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THEMATIC ISSUE

Sustainability aspects of thermal water production in the region of Hajdúszoboszló-Debrecen, Hungary

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Abstract As geothermal energy usage becomes more conspicuous the long-term effects of thermal water extraction become more significant. The greatest extent of exploitation in East Hungary occurs in the area of Hajdúszoboszló and Debrecen. The extracted thermal water is utilized mainly by their baths. In this paper, the sustainability of this system was examined with a steady state hydrodynamic model. The solid model is based on sequence stratigraphic interpretation while the hydraulic conductivity values were estimated based on the values of geophysical well-logs. The closely spaced wells cause a great subregional decrease of hydraulic head, particularly in the most intensively extracted layer, i.e. the layer of the delta front facies. The effects of extraction by the two spatial groups of wells intersect resulting in decreased profitability of subsequent wells. However, rationalizing thermal water utilization using water from shallower zones simultaneously may have beneficial effects on the yield distribution among the different layers.

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Introduction

In some parts of Hungary investments into thermal baths are supposed to be a key factor of local economic development. In Hungary, the annual water extraction is about 50, 3.5 million m^3 of which is extracted in Hajdú-Bihar county. Moreover, this value is growing due to the development of spa tourism. The two areas of major water extraction in the county can be defined around Hajdúszoboszló and Debrecen (Kozák et al. 2011). Thermal water extractions at Hajdúszoboszló and Debrecen are around 2 million and 0.6 million m^3/year respectively, with near constant yield of the wells in each month.

The sustainable operation of these systems is very important considering environmental, technical and economical aspects. In the case of overproduction, decreasing potential means decreasing reservoir pressure and/or decreasing well-head temperature, consequently, the operation cost increases and the energy content of the produced water decreases. During water and geothermal energy extraction pressure and temperature should be decreased to force water and energy movement, thus, the potential also decreases temporarily. In this aspect the assumption of sustainability could be a constant operational water level related to a given yield.

Thermal water exploration in the area started in the early twentieth century by Ferenc Pávai-Vajna. As the healing effects of the water were discovered soon several wells were drilled both in Hajdúszoboszló and Debrecen (Csath 1975, 1984) and after the initial difficulties these two poles have developed rivaling each other. Today the spas of

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Hajdúszoboszló are supplied by 15 wells, while those in Debrecen by 9 wells and there are other wells for energy utilization (Fig. 1). Intensive exploitation caused the decrease of the standing level by 30–50 m indicating clearly unfavorable changes in the reservoirs (Tóth 2010). This is a general phenomenon in areas of intense water extraction in the Great Hungarian Plain (Tóth et al. 2010; Szanyi and Kovács 2010).

Similar problem occurs in shallower layers. Well-documented compaction, depression and strong vertical water-flow were caused by the intensive water extraction from the drinking water aquifers of Debrecen drawing attention to the problem of overproduction (Orlóci 1968; Bendefy 1968).

The effects of extraction have been studied around the two well-groups separately but the effects on the production of the overall reservoir are yet to be examined. A regional steady state flow model was developed to study the joint effects of the two groups of wells, details and results of which are presented in this paper.

Study area

Geological settings

The depth of the dominantly Palaeozoic basement of the study area—located in the Tisza Megaunit (Fülöp 1989)—ranges between 300 and 5,000 m and is characterized by ridges, isolated blocks, range blocks, grabens and depressions striking SW-NE together with overthrusts and imbrications as a result of compression from the SW (Pap 1990).

A fine example of imbricated structures is the Ebes Thrust below Hajdúszoboszló where the Mesozoic limestones and siliciclastic formations of the Mecsek Structural Belt are overlapped by the Variscan metamorphic rocks of the Körös Complex (Pap 1990; Haas et al. 2010).

The youngest and dominant formation of the basement is the Campanian-Maastrichtian Debrecen Formation composed of sandstone and silt sometimes with conglomerates. The Nádudvar Complex, the other notable formation in the flysch belt is similar to the Debrecen Formation with more dominant flysch characters particularly in the Upper Eocene and Oligocene tracts.

The Pannonian Basin was closed in the Miocene isolating an inland sea gradually becoming brackish. The documented facies series of the basin filling (Fig. 2)—dominantly Pannonian succession—ranged from tidal marshes to an 800 m deep basin (Juhász 1992).

Small amount of fine-grained sediments are transported into the inner deep zones of the basin. Hemipelagic sediments, like calcareous marl, marl, clay marl were deposited constituting the Endrőd Marl Formation in a thickness of around 100–200 m. The formation occurs almost all over the basin except for the uplifted parts where it may pinch out. Depending on the distance from the source area delta slopes could extend towards the deeper parts of the basin. On the distal parts of these slopes turbidites of sandy-silt could be accumulated in great stratigraphic range (Szolnok Sandstone Formation). Its maximum thickness can reach

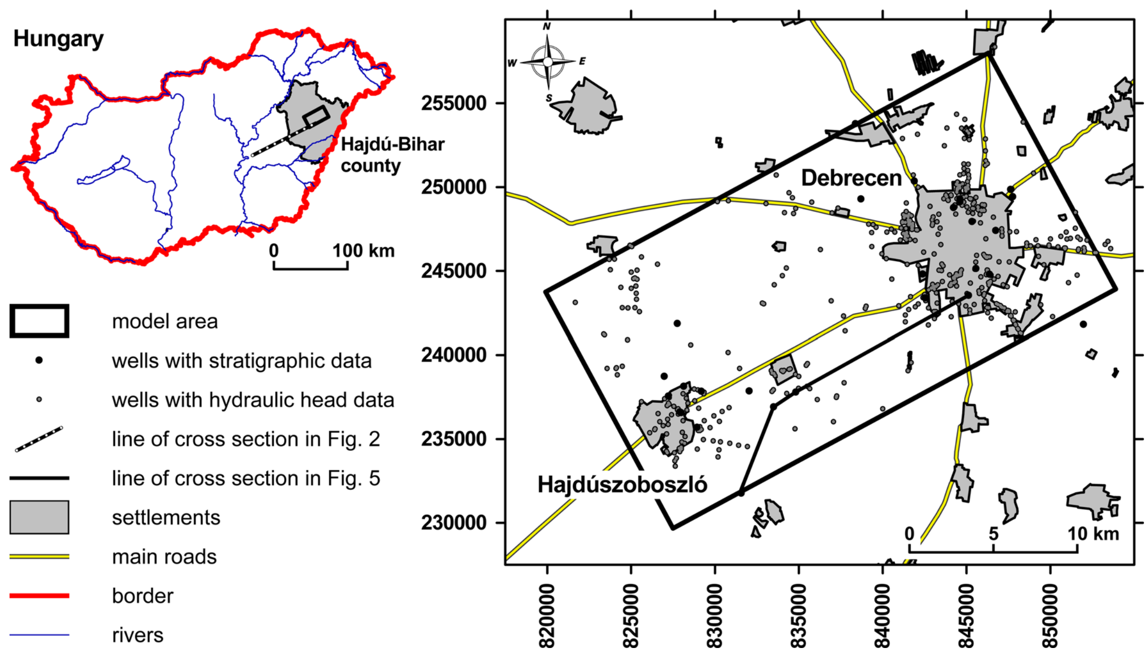

Fig. 1 Location of the model area with the wells and the path of the cross sections shown on Figs. 2 and 5

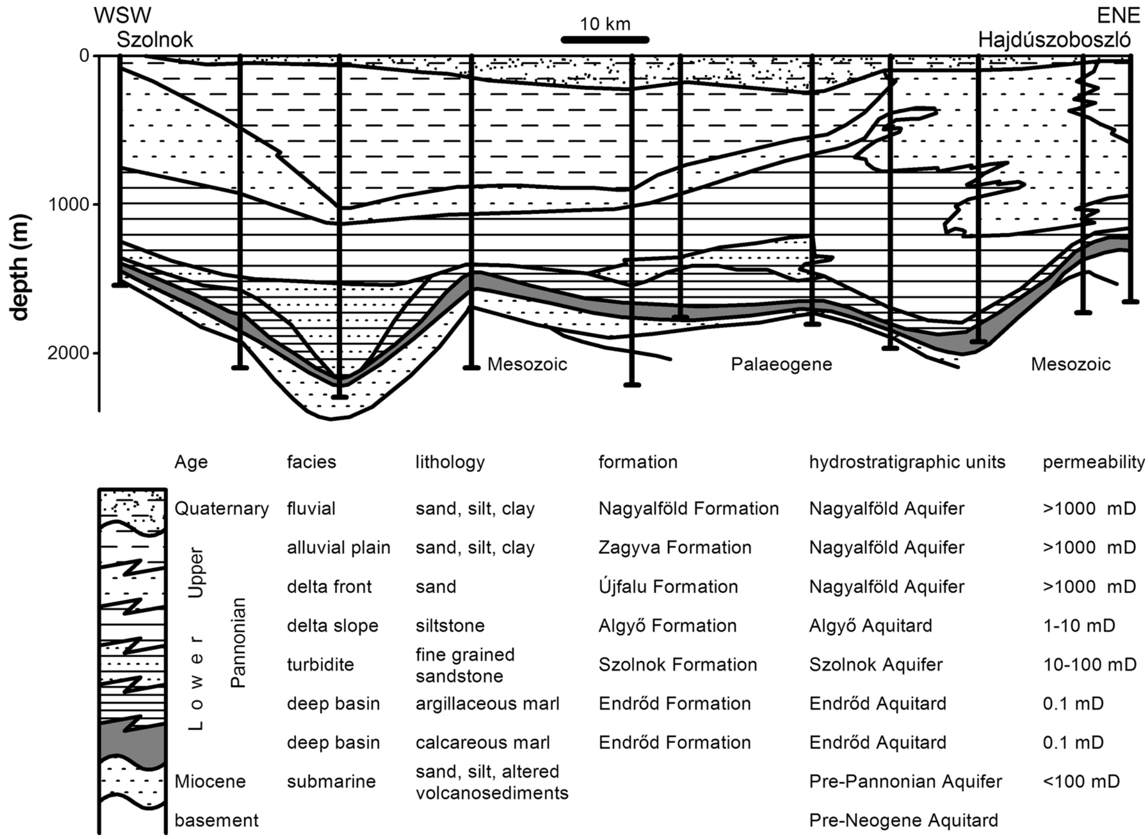

Fig. 2 Characteristic cross-section in the middle of the Great Hungarian Plain (modified after Juhász 1992; Tóth and Almási 2001)

1,000 m. It occurs mainly in the deeper basins, in shallower zones like the study area these turbidites do not form a discrete lithostratigraphic unit (Juhász 1992).

The greatest part of the sediments is deposited in coastal areas in delta systems. On the proximal part of the delta slopes pelitic sediments (Algyő Formation) are deposited and sand is underrepresented. The Algyő Formation is widespread in the Pannonian Basin with thickness ranging between 200 and 1,000 m. On seismic sections parallel to the strike of the progradation the basinward dip of clinoforms can be recognized clearly in the formation. In the margins where the Szolnok Sandstone Formation did not develop the Algyő Formation and the non-calcareous Nagykörű Member of the Endrőd Marl Formation are hardly distinguishable.

The upper boundary of the formation is traditionally declared as the boundary between the Upper and Lower Pannonian Stages which can be mapped well by geophysical methods (logs and seismic data). Nevertheless, this boundary is not an isochronous facies boundary but becomes younger dipward (Juhász 1992).

In the coastal areas, the sandy sediments of the delta front (Újfalu Sandstone Formation) is laterally interfingering with channel-bed sediments of the back marshes. It comprises fine-grained and medium-grained sandstone with intercalated clay marl. These sand beds were deposited primarily in mouth bars and delta channels and occasionally represent crevasse splays. The finer-grained sediments of the Újfalu Formation were deposited in marine swamps, abandoned meanders or lagoons. Due to the oscillation of the accommodation space, intercalation of the Újfalu Formation (delta front) and Algyő Formation (delta slope) can also be detected (Juhász 1992, 1993). In some parts of the Pannonian Plain, like the research area, this intercalation can be observed clearly.

The sand bodies of the Újfalu Formation frequently connected laterally can be found all over the basin. Therefore, the vertical and horizontal hydraulic connections in the formation are good and the recharge area is large. The maximum depth of the Újfalu Formation is around 2,000 m, thus its temperature may make it appropriate for thermal water extraction.

In the coastal belt, fine sediments (gray silt, clay marl and sands with coal interbeddings) were deposited in lacustrine, fluviolacustrine and fluvial facies of floodplains. This formation named Zagyva Formation comprises of less consolidated rocks. Although it is widespread in the basin it pinches out in the western margin of the study area (Juhász 1993).

Pleistocene deposits also comprise of fluvial, lacustrine and fluviolacustrine sediments. The dynamism of landscape evolution was affected by the changes in fluvial transport capacity controlled by climatic and structural events of the Quaternary period. The Pleistocene beds can traditionally be divided into three tracts the so called "upper", "middle" and "lower" ones. The upper and lower tracts comprise of the sediments of channel belt complexes and overbank deposits. The middle tract is dominantly lacustrine and fluviolacustrine, coarse-grained sediments are underrepresented and mostly limited to small lacustrine delta complexes.

Hydrogeological settings

Large-scale hydrodynamic research started in the middle of the 1970s, and the results clarified the main questions of groundwater flow in the Pannonian Basin (Erdélyi 1975). In the frame of the "Pannonian Basin Hydrogeological Research Program" (PBHRP) directed by József Tóth geological and hydrodynamic data from more than 1,270 boreholes were evaluated and the spatial range and hydrogeological character of the hydrostratigraphic units were derived in the second half of the 1990s (Tóth and Almási 2001; Tóth et al. 2000).

In the course of the above research projects, the basin filling sedimentary succession with a thickness exceeding 5,000 m in the deepest subbasins was considered to consist of strata with significant lateral extent, frequently with lenticular shaped formations. The hydrostratigraphic units are derived from the lithostratigraphic ones (Fig. 2). The non volcanic Pre-Pannonian sediments are regarded as aquifers (permeability is around 100 mD) while clayey variations as aquiclude. The Endrőd hydrostratigraphic unit is regarded as aquitard (permeability is 0.1 mD), the Szolnok unit is aquifer (permeability is between 10 and 100 mD as a result of aquitard lenses), while the Algyő unit is regarded as aquitard (permeability is between 1 and 10 mD). The most important non-karstic aquifer of Hungary is the Nagyalföld Aquifer (the Újfalu and Zagyva Formations and younger sediments together) with aquitard lenses occurring due to the pattern and conditions of the shoreline in the lower part and the channel complexes in the upper part. The characteristic permeability of the Nagyalföld Aquifer is considered to be higher than 1,000 mD (Tóth and Almási 2001).

Two hydraulic regimes developed in the basin. Groundwater flow is driven by gravitational forces in the upper one, while overpressure appears generally in the lower one. In the unconfined gravity-driven zone, the main source of recharge is precipitation. The thickness of this zone is variable, occasionally exceeding 1,700 m. Overpressure in the lower regime is caused primarily by the rapid subsidence of marl sediments, overpressed by compaction due to basin development and by the tectonic events of the basement. Hydraulic connection between the two regimes is ubiquitous and especially significant where the layers with low-permeability pinch out. Zones of overpressure have hydraulic connection to the basement near the karstic limestone blocks or along deep fractures.

The early studies (e.g. Erdélyi 1975) concluded that the Nyírség, as an alluvial fan buried with wind-blown sand and located NNE from the study area is the recharge area of the Pleistocene reservoirs, while the Hortobágy (SSW of the study area) is a discharge area, consequently the study area—in between the two—has a transitional character. These are also proven by the characteristics of the hydraulic layers. In addition, isotope-hydrogeological

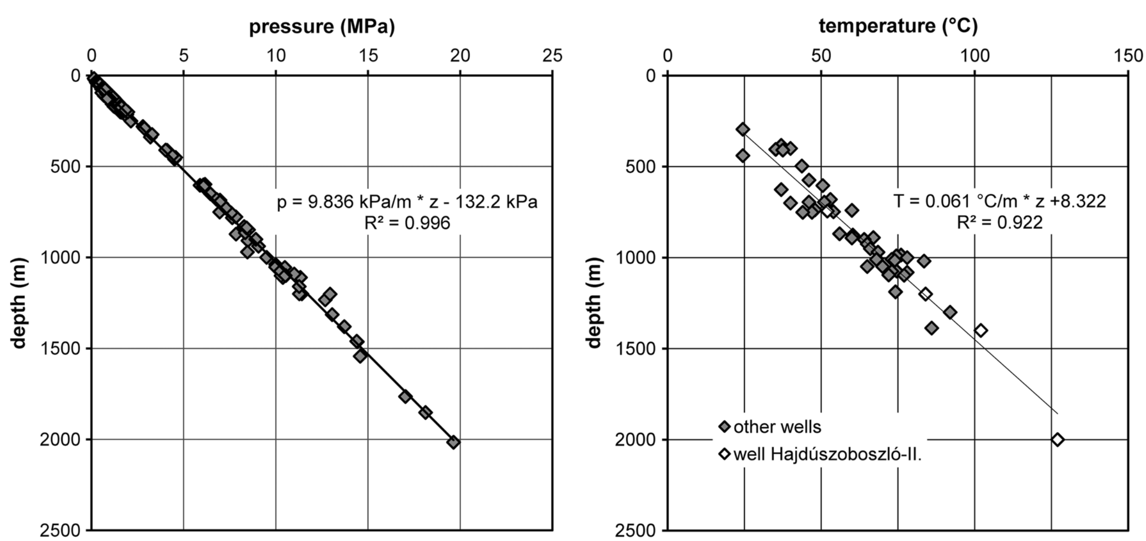

Fig. 3 Characteristic p(z) and T(z) conditions of the studied area

studies revealed the downward migration caused by the decrease of hydraulic heads (e.g. Marton and Mikó 1990).

Based on more than 500 hydraulic head data of the area, the reservoir discussed in this paper is related to the gravitation driven regime with near hydrostatic pressure (Fig. 3). The initial hydraulic head values reach 120 m in the *N* part of the area, while they are less than 100 m in the SW part, in accordance with the topographic features. The horizontal hydraulic head gradient is approximately, 1 m/km in the Pleistocene layers. The hydraulic head of the *N* part decreases in the lower layers to 109 m, while in the SW part of the area the hydraulic head values increase to 107 m in the lowest layer. In the fourth layer, the horizontal hydraulic head gradient is 0.5 m/km, while it is 0.25 m/km in the fifth layer, and it is 0.1 m/km in the most important aquifers which are the sixth and seventh layers. The geothermal gradient of the study area is 61 °C/km based on some temperature data measured in the wells (Fig. 3).

The well Hajdúszoboszló-I produced a mixture of water and natural gas with a yield of 1.6 and 5.07 m^3/min, respectively, the static level of the water with a temperature of 73 °C was 14–20 m above the surface (Csath 1975). The well Hajdúszoboszló-II produced 1.25 m^3/min thermal water with a temperature of 78 °C and additional natural gas with a yield of 2.5 m^3/min. It was necessary to re-drill both boreholes. The screenings in the new well Hajdúszoboszló-Ia are located at depths between 912 and 1,052 m, while the screenings of the new well Hajdúszoboszló-IIa were installed at depths between 743 and 889 m.

The well Debrecen-I produced thermal water with a temperature of 65 °C and a yield of 1.18 and 1.56 m^3/min of gas, while the amount of dissolved solids was 5,390 mg/l (Csath 1984). Four screenings were installed in the well at depths between 826 and 1,025 m.

Baths of Hajdúszoboszló and Debrecen have international reputation thanks to the medical effects of their thermal water. Patients with chronic locomotor disorders, degenerative illnesses and locomotor disorders of surgical, neurological, internal and dermatological origins are treated in the establishments of the baths. The healing effects of the thermal water are associated with the amount and composition of the dissolved substances.

Salinity has a good correlation with depth. The value of total dissolved solids (TDS) at the depth of 500–800 m is about 1,500–2,500 mg/l, the most characteristic ions are the sodium and the hydrogen-carbonate ions. In the main zone of thermal water extraction (900–1,100 m) the concentration is 4,000–5,000 mg/l and the chloride ion becomes the most important anion. Below this zone the samples of the well Hajdúszoboszló-I describe the changes in the solution: the TDS reaches the value of 16,000 mg/l, the concentration of each parameter is increasing by depth. However, the relative amount of chloride ion further increases to 80 eq. %, while the relative amount of hydrogen-carbonate decreases indicating the marine origin of the sediments and fluids and the lack of intensive fluid circulation.

Due to the intensive water production, the hydraulic head of the reservoir decreases. In some wells, the hydraulic head decreased by more than 40–70 m over 80 years (Fig. 4). Most of the wells were flowing artesian wells at the time of drilling, but well-head pressure values decreased within a short time. This suggests that local overpressure as a result of gas migration and accumulation, in addition to sediment compaction caused the initial higher values. The natural gas content of the layers decreases due to hydrocarbon extraction north of Hajdúszoboszló and to the extraction of dissolved gas with thermal water. Reduction of free and dissolved gas content decreases the static level. In other wells, initial overpressure and significant decrease in static water level have not been observed. The behavior of the wells strongly depends on the number and transmissivity of the screened layers, and the vertical hydraulic conductivity of the clayey interbeddings, however, exact pressure and yield of each screened layer is usually unknown.

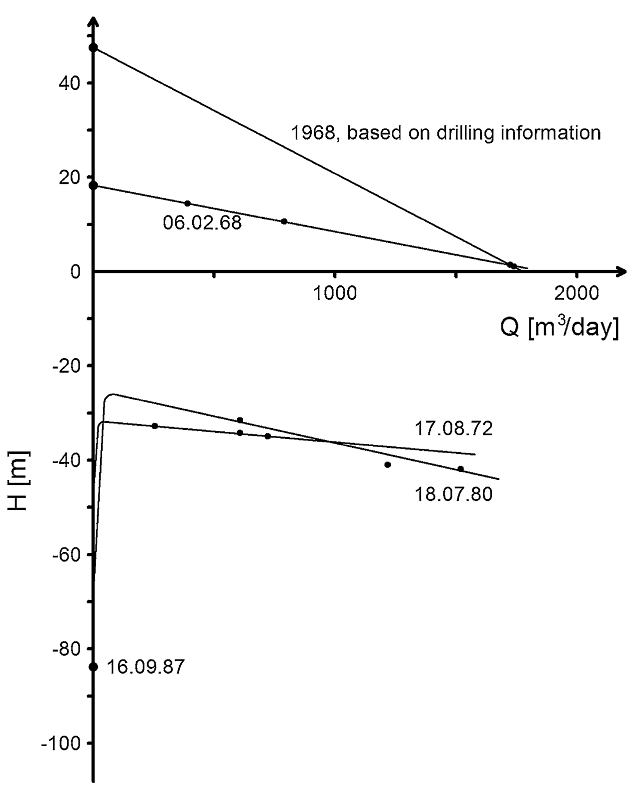

Fig. 4 Changes in static levels due to overproduction in the well of the market garden of Debrecen

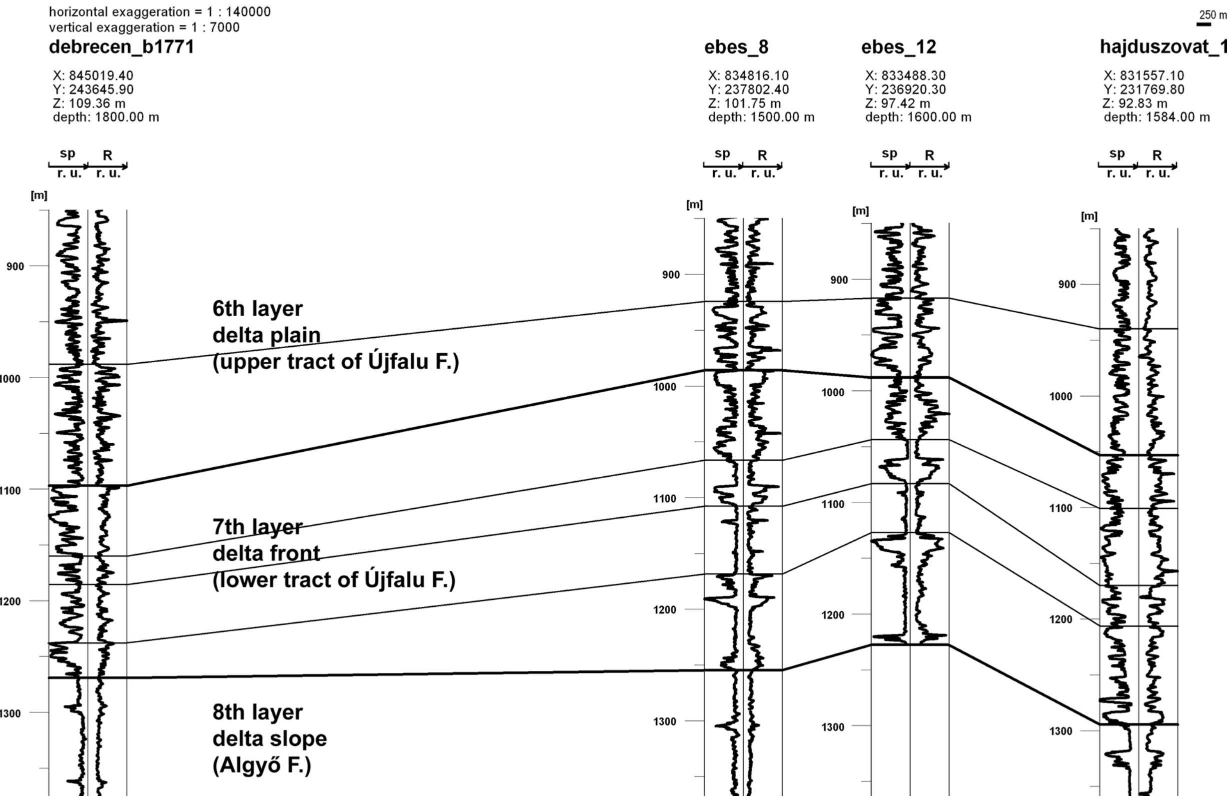

Fig. 5 Well-log correlation section of the Újfalu Formation in the south part of the Debrecen—Hajdúszoboszló region

Table 1 Hydraulic parameters and water production data of the model layers

No. of layer	Age and/or facies	Horizontal hydraulic conductivity (m/days)		Vertical hydraulic conductivity (m/days)		Porosity (−)	No. of wells	Produced water (m^3/days)
		Range	Average	Range	Average			
1	Upper tract of Pleistocene	1.10–9.13	5.81	3.23×10^{-4} to 1.11×10^{-1}	2.96×10^{-2}	0.10	–	
2	Middle tract of Pleistocene	0.08–7.28	1.40	1.18×10^{-4} to 3.82×10^{-2}	4.43×10^{-3}	0.05	–	
3	Lower tract of Pleistocene	5.08–9.53	6.92	3.23×10^{-4} to 1.12×10^{-1}	2.56×10^{-2}	0.10	–	
4	Terrestrial fluviolacustrine	0.51–5.87	2.00	1.26×10^{-4} to 9.33×10^{-4}	3.83×10^{-4}	0.05	1	324
5	Terrestrial lacustrine	0.003–3.28	1.31	1.48×10^{-4} to 1.47×10^{-2}	1.19×10^{-3}	0.03	1	558
6	Delta plain	0.64–4.95	2.61	2.02×10^{-4} to 1.73×10^{-2}	1.48×10^{-3}	0.05	2	672.4
7	Delta front	1.01–7.80	3.41	1.66×10^{-4} to 9.82×10^{-4}	4.30×10^{-4}	0.10	9	5,079.9
8	Delta slope	0.001–0.70	0.24	1.03×10^{-4} to 1.66×10^{-4}	1.24×10^{-4}	0.03	–	

Methods

A steady-state hydrodynamic model was performed using MODLFOW-2000 finite element numerical software with Processing Modflow Pro (PMWIN Pro) pre- and postprocessor (Chiang 2006; Chiang and Kinzelbach 2001) for determining the effects of thermal water production in the region. After determining the hydraulic head distribution by the steady state model, the recharge area of the wells was studied using PMPATH, a particle tracking program for Processing Modflow.

Considering the geological conditions and the requirements of the program, the study area is rectangular (30 km by 16 km) and covers the area of Hajdúszoboszló and Debrecen (Fig. 1). The azimuth of the longer side is 28° reflecting the direction of the basement features. The size of the cells is 200 m in both horizontal directions therefore the number of rows is 80, while the number of columns is

150. Some larger hydrodynamic models cover the studied area (Székely 2006; Tóth et al. 2010). Since the boundary of the area is not a hydraulic boundary, the applied hydraulic head values were derived from the regional model of Székely (2006, 2007) with his permission.

The area is well-explored. The number of boreholes deeper than 200 m with appropriate documentation is more than 250, of which more than 100 are deeper than 1,000 m. Definition of the stratigraphic based solid model was based on 27 boreholes (Fig. 1).

Data were acquired from the Trans Tisza Region Environmental and Water Directorate, and from the Hungarian Geological, Geophysical and Mining Database as part of an international research project. The distribution of the wells is good; however, the data of hydrocarbon exploration boreholes proved to be productive are often secret or limited. The wells in the thermal well registry of Hungary are considered to be the most important data in the interpretation.

Digitizing of well-log data was performed using the GeoGörbe software developed at the Department of Mineralogy and Geology, University of Debrecen (Gyula and Németh 2005) and the data were imported into a Microsoft Access database (Kozák et al. 2011).

The sediment succession was divided into lithostratigraphic units based on well-log data (Juhász 1992), e.g. spontaneous potential, resistivity and natural gamma (Fig. 5). The main target formations of the thermal water extraction are the Zagyva and Újfalu Formations, however, the shallower (Pleistocene) layers were also studied to determine the rate and possibility of vertical infiltration from the surface (Table 1). The facies-based model was applied since both the coastal delta facies and fluvial facies may consist of laterally finite bodies that the applied software cannot handle. In addition, most of the wells are multi screen wells, in some cases the depth difference of the upper screen and the lower screen is around 500 m. However, there is no flow meter or pressure survey in each well, therefore, we cannot analyse the layers separately.

The lowest model layer is the Algyő Aquitard of delta slope facies. Since the arrangement of the overbedding Pannonian layers would not be accomplished in each case, the Pre-Quaternary part of the Nagyalföld Aquifer is divided into model layers based on the sedimentary features.

Above the delta slope sediments thick beds of delta front sediments were deposited (lower track of the Újfalu Formation) representing the most important thermal water reservoirs in the region. The delta front sediments are replaced by delta plain sediments upward, characterized by low-middle resistivity (upper tract of the Újfalu Formation). The delta plain becomes alluvial plain (Zagyva Formation) upward where silty sediments are dominant in the lower part (lacustrine) and coarser sediments of channel belt complexes can occur in the upper part (fluviolacustrine).

The silty layers of the Pannonian sediments characterized by brackish pore water are buried by fluvial sand and gravel of the lower tract of the Pleistocene succession containing fresh water, thus the resistivity values increase significantly. In the middle tract of the Pleistocene fluviolacustrine sediments were deposited, while in the upper one the sediments are coarser again.

Based on the combination of downhole and seismic data (De-27, De-29, Vé-27 seismic lines) a solid model was built by the software GOCAD (Bódi and Buday 2012). Since the hydrodynamic modeling software requires spatially continuous surfaces with real thickness, all the layers were extended to the entire space of the geological model.

For the hydrostratigraphic properties the results of previous regional studies and models were considered. Hydraulic conductivity data were based on the characteristic formation values of Tóth and Almási (2001) and refined based on the normalized well-log values (Buday and Bulátkó 2012). The normalization was based on the shale index calculation of the formation groups. The calculated values were analysed in each well per formation to estimate the shale/silt/sand ratio. The conductivity values were calculated based on the mathematic equation of layered porous sediments.

The expected grid decrease of the water level (both static and dynamic) is lower in the presented model than the measured values as a result of three conditions: the hydraulic head values of the regional model by Székely (2006) are lower than the initial static level in the wells and the topographic level around Debrecen; the solid model was built using facies-based units instead of lithology-based units; and the wells partially penetrate the model layer.

The applied MODFLOW simulation package is based on the well-known finite difference approach which means that a grid system is used to cover the modeled area. The grid size (ΔX) can determine the resolution of the flow model, because the average hydraulic head is calculated inside a grid. Consequently, regional flow models can describe the general trends concerning the hydraulic head distribution; however, only local models are able to describe the accurate depression cones around the production wells if the grid size is small.

If it is required, the local drawdown can be accurately calculated with the help of the following expression. In case of a finite difference, approach like MODFLOW, the local drawdown swell in any particular well is obtained as the sum of the grid drawdown (s_{grid}) and the corrected increment drawdown ($\mathrm{d}s_{\mathrm{well}}$). The corrected increment drawdown can be calculated based on the following equation (Peaceman 1983):

$$ds_{well} = \frac{Q}{2\pi T}\ln\left(0.2\frac{\Delta X}{r_{well}}\right) \quad (1)$$

where

ds_{well} is corrected increment drawdown (m)

Q is discharge of the pumping well (m^3/s)

T is average transmissivity of the pumped layer (m^2/s) around the well

ΔX is horizontal extent of the grid (m), 200 m in this case

r_{well} is the radius of the well (m), between 0.05 m and 0.09 m in this case.

Using this expression, the computed well drawdown values were nearly equal with the measured ones in case of the investigated area. As the calibration error of the flow model (RMSE = 0.4 m) was rather low, this means that the reliability of the regional flow model can be considered to be satisfactory. This also means that the results of the regional model can be used to interpret the hydraulic state of the targeted thermal water aquifers.

The production and temperature data of thermal wells are also stored in the database of the Directorate. Characteristic yearly water production data were selected for the model. The effects of fresh water production from the Pleistocene and uppermost Pannonian layers were not considered here. The thermal power of extracted water was determined based on the yield and well-head temperature data with selecting 15 °C as the lower temperature limit of utilization.

Results and discussion

Characteristics of the hydrostratigraphic units

The sediments of the delta succession are deposited directly on the top of the marls of the Endrőd Formation. The Algyő and Újfalu Formations are interfingered, the typical sediments of the Szolnok Formation are missing while the sediments of the Zagyva Formation cannot be separated convincingly from those of the Újfalu Formation. The generalized top of the Algyő Formation varies between the depths of 900 and 1,100 m below sea level, temperature here is approximately 80 °C. Considering the average geothermal gradient in the study area, thermal water (>30 °C) extraction seems to be perspective in relation to the sand bodies of the delta front and delta plain facies.

In the lower tract of the Újfalu Formation lateral facies variations have been observed in the study area (Fig. 5). Based on log data, thick pelitic interbeddings can be detected between the sand bodies of the delta front facies above the Ebes Thrust. These silty interbeddings become thinner basinward. This stratigraphic pattern can be interpreted as a result of periodic, temporary occurrence of delta front facies above the Ebes Thrust, contrary to the almost permanent occurrence of the delta front conditions in the sub-basins at Hajdúszoboszló and Debrecen. These pelitic interbeddings cause significant decrease of both the horizontal and vertical conductivity in the Újfalu Formation, thus decreasing the hydrodynamic communication between the area of Hajdúszoboszló and Debrecen (Buday and Püspöki 2011, Kozák et al. 2011).

Results of the steady-state model

In the steady-state model, the thermal water extraction causes drawdown in the Pleistocene layers around Hajdúszoboszló, however, its value is lower than 0.2 m. The 4th layer contains one production well. The grid drawdown in the surroundings of this well is higher than 0.6 m, while the subregional value is 0.1–0.2 m in this layer.

The well Hajdúszoboszló–X producing from the 5th layer causes more than 3 m of grid drawdown in this layer. Similar value of grid drawdown appears in the 6th layer near the well Hajdúszoboszló–XIV (Fig. 6a). Only one of the wells in Debrecen is producing from this layer, in addition its yield is not so high; consequently it does not modify the regional drawdown values significantly.

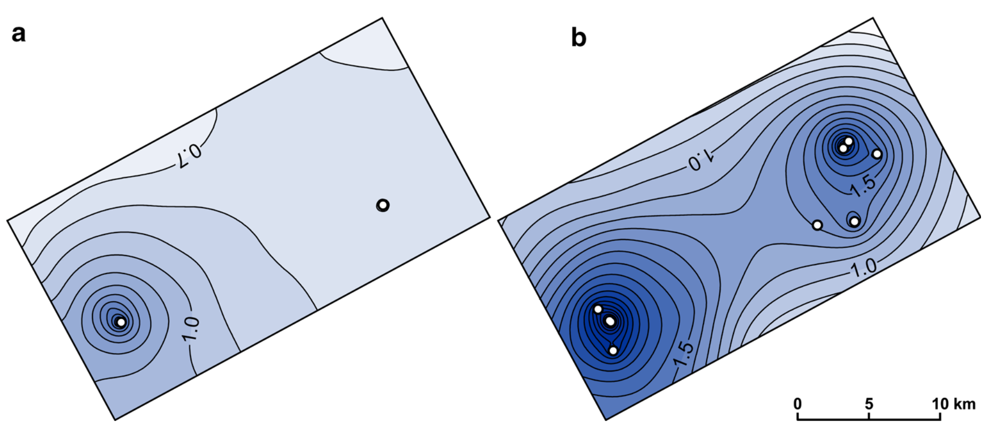

Fig. 6 Modeled grid drawdown **a** in the 6th layer and **b** in the 7th layer (in meters, contour line interval: 0.1 m) with the location of the wells producing water from the given layer

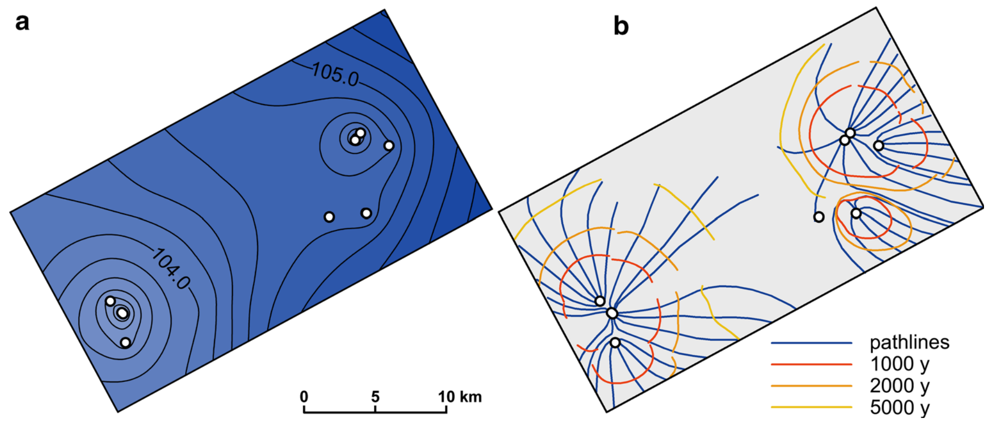

Fig. 7 Modeled **a** hydraulic head distribution (m asl., contour line interval: 0.2 m) and **b** recharge directions and time in the 7th layer of steady state model

Most of the wells produce thermal water from the 7th layer. The production causes 0.4–0.5 m of drawdown in the boundary of the model, while near the towns, these values increase to 1.4 m in Debrecen and 2 m in Hajdúszoboszló. The grid drawdown values around the wells are higher than 2.5 m (Fig. 6b).

The changes of the hydraulic head distribution of the 7th layer are significant (Fig. 7a). The radius of the hydrogeological "B" area (particle movement to the well over 50 years) is 500–600 m in the case of the wells of the two large spas (Fig. 7b), while the value of the Kerekestelep open-air pool (south of Debrecen) is approximately 400 m. Both producing well groups are supplied mainly from the NE, however, Debrecen receives no supply from the direction of the Ebes Thrust neither does Hajdúszoboszló in the 7th layer due to the deteriorated hydrogeological communication as described in "Characteristics of the hydrostratigraphic units". Therefore, water rather moves into the 6th layer to the wells of Hajdúszoboszló, as in this unit hydrogeological communication is somewhat better.

The layer of the Algyő Aquiclude has significant drawdown; even pore water migrates upward due to the decreased hydraulic head.

The value of the corrected increment drawdown (Eq. 1) around the most important wells regarding $r_{\mathrm{well}} = 0.07$ m, $Q = 0.01$ m^3/s, $T = 6 \times 10^{-4}$ m^2/s is 17 m, which means that the local drawdown is higher than the grid drawdown with one order and similar in most cases to the values measured by casual well test, however, the local drawdown in some wells is significantly higher than the measured values. The difference between the measured and modeled value is higher where spreading aquitard clayey interbeddings retard the vertical water recharge around the well. In the Pannonian delta front sediments the presence of clayey layers is generally rare, however, in the studied location the interfingering of delta slope and delta front sediments is proven in the lower part of the studied formation, which is the main target of thermal water production. This facies variability may explain the drawdown differences between the wells, but it was not possible to incorporate these interbeddings into the applied solid model, since the layers were based on facies and not on lithology. The effects of degassing in the wells on the standing level in the case of a flowing well and the decreasing natural gas content of the reservoir have not been incorporated into the model either, however, these can also be responsible for the differences between the model and the measured values.

In the studied systems the thermal water is extracted mainly for balneological purposes. In this way, the re-injection of the produced water is prohibited. The legislation of thermal water extraction for energetic purposes is changing in Hungary, the obligation of re-injection was obliterated in 2013. Some of the currently operating thermal water utilization systems in Hungary have good experience in the field of thermal water re-injection to porous reservoirs (Szanyi and Kovács 2010), while others have significant problems. The scientific analysis of the possibilities of re-injection is still in an initial stage where models are continuously refined on the basis of the results to represent reality as closely as possible.

Role of the wells in geothermal energy exploitation

The total surface thermal flux of the wells is 13.6 MW which is approximately 0.9 % of the total potential of the Hungarian thermal wells considering the ambient temperature of 15 °C (Tóth 2010). The flux of individual wells is rather different depending on the yield and the outflow temperature. The minimum value is lower than 0.6 MW regarding industrial utilization or the Kerekestelep open-air pool, while the maximum values are higher than 2 MW. Based on the hydrogeological study, the well-head temperature values will decrease, as water from shallower reservoirs reach the wells, meaning lower geothermal potential.

Earlier the heat content of the water was not used to suffice the heat demand of the buildings. Both spas have constructed new building service systems therefore, the energetic use of the heat content became possible. The pre-pool usage includes space heating and sanitary hot water warming, while the heat content of the used water is appropriate for pre-heating, increasing the temperature of the air or heat pump appliances.

Significant amount of methane is also extracted with the water and it has approximately, 0.65 MW heat content if burnt. It was used for public lighting; however, after electrification the gas was not utilized. Nowadays, the methane is used for generating electricity in Hajdúszoboszló.

Conclusions

Pressure drop in the reservoir is one of the most important phenomena revealed in several countries related to intensive thermal water extraction. It causes the decrease of static water level or porosity, consequently the efficiency of the production is reduced. These effects are manifested significantly where water production is concentrated.

In the studied area, the load of the reservoir is significant; however, the influence between the well-groups is not appreciable due to the distance between them. In addition, the detected facies variation in the 7th layer in the middle of the model area also reduced the hydraulic connectivity between the two reservoirs.

Between the wells in both groups, the effects are significant referring to the importance of sustainable thermal water production and geothermal heat extraction. Two best practice technologies were developed in the region for these purposes; both of them could significantly influence geothermal energy utilization in Hungary. The heat content of the produced water has to be extracted as efficiently as possible considering that re-injection is prohibited in case the contamination of the used water is possible. On the other hand, the amount of used thermal water has to be decreased. This could be achieved by utilizing deeper and shallower groundwater for different purposes. Medical water from greater depth could be used for medical purposes, however, for bath purposes shallower thermal water alone would be suitable as well. In this way several reservoirs in different depths would be included in the utilization thus the overproduction of one of them could be decreased.

Apart from the two large spas, several smaller baths, agricultural and industrial utilizations are in operation or planned to be in operation in the near future in the area. To maintain sustainable utilization common reservoir management is required. The reservoir overproduction could be reduced by re-injection as well which is suggested in all closed systems where technical possibilities are given.

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