available till the first half of 2010. In Slovenia, there were 13 direct heat users at 11 locations, and in Hungary 29 users at 20 locations (Table 1) (Lapanje et al., 2011). On the Slovenian side, the 13 users used geothermal energy for individual space heating (Moravske Toplice, Murska Sobota, Lendava, Banovci, Ptuj), district heating (Murska Sobota, Lendava, Benedikt), cooling (Moravske Toplice), greenhouse heating (Tešanovci, Dobrovnik) and bathing and swimming (Moravske Toplice, Murska Sobota, Lendava, Mala Nedelja, Banovci, Radenci, Ptuj, Maribor). In Hungary, the overwhelming majority of thermal water utilization systems is developed for bathing and swimming (Zalaszentgrót, Letenye, Hévíz, Alsópáhok, Zalakaros, Bázakerettye, Lenti, Galambok, Nagykanizsa, Kesidakustány, Gelse, Zalaegerszeg, Pusztaszentlászló, Vasvár, Mesteri, Szentgotthárd, Borgáta, Celldömölk, Sárvár, Szombathely), district heating exists only at Vasvár.

In north-eastern Slovenia, the total direct heat use was 382 TJ in 2010 while in south-western Hungary it was 648 TJ. The total installed capacity of the 13 Slovenian users was 38.8 MW_t, while that of the 29 Hungarian users was 70.6 MW_t in 2010 (Table 1). The average flow rate is about 40-50% of the maximum on the Slovenian as well as on the Hungarian side, which shows that wells do not operate efficiently, or the maxima are overrated. The thermal capacity factor is about 0.3 in both countries.

In Slovenia, the maximum wellhead temperatures in Neogene clastic reservoirs were reached in Terme 3000 in Moravske Toplice (72 °C), in Terme Banovci (68 °C) and in Lendava (66 °C). In Benedikt, the wellhead temperature was also 72 °C, with water discharging from the fractured metamorphic basement rocks. In Hungary, the wellhead temperatures were higher in wells discharging from the Mesozoic basement reservoirs (106 °C in Zalakaros and 98 °C in Zalaegerszeg), but the Mura/Újfalu reservoir close to the Slovenian border also showed high values (70 °C in Lenti).

Hydrogeochemical evidence on transboundary groundwater flow in the Mura-Zala basin

Although thermal groundwater is abstracted at few locations from the karstified-fractured Upper Triassic dolomites and limestones (e.g. Alsópáhok, Borgáta, Mesteri, Vasvár), Triassic-Cretaceous karstified limestones (Zalakaros, Zalaszentgrót) or from fractured Palaeozoic rocks (Benedikt) in

Table 1. Direct heat utilization of geothermal energy in the T-JAM project area in 2010 (NE-Slovenia and SW-Hungary).

Use	Unit		Individual space heating	District heating	Air conditioning (cooling)	Greenhouse heating	Bathing & swimming (incl. balneology)	Total
Flow rate at maximum utilization	(l/s)	**SLOVENIA**	81.0	32.2	1.0	57.8	122.6	**294.6**
Installed capacity	(MW_t)		11.86	3.29	0.13	7.06	16.49	**38.83**
Average flow rate	(l/s)		38.0	20.0	0.5	11.0	54.3	**123.8**
Annual energy use	(TJ/yr)		133.91	43.98	2.04	25.59	176.52	**382.04**
Capacity factor			0.36	0.42	0.50	0.11	0.34	**0.31**
Flow rate at maximum utilization	(l/s)	**HUNGARY**		10.0			985.9	**995.9**
Installed capacity	(MW_t)			1.76			68.84	**70.60**
Average flow rate	(l/s)			2.3			501.2	**503.4**
Annual energy use	(TJ/yr)			12.46			635.51	**647.97**
Capacity factor				0.22			0.29	**0.29**

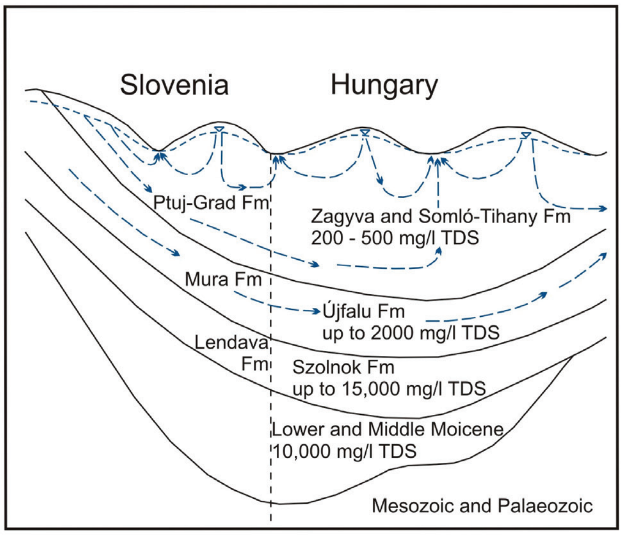
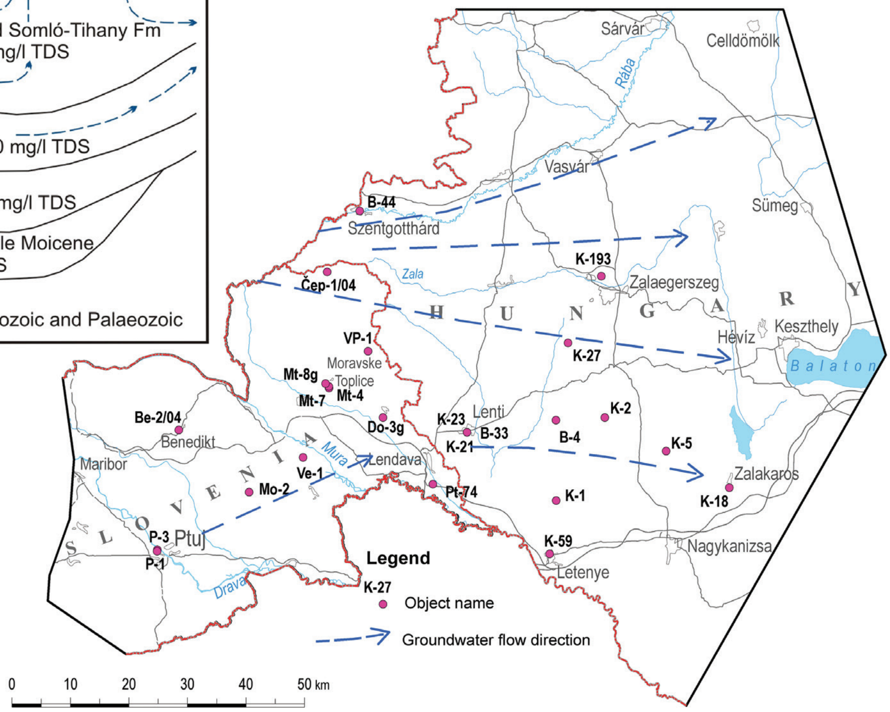


Fig. 8. Main groundwater flow directions and sketch of investigated hydrostratigraphic units and transboundary aquifers (Szőcs et al., 2012)



the basement, the best and most widely exploited geothermal reservoirs in the Mura-Zala basin are the Upper Miocene delta-front sands and sandstones, which correspond to the Újfalu formation in Hungary and lower part of the Mura formation in Slovenia. A detailed hydrogeochemical survey (Rman et al., 2011d; Szőcs et al., 2012) contributed to the characterization of different transboundary aquifers (Fig. 8).

The uppermost (shallow) groundwater flow system is developed in unconfined Quaternary aquifers. The underlying Pliocene delta- and alluvial plain aquifers (Ptuj-Grad Fm. in Slovenia, Zagyva and Somló-Tihany Fms. in Hungary) are a part of the intermediate flow system and contain thermal water in their deeper parts, while from the shallower parts fresh drinking and industrial water is produced. In the Quaternary and Pliocene aquifers the Ca-Mg-HCO_3 water type prevails with a low total dissolved solid content. The Zagyva, Somló-Tihany and the lower part of the Ptuj-Grad Fm. show a developing trend of cation (calcium-sodium) exchange characteristic due to longer groundwater retention time. The water type changes from Ca-Mg-HCO_3 to Na-HCO_3 in these deeper levels. These waters are recent to a few thousand years old.

The deep regional thermal groundwater flow system is developed in the Mura/Újfalu aquifers and is characterized by an alkaline Na-HCO_3 character with a total dissolved solid content increasing with depth, with the highest values reached in depths from -1,500 to -2,000 m a.s.l., below which lower TDS contents is again measured. The Hungarian groundwater contains higher TDS values than the Slovenian in the -1,300 to -3,500 m a.s.l. depth interval, which can be attributed to a longer flow path on the Hungarian side. Locally, this water is enriched in chloride or sulphate anions, mostly due to mixing. Most of the δD and $\delta^{18}O$ data of the sampled groundwater from the Mura/Újfalu aquifers are positioned on the meteoric water line, indicating that they are old infiltrated rainwater. The ^{14}C values indicate age above 20,000 years. The $\delta^{18}O$ and δD values are more positive than the "typical ice-age" groundwater values which suggests a recharge during a warmer period of the Pleistocene. Based on the modelled travel times of a water particle (roughly equivalent to the age of infiltration), the majority of thermal groundwater in the Mura/Újfalu aquifer might have been be recharged into the flow-system before the last ice-age, most probably in the Riss-Würm interglacial period (between 93,000-132,000 years BP).

Based on the geochemical character, the thermal groundwater of the Mura/Újfalu aquifer can be well distinguished from the groundwaters stored at greater depths, whose geochemical character shows that they are not (or are only to some extent) a part of the regional thermal groundwater flow system. Groundwater of the marly delta-slope sediments (corresponding to Algyő Fm. in Hungary and Upper Lendava Fm. in Slovenia) is a rather isolated brine of Na-Cl type. In contrast, the sandy turbiditic bodies (Szolnok and

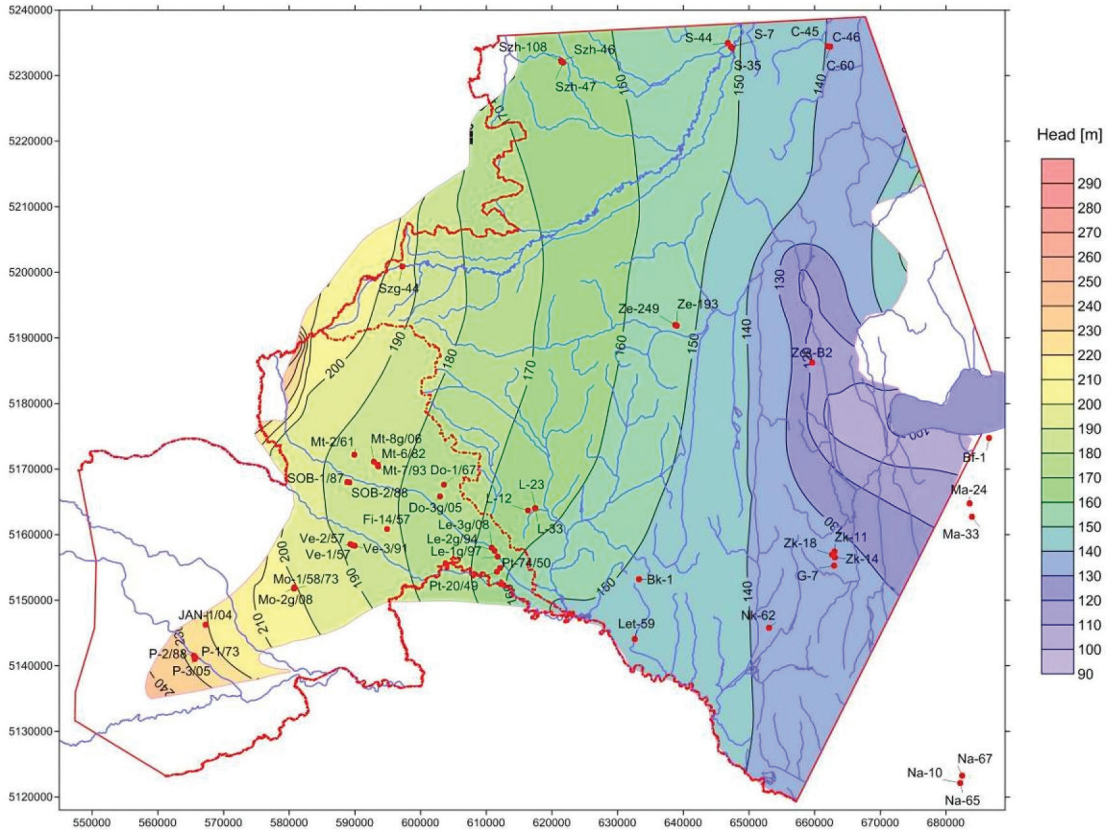


Fig. 9. Modelled environmental heads for the Mura/Újfalu aquifer in natural, pre-exploited state

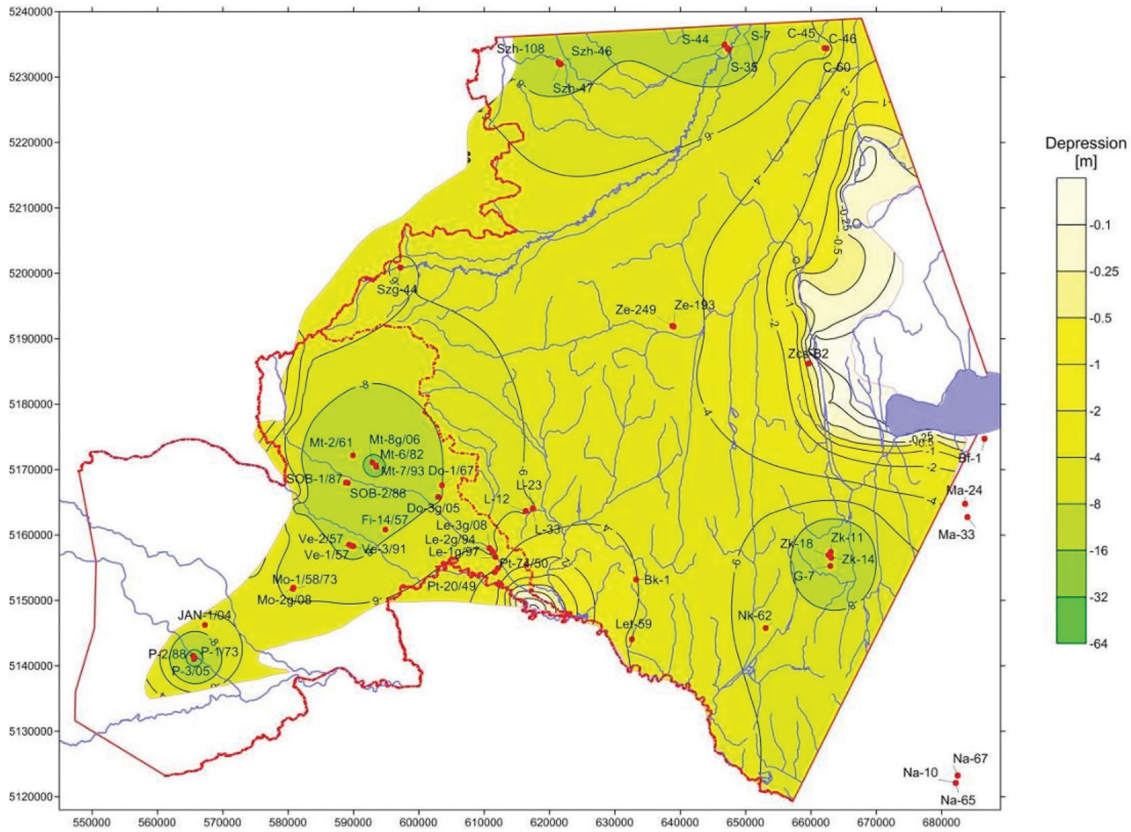


Fig. 10. Depressions for the 6th model layer, thermal aquifer of the Upper Miocene delta front sediments (Mura/Újfalu Fm.), reflecting the joint effects of the cold and thermal water production of both countries.

Lower Lendava Fms. respectively) store water which is less isolated from its surroundings and is often mixed with other groundwater from Miocene aquifers therefore anions show a wide range. The Middle Miocene formations store different waters depending on the burial depth. Where layers outcrop, the infiltrating Ca-Mg-HCO_3 water type is observed while towards deeper parts the longer retention time, cation exchange, mixing, dissolved gas and other geochemical processes modify its composition, so Na-HCO_3 to Na-Cl types prevails.

Numerical groundwater flow model of the Upper Miocene to Quaternary aquifers in the Mura-Zala basin

The modeled potential fields indicate that groundwater recharges from NE Slovenia and the flow direction is from west to east (Fig. 9). The model showed that depressions in the cold-water aquifer (upper part of the intermediate flow system, corresponding to model layer 2) were local, caused mainly by water abstraction in Radenci, Szombathely and Zalaegerszeg, and could be neglected along the state border. If solely thermal water abstraction is modeled (which is currently 61.8 l/s in the Slovenian and 67.3 l/s in the Hungarian part of the model area), the depression would be 5-7 m along the state border in the Mura/Újfalu aquifer (6th model layer, Fig. 10). If only Slovenian thermal water abstraction was applied to the model, a depression of 4-5 m would be computed along the border, while if only Hungarian abstraction was considered, the depression would be only 1-1.5 m along the border. This indicates that thermal water abstraction on the Slovenian side close to the border (Murska Sobota, Moravske Toplice) has much greater effect on the size and depth of the hydraulic depression of the transboundary area than current abstractions in Hungary, which are further away from the border (major regions are around Zalakaros and Szombathely). However, if cold and thermal water production data are considered together, the depression in the Mura/Újfalu aquifer in north-eastern Slovenia may exceed 20 m and reaches 6-8 m along the state border (Fig. 10), clearly showing the hydrodynamic connection between the deep thermal and shallow cold water aquifers.

Delineation of the Mura-Zala transboundary thermal groundwater body (TTGWB) and recommendations on its management

Based on the presented results a transboundary thermal groundwater body (TTGWB) was outlined (Fig. 11), also taking into account the major recharge and discharge areas, as well as the potential impact areas (Tóth et al., 2011b). In the Hungarian part, the vicinity of Lake Hévíz was also included because it is a groundwater dependent ecosystem closely connected to the investigated thermal groundwater flow system. The upper boundary of the common transboundary thermal groundwater body was suggested at 500 meter below the surface because the majority of the thermal water wells are screened below this level. TTGWB Mura-Zala is not hydrodynamically confined except for the bottom (clayey aquitard-aquiclude complex of the Upper Miocene delta slope facies of Lendava and Algyő Fms.), which is recommended to be outlined at 2,200 m below the surface. It has an open hydrodynamic connection to the neighbouring cold and thermal intergranular, fissured and karst aquifers from where it is recharging and discharging.

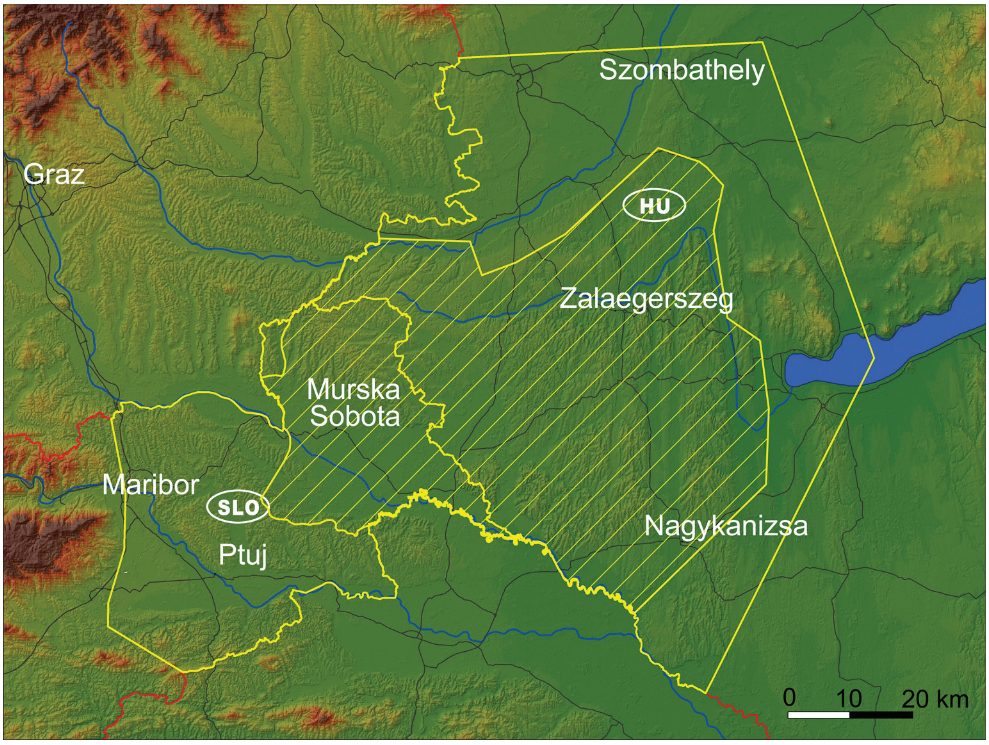


Fig. 11.
Delineated transboundary thermal groundwater body Mura-Zala (TTGWB)

neighbouring body	Budget of the Hungarian part of the delineated transboundary thermal porous groundwater body (m^3/day)								
	pre-exploited state			present production (thermal and cold)			5 x present thermal production		
	in	out	total	in	out	total	in	out	total
colder zone above 500 m depth	11676	-18799	-7123	12780	-16205	-3425	21626	-11276	10350
thermal wells	0	0	0	0	-3085	-3085	0	-15425	-15425
Hungarian part, deeper than 500 m	5891	-4305	1586	5788	-4472	1316	9443	-7324	2119
Slovenian part, deeper, than 500 m	7698	-2561	5137	6842	-2512	4330	4349	-3692	657
Croatian part,deeper, than 500 m	721	-424	297	1145	-475	670	2395	-553	1842
Total	25986	-26089	-103	26555	-26749	-194	37813	-38270	-457

neigbouring body	Budget of the Slovenian part of the delineated transboundary thermal porous groundwater body (m^3/day)								
	pre-exploited state			present production (thermal and cold)			5 x present thermal production		
	in	out	total	in	out	total	in	out	total
colder zone above 500 m depth	9740	-5573	4167	11210	-5273	5937	20181	-4806	15375
thermal wells	0	0	0	0	-4069	-4069	0	-20345	-20345
Hungarian part, deeper than 500 m	2561	-7698	-5137	2512	-6842	-4330	3708	-4357	-649
Slovenian part, deeper, than 500 m	1445	-22	1423	1641	-35	1606	2300	-105	2195
Austrian part, deeper than 500 m	23	-1	22	37	-2	35	117	-12	105
Croatian part,deeper, than 500 m	2322	-2446	-124	2779	-2186	593	4727	-1722	3005

Table 2. Water balance zone budgets of the Mura-Zala TTGWB.

The area of the Mura-Zala TTGWB is 4,974 km^2 wide of which 1,151 km^2 falls in the territory of Slovenia and 3,823 km^2 in Hungary (PRESTOR et al., 2011). In Hungary, the borders of the intergranular thermal groundwater water bodies delineated for the EU Water Framework Directive River Basin Management Plan were followed where possible. In Slovenia, the suggested Mura - Zala TTGWB is delineated by the Slovene – Croatian state border in the south and by the Slovene – Austrian state border in the north. Respectively, in the northwest by the pinching out of the Mura formation and in the west by the surface water divide between Mura and Drava rivers at the Slovenske Gorice Hills. As the modelling showed that the west-lying thermal water abstraction has quite insignificant impact on the aquifers quantitative status at the SI-HU border, the latter decision was made although the authors are aware that this surface water divide does not affect the thermal groundwater flow. This compromise was set also to ease the administrative and management strategies of the TTGWB.

The numerical flow model was used to calculate the groundwater budget components of the delineated thermal groundwater body across the Slovenian-Hungarian state border, also considering the connections towards Croatia and Austria. The budget was calculated for three scenarios: (1) pre-exploited state, (2) present production, (3) extreme production conditions, assuming production five times higher than at present (Table 2). Recharge (inflow) water comes from the zones above 500 m depth and laterally from the neighbouring thermal water bodies of Slovenia, Hungary, Austria and Croatia.

The pre-exploited balance of the transboundary thermal groundwater body Mura-Zala between Slovenia and Hungary was strongly positive for Hungary: 59.5 l/s water surplus from Slovenia. At the present production (61.8 l/s in the Slovenian and 67.3 l/s in the Hungarian part of the TTGWB) this decreased to 50.1 l/s. The extreme production scenario would cause much stronger change: only 7.5 l/s surplus would remain from Slovenia.

Based on these results it was possible to phrase some tangible recommendations regarding the future management of the Mura-Zala TTGWB. The general environmental objective is to maintain the good status, i.e. to prevent the deterioration of the actual status. This can be achieved by maintaining the long term positive water balance, which means that thermal water abstraction should not stop or redirect the recharge surplus from Slovenia to Hungary. Consequently, regional abstraction should not approximate to as much as 5-times higher thermal water production as present in both countries. If we take into consideration that the available reserves would not be endangered if the abstraction does not exceed 70 % of the renewable volume of groundwater, the increment factor should not be more than 3.5. The critical point of 3.5 factor of abstraction increment should be lowered in those cases where significant negative long-term trends in the piezometric heads are observed or any kind of other groundwater intrusions occur, i.e. significant long-term negative trends arise in the quality, quantity or temperature of the thermal water. Abstraction from an individual well should not be increased in such a way that this affects neighbouring wells of the neighbouring users. Increase of abstraction should not provoke a drawdown or long term trend that could significantly diminish the conditions of exploitation in the future from the technological or economical point of view. This constraint is a maximum allowable local lowering of the pre-exploitation piezometric head that is being limited to 30 m.

Conclusions

The presented two-year research has confirmed the existence of transboundary and regional aquifers in the Mura-Zala basin. The most widely exploited transboundary geothermal aquifer is identified in the Upper Miocene delta front sandy deposits of the Mura/Újfalu Fm. The extent and distinctive hydrogeological characteristics of the so called transboundary thermal groundwater body Mura-Zala were defined in details. Regarding the sustainable use of these groundwater resources, it was realised that the future increase of actual abstraction rate by a factor below 3.5 would theoretically enable to follow the renewable energy utilization objectives till 2020 in Slovenia and in Hungary without threatening environmental objectives. However, priority should not be put on increased abstraction, but rather on improved thermal efficiency, lowering the temperature of the discharged thermal waste water and promotion of reinjection, where it is possible.

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