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A half century of reservoir property changes in the Szentes geothermal field, Hungary

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The general characterization of the Hungarian Szentes geothermal field is presented based on the review of previous research and is supplemented with the analysis of well hydraulic tests. Forty thermal wells were included in the study area, producing mainly from Upper Pannonian sandstone reservoirs. The intensive and long-term production of thermal water reservoirs without reinjection resulted in significant reservoir pressure decrease from natural conditions. By means of deep-well pressure build-up curves, deep-well capacity curves and surface pressure curves the reservoir condition changes were described in the last half century.

Keywords: Szentes, geothermal, production, well test analyses, pressure decrease

Introduction

The Szentes geothermal field is one of the oldest and most intensively produced areas in Hungary. The geothermal operation began in 1958 with the drilling of the Kórház-I thermal well, the success of which encouraged drilling of new geothermal wells both in the investigated area and in Hungary in general. By now there are 40 thermal wells in the Szentes geothermal field including the Fábiánsebestyén and Szegvár areas; 34 of them were drilled before 1980 (Table 1).

Korim and Liebe (1973) made a summary description based on the data of 22 thermal wells, and later Korim (1991) completed his previous research with the his-

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tory and effects of 3 decades of production. In this present study we summarized the results of the former investigations and analyzed the pressure changes of the geothermal reservoir based on well hydraulic tests.

Table 1
List of thermal wells

Well name	Registry number	X local coordinate	Y local coordinate	Well depth	Elevation (m asl)	Year of establishment
Alkotmány-I	K-561	741341	151760	2025	81.6	1969
Alkotmány-II	K-578	742231	151195	2401	81.6	1971
Árpád-I	K-498	747457	149538	1995	84.7	1965
Árpád-II	K-562	748488	149493	1800	82.8	1969
Árpád-III	K-563	746484	148356	1993	83.2	1970
Árpád-IV	K-586	747234	149283	2303	83.9	1972
Árpád-V/1	K-640	747674	150857	2240	84.5	1980
Árpád-V/2	K-641	747862	150868	2000	85.0	1980
Árpád-VI/1	K-642	749981	150150	2398	83.4	1978
Árpád-VI/2	K-643	749983	150164	1998	83.4	1978
Árpád-VII/1	K-644	747112	152442	2257	84.6	1979
Árpád-VII/2	K-639	747109	152475	1806	83.3	1980
Árpád-VII/3	K-645	747103	152539	1999	85.0	1980
Árpád-VIII	K-666	749166	151855	3400	85.2	1987
Berekhát	K-557	743485	142855	2050	83.5	1970
Donát-I	K-503	751166	147698	1997	84.1	1966
Donát-II	K-514	751958	146712	2199	83.8	1967
Donát-III	K-560	751114	147699	1815	83.5	1969
Felszabadulás I	K-515	748528	147343	2203	82.7	1968
Felszabadulás II	K-564	748240	147414	1900	83.5	1970
Ilonapart-I	K-505	741000	145600	2004	79.1	1967
Ilonapart-II	K-533	741178	147135	2000	80.6	1969
Ilonapart-III	K-558	739953	145828	2001	79.7	1969
Ilonapart-IV	K-577	738613	145746	2500	80.1	1970
Kertészeti Kutató	K-559	741695	145798	1796	80.8	1969
Kontakta	K-652	744358	145584	2346	83.4	1983
Kórház-I	B-17	742000	147300	1725	80.6	1958

Table 1 (cont.)

Well name	Registry number	X local coordinate	Y local coordinate	Well depth	Elevation (m asl)	Year of establish-ment
Kórház-II	B-629	742136	147389	1593	82.0	1976
Városközpont-I	K-657	743863	146107	1997	83.3	1986
Hámán Kató ltp. II	B-658	742170	147389	2345	81.5	1986
Fábiánsebestyén Kinizsi MGTSZ	K-60	754500	149800	2190	82.3	1971
Fábiánsebestyén Pankota-Kórógy I	K-57	753957	149092	2004	83.7	1969
Fábiánsebestyén Pankota-Kórógy II	K-59	755008	148854	2001	83.5	1970
Szegvár-I	K-94	742948	138481	2193	83.5	1968
Szegvár-II	K-96	741796	138317	2500	83.4	1970
Szegvár-III	K-102	742952	138332	1800	83.0	1978
Szegvár-IV	K-103	743718	137978	2500	83.5	1980
Szegvár-V	K-106	742443	138739	2496	83.4	1988
Szegvár-VI	K-107	743737	139182	2291	80.5	1990
Szegvár Kendergyár	B-87	741684	138958	915	83.5	1963

Geologic background

The Szentes geothermal field is located in the southern part of the Great Hungarian Plain (Fig. 1) on the left bank of the Tisza river, including the Szentes, Szegvár and Fábiánsebestyén areas (hereafter in this study named the Szentes area). The Szentes area belongs to the northeastern wedging part of the Makó–Hódmezővásárhely Trough, where the pre-Neogene basement is at depths between 4,500 and 5,000 m (Szanyi and Kovács 2010). The trough was filled with gravel and conglomerate from the erosion of the Algyő and Pusztaföldvár Highs, as Pannonian porous sediments (Budai and Gyalog 2010). In the study area the pre-Neogene basement was reached by only two boreholes. In the east side of the area the *FÁB-4* exploration well, after intersecting the Miocene layers, exposed Upper Cretaceous sandstone and siltstone at 3,153–3,750 m and finally stopped in Lower Triassic sandstone and clay layers, with total depth of 4,239 m (Korim 1991). Also, in the northeastern part of the study area the *K-666* (also known as *Szentes ÉK-1*) well, with a total depth of 3,400 m reached the Upper Cretaceous layers at 3,205 m. West of the study area, approximately 8 km from the town of Szentes, the *FELGYO-I* borehole also reached the Upper Cretaceous layers at 2,740 m, while north of the area the *KUNSZ-1, -2, -3* boreholes stopped in Miocene sediments.

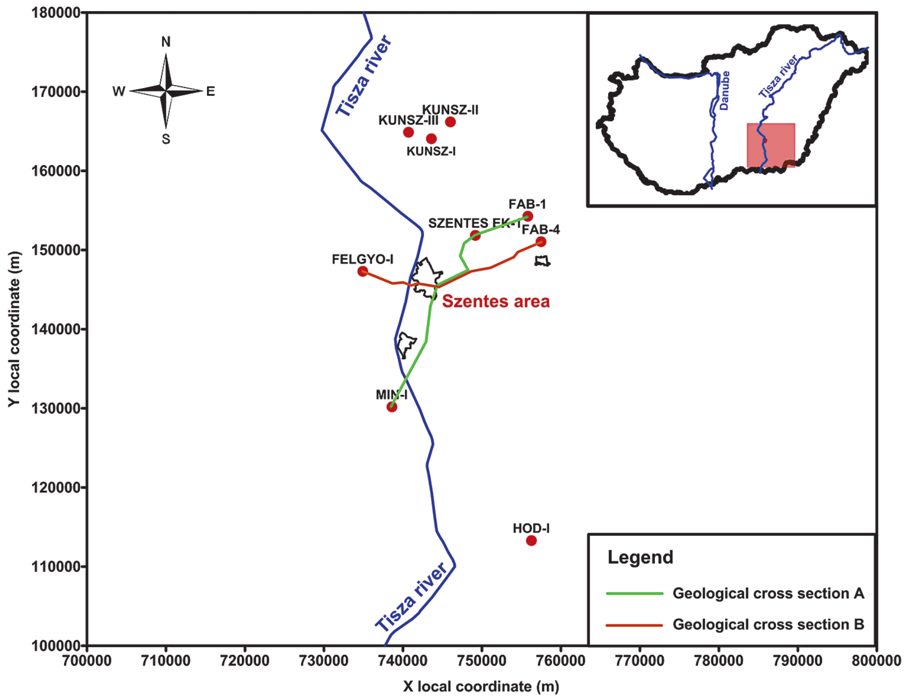

Fig. 1
Map showing the location of the Szentes geothermal field and adjacent areas

In the evolution of the Pannonian beds a rapidly prograding delta system from the NW played a decisive role. The sedimentary environments change upsection, from deep basin through delta slope, delta front to delta plain (Juhász 1991). The total thickness of the Pannonian (s. l.) sediments can exceed 3,000 m (Juhász 1989). The thermal wells in Szentes exposed the Upper Pannonian Újfalu Formation (delta front and delta plain facies) as well as the delta top and alluvial plain facies (Zagyva Formation; Fig. 2). The Újfalu Formation, which is stratigraphically deeper, was only intersected by the petroleum exploration wells of Fábiánsebestyén, and the *K-577*, *K-642*, *K-578*, *K-557* and *K-60* thermal wells. The Upper Pannonian layers in the western part of Szentes, based on the data of the *K-577*, extend to the depth range of 2,400–2,500 m, while in the eastern part they only reach that of 2,150–2,300 m. The *KUNSZ-1,-2,-3* petroleum wells intersected the Upper Pannonian layers at 1675–1775 m (Juhász 1989); therefore the thickness of the Upper Pannonian layers probably slightly decreases northward. South of Szentes the *MIN-I* reached the base of the Upper Pannonian at 2,540 m (Juhász 1989), and the *HÓD-I* CH exploration well at a depth of 2,470 m.

The term “Szentes thermal reservoir system” means in practice the Upper Pannonian sedimentary beds. The Újfalu Formation contains sandstone, siltstone, and

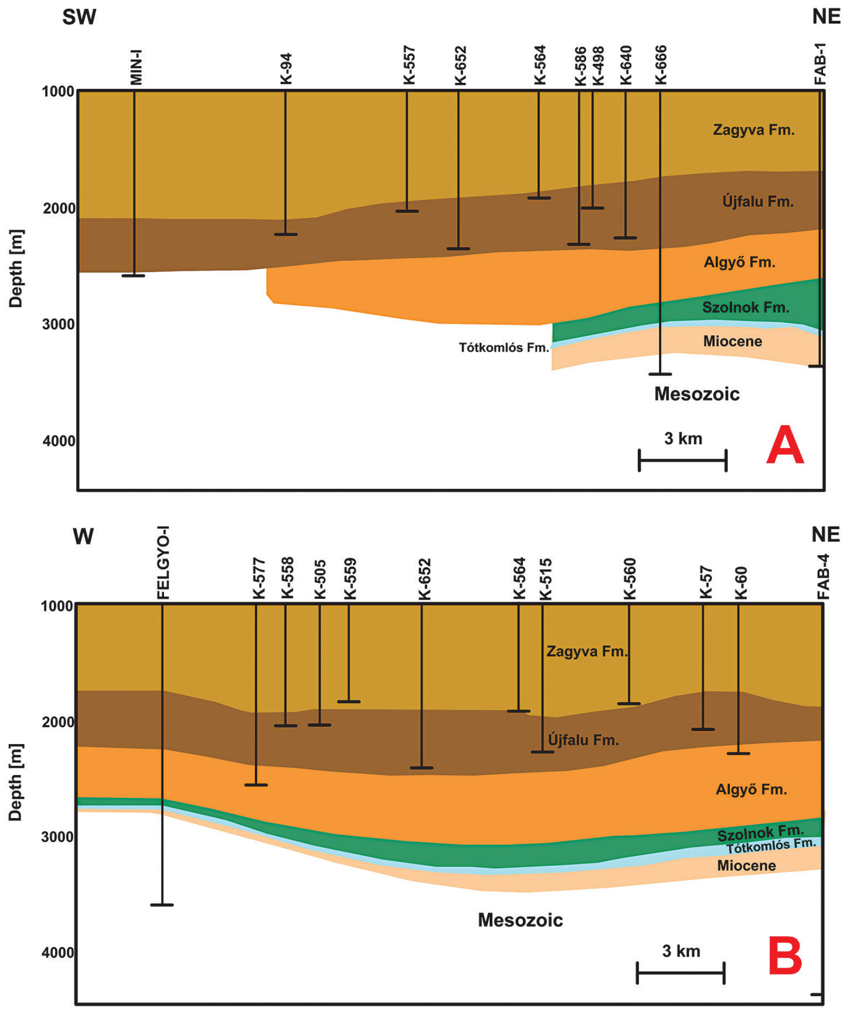

Fig. 2
Geological cross-section A and B, based on Juhász, Gy. (1989)

clay marl, with a predominance of sandstone layers. It typically consists of channel and mouth bar sediments, which have good reservoir properties and limited lateral extension; however, due to the multiple erosion and superposition events they are in hydrodynamic connection. The overlying Zagyva Formation represents an alluvial plain depositional environment, which has an extremely heterogeneous constitution; the alternation of sandstone, silty sand, silty clay and clay layers is very common. In the alluvial plain channel and point bar sediment pattern cycles predominate (Juhász 1989). The upper boundary of the Zagyva Formation is marked by the decreasing rate of sandstone, which usually can be easily identified. The Quaternary layers deposited over the Late Pliocene sediments have an average thickness of 600–700 m and contribute to the water supply of Szentes.

Characteristics of the Szentes geothermal reservoir

The Upper Pannonian sediments, with a thickness of 1,600–1,800 m, form a multilevel, extremely heterogeneous anisotropic reservoir. The thermal water-bearing deposits have a very variable shape extent and appearance, and the layers are not totally horizontal. Sand bodies appear in the area mostly as sand sheets, which have a thickness of 1 to 20 m and long lateral extension. Lenticular sand bodies and multilateral rock bodies of considerable horizontal extent and 50–150 m thickness are also common (Korim 1991).

The variable appearance, the capricious horizontal extension of sand layers, the irregular well distribution and 2–4 km average distance between the wells make the correlation quite uncertain or even impossible if the wells are farther apart than 1–1.5 km (Korim and Liebe 1973; Juhász 1989). Among the individual layers a relatively reliable correlation can be made in the case of 2- or 3-member well groups, while at distant wells formation-based classification provides a possibility of orientation.

The Upper Pannonian thermal reservoir system is divided into 3 groups of layers by Korim (1991):

- Upper aquifer layer group: between 1,300–1,800 m
- Middle aquifer layer group: between 1,800–2,000 m
- Lower aquifer layer group: between 2,000–2,500 m

The above-mentioned simplified division was probably created on the basis of the exposed sections of the wells at different depths and does not depend on geologic information; however, it is still used nowadays due to its ease of handling (Barcza et al. 2011; Szongoth 2012).

The inner structure of sand bodies and shape factors also have a great effect on the forming of the hydrodynamic conditions and behavior of thermal water-bearing reservoirs (Korim 1972). The fundamental problem of the geologic description is that despite the large number of wells, no core samples were ever taken in the study area; the inner structure and physical properties of rocks were described by the research of Upper Pannonian layers in the southern part of Great Hungarian Plain and the core analysis of samples of the *FÁB-I* petroleum exploration well, which is located northeast of the study area (Bélteky et al. 1970).

Considering the above, Korim and Liebe (1973) recommended the following for porosity values in the Szentes thermal reservoir system:

- 1,000–1,500 m depth section: 28%
- 1,500–2,000 m depth section: 21%
- below 2,000 m depth section: 14%

These recommended porosity values are in line with the calculated porosity values from geophysical measurements of well *K-657*, which returns a 27–21% uniform porosity decrease within the 1,300–1,900 m interval (Korim 1991).

Considering the mineral composition, in the absence of core samples and surveys we must rely on the average composition of Upper Pannonian sandstone. According to these, the sandstone contains 70–90% quartz with clay or carbonate cement (Korim 1991). In both Upper and Lower Pannonian layers there is a local enrichment in carbonate cement up to 30–60%; this sandstones is of low permeability (Korim 1972). The carbonate cement is unequally distributed in the Pannonian sandstone and it plays a very important role in the forming of heterogeneous reservoir properties. The Upper Pannonian layers have an average grain size of 0.2–0.1 mm, and their average bulk density is 1.9–2.2 g/cm^3 (Korim 1966).

Deep-well pressure build-up tests were used to define the permeability of layers. The Horner method, used most often, was selected from among the different kinds of analytical methods presented by Bélteky et al. in 1965. Calculations were carried out on the data of 39 wells, on the assumption that within the wider environment, the rocks have not changed. Thus, to avoid formation skin effects, usually the oldest available measurement data was used. Along with our calculated results we also give the recommended permeability values of Korim and Liebe (1973):

- 1,600–1,800 m depth section: $K_{avg(1973)}$ = 400 mD; K_{avg}: 465 mD
- 1,800–2,000 m depth section: $K_{avg(1973)}$ = 265 mD; K_{avg}: 355 mD
- Below 2,000 m depth section: $K_{avg(1973)}$ = 220 mD; K_{avg}: 280 mD

Our calculated permeability values were within a rather narrow range, but in the middle and upper layer group the average is formed by extreme permeability values; the difference can even exceed 1,000 mD. The small deviation between our calculated and the former (1973) results may have been caused by the inaccuracy of the graphical curve method; wells drilled later than 1973 were also taken into account.

There are no structural discontinuities and faults in the Szentes thermal reservoir system. The reservoir properties were formed by the sedimentation processes (Bélteky et al. 1970).

Thermal wells: location and technical characteristics

The placement of thermal wells within the geothermal field is very uneven (Fig. 3). The wells are concentrated in 3 greater areas: the Szegvár area, the Szentes town area and the Szentes outskirts area. They often make up relatively close (within few 100 m) well groups drilled to different depths; however, there are usually distances of 2–4 km between the well groups. The wells are nearly equally distributed among the Upper Pannonian layer groups, while at the same time a few drilled through the section overlying them. The number of perforated sections are 3 to 17, with 90 m average total thickness, but they can be very different at each well, and can expose

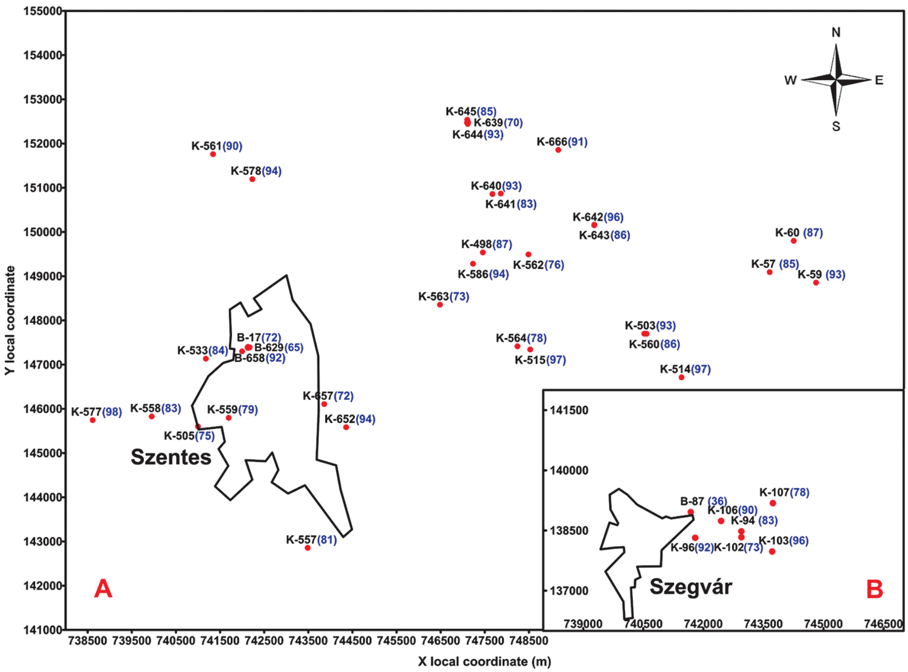

Fig. 3
Thermal well placement in the Szentes–Fábiánsebestyén (A) and in the Szegvár area (B) and outflow water temperature given in brackets

more than 400 m of interval! The wells usually reach the appropriate depth with 3, in few cases with 4 different casing diameters; the deepest ones are of 6 5/8" or less frequently 7 or 4 1/2" diameter.

Changes of thermal water production

The first extensive well hydraulic and well interaction tests in the Szentes geothermal field were carried out in 1968 at the first 7 thermal wells by the research group of the National Technical Development Committee (Bélteky et al. 1970). Based on this early research and the measured data of 22 newly drilled wells, Korim and Liebe (1973) determined that a connection exists between the different layer groups; 40.89 million m^3 of thermal water were produced up to 31 August 1972, resulting in a slight decrease of reservoir and wellhead pressures. In 1971–1972, 19 thermal wells produced 7.58 million m^3 and the pressure decreases were estimated to be 0.2–0.5 bar/million m^3 for each well.

Thereafter, in 1991 Korim summarized the production data and pressure changes until the end of 80s. By this time it became obvious that long-term intensive production without reinjection, with the decrease of dissolved gas content, created a significant reservoir energy drop. At the beginning of 1991 the total extracted thermal water was estimated at 250 ± 10 million m^3 (Korim 1991), and about 6.5 million m^3/year production at this time (Szanyi and Kovács 2010). Until 1991, the majority of the thermal wells became unproductive, or the water amount with free outflow decreased at such a scale that submersible pumps had to be installed (Korim 1991). Up to 2004, moderated, 4–8 m increase of hydraulic heads were observed by Kovács and Szanyi (2010), which was assigned to the decrease of production to 5.7 million m^3/year (Fig. 4).

After the political system change in Hungary at the end of the 80s, the former "regular" well hydraulic tests were not carried out by the authorities. Extensive and reliable measurements were not made until 2009–2010, when 20 thermal wells were measured together. These well tests were funded under the Jedlik Project. This test series provided the opportunity to analyze the effects of a half century of intensive production and to investigate the current state of the reservoirs. Unfortunately, measurements were only made on nearly half of the wells, those of the Árpád Agricultural Company, the Alkotmány well group and the Szegvár well group. Even with the new measurements carried out, usually there were 3–4 deep-well tests for each well and in many cases more than 30 years had gone by between the different measurements!

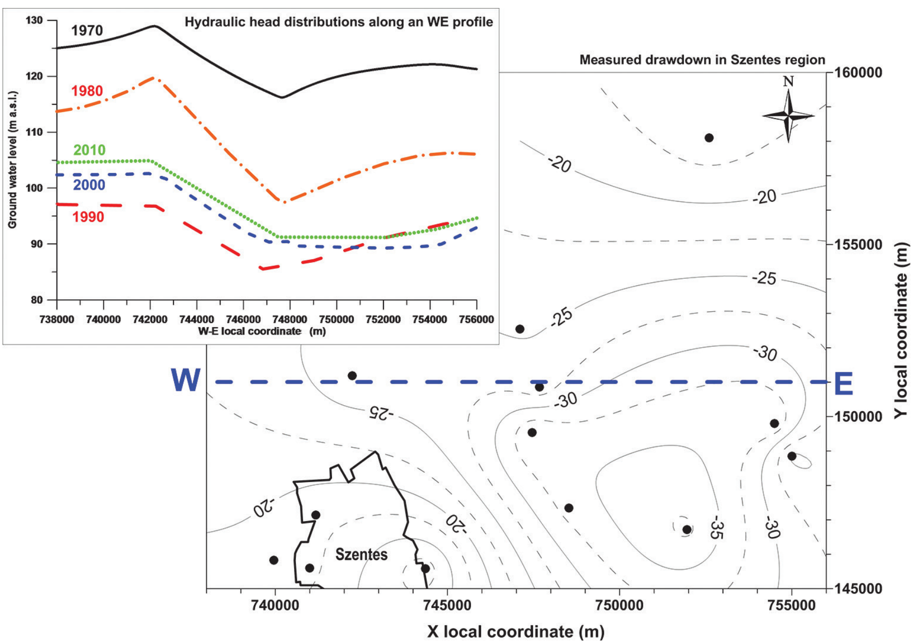

Fig. 4
Changes in the drawdown at Szentes from the 1970s along an EW profile (based on Szanyi and Kovács 2010)

We only have limited information about the operation of the wells during the same year. In the summer months, the wells used for agricultural purposes did not produce, or did so only at reduced amounts to avoid well start-up problems. On the other hand, in the colder winter period wells produce at above average yield and the less used wells are also involved in production. The flow rate of individual wells is available only approximately; instead, the flowrates of well groups are known.

Reservoir energy conditions

Reservoir energy conditions of geothermal reservoirs are influenced by many parameters, such as pressure, temperature, gas content, water and rock compressibility, dissolved solid content as well as the reservoirs extension, shape and heterogeneity (Bélteky et al. 1970). Since in the case of the Szentes geothermal reservoir the temperature and the dissolved solid content have remained practically unchanged, the reservoir pressure and the changing gas content play the decisive role in forming the current reservoir energy conditions. Reservoir pressure changes were presented with deep-well pressure build-up, deep-well capacity and different kinds of surface pressure curves.

Thermal conditions

The great number of thermal wells, and the extensive utilization of thermal water, is based on excellent geothermal conditions. The outflow water temperature is more than 90 °C in the case of 17 wells, and with the exception of a few shallower ones it is above 70 °C everywhere (Fig. 3).

Bottom-hole temperatures were presented in the Szegvár, Szentes town and Szentes outskirts areas (Fig. 5). The 2010 bottom-hole measurement results were used where possible, while in other cases the most acceptable data were selected from the old ones. The *K-561* and *K-578* wells cannot be classified according to location, but their bottom-hole temperatures are more similar to the Szentes outskirts area. On the basis of Fig. 5 the average geothermal gradient is 4–5 °C/100 m, possibly due to the increasing thickness of sediments southward. At the Szentes outskirts area the temperature data are quite scattered; the *Donát* (*K-503, K-514, K-560*) and *Felszabadulás* (*K-515, K-564*) wells south of the Árpád wells have 5–10 °C higher bottom-hole temperatures than the others in the same area. The highest bottom-hole temperature can be found in the Szentes town area, with 5 °C/100 m average geothermal gradient.

Gas content of thermal wells

Analyzing gas content of the Szentes geothermal wells, the specific total gas content (STG) and the specific total methane content (STM) data were compared to the 1977–1982 and the 2006–2011 period in the 1,500–2,000 m and below 2,000 m depth intervals. Figures 6–9 show that thermal wells exposed to the lower layer group have

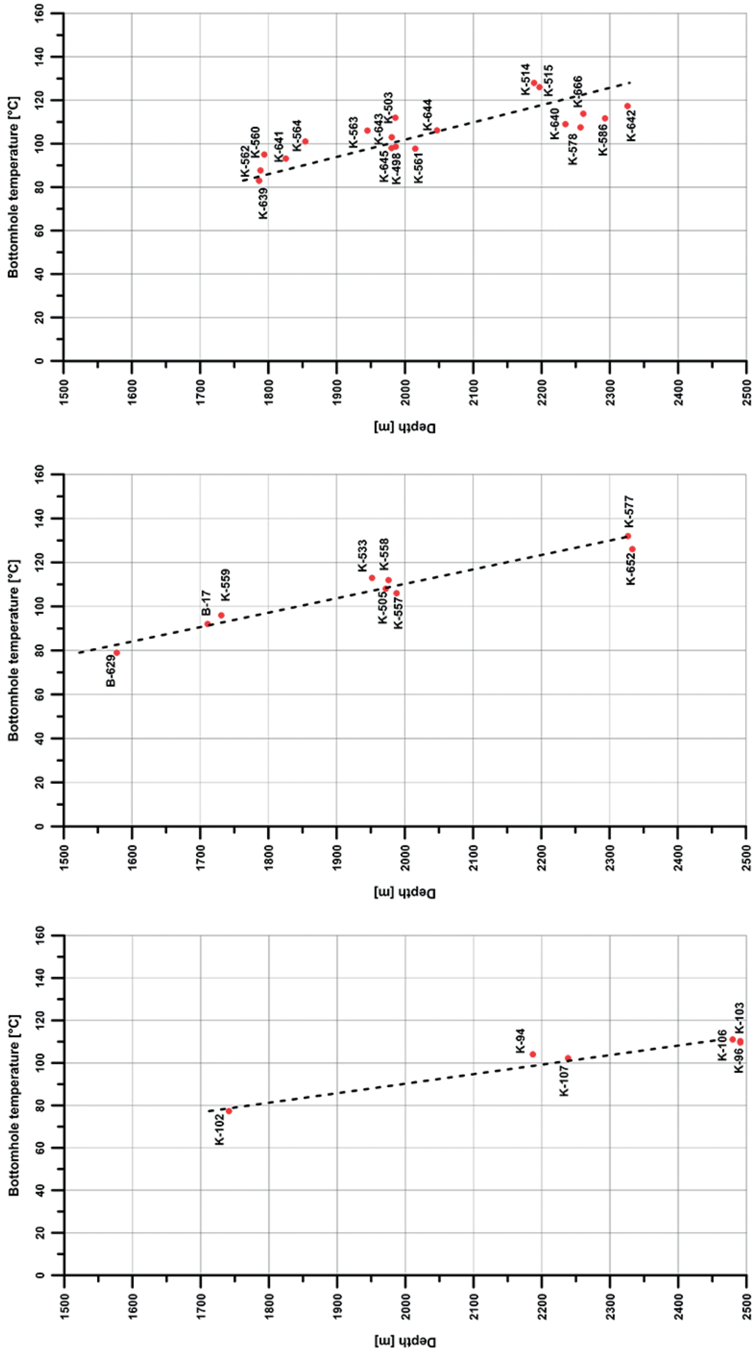

Fig. 5
Bottomhole temperatures in the Szegvár, Szentes outskirts and Szentes town area (from left-to-right, respectively)

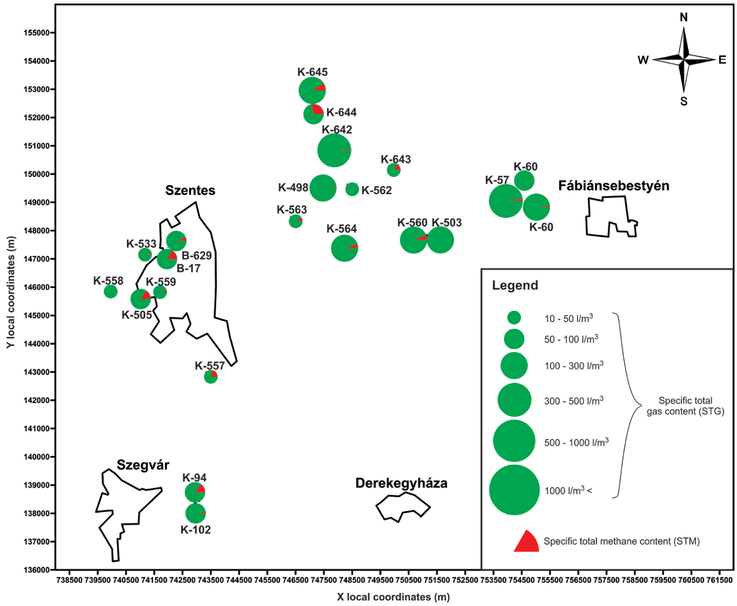

Fig. 6
Specific total gas and methane content of the thermal wells in 1500–2000 m depth, 1977–1982

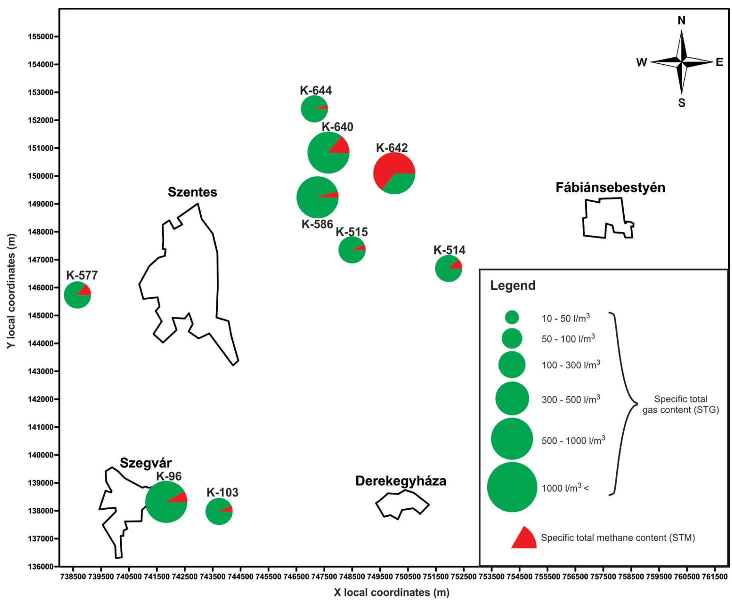

Fig. 7
Specific total gas and methane content of the thermal wells below 2000 m, 1977–1982

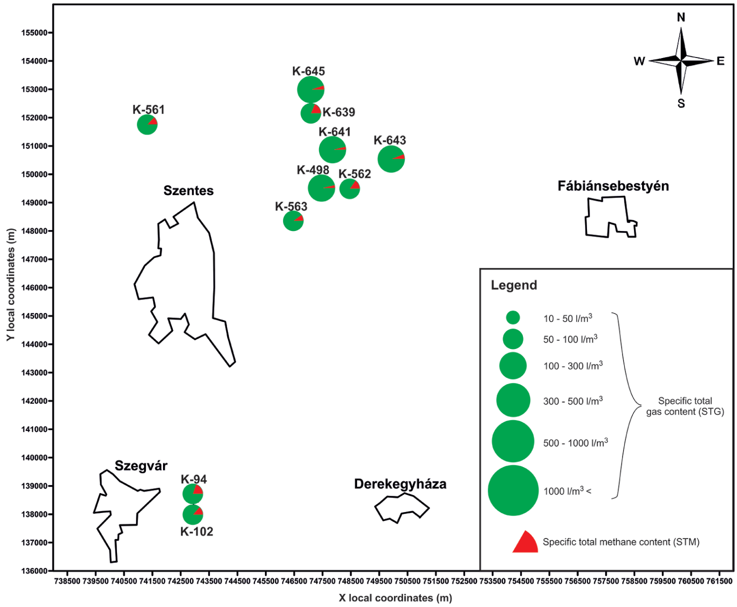

Fig. 8
Specific total gas and methane content of the thermal wells in 1500–2000 m depth, 2006–2011

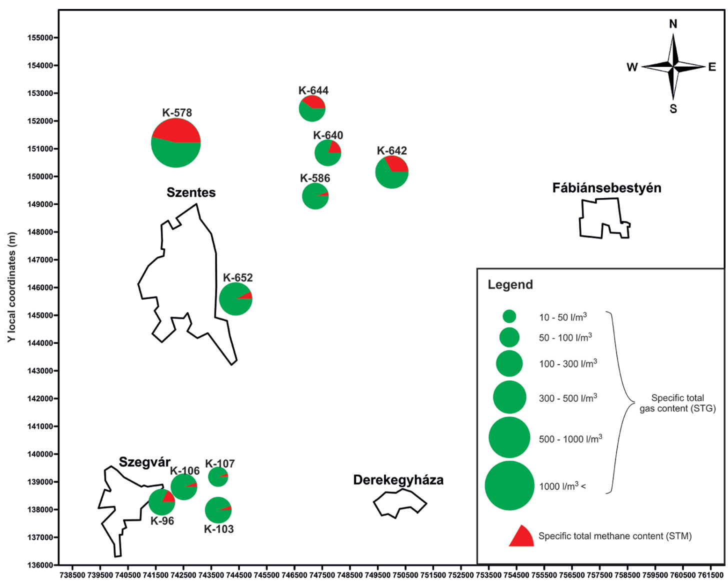

Fig. 9
Specific total gas and methane content of the thermal wells below 2000 m, 2006–2011

greater gas content than those opened to the middle and upper layer groups, even if they are in the same area. The *Árpád-V* (*K-640, K-641*) and *Árpád-VII* (*K-644, K-639, K-645*) well groups are exceptions, where there are no significant differences in the layer groups. The specific total methane content was greater in the layers below 2000 m.

Investigating the spatial distribution of the gas content, lower values can be expected in the 1500–2000 m depth interval of the Szentes town area than the Szegvár or Szentes outskirts areas, based on the data from 1977 to 1982 (Fig. 6). Unfortunately, for below 2,000 m and for the 2006–2011 period (Figs 7–9) we do not have enough measurements to establish definite results on the spatial distribution.

In the case of the middle and upper aquifer layer groups the dissolved gas and methane contents did not change in order of magnitude through time; however, at few wells a small increment was observed. On the other hand, in the lower layer group the decrease can be few 100 l/m^3.

While in the 1977–1982 period specific total gas contents were higher than 500 l/m^3 at 4 wells, in the 2006–2011 period a greater value was measured only at the *K-578* well with 1,086 l/m^3 STG and near 500 l/m^3 STM value. The most important gas contents in the thermal wells beside methane are nitrogen and carbon-dioxide.

The methane content did not change significantly, with the exception of *K-642* well where the amount of methane was halved.

Chemical characteristics of thermal water

The thermal waters of Szentes belong to the sodium bicarbonate group of waters. Beside sodium, other cations are in negligibly small amounts, while among the anions the chloride ion is the most important; it varies between 3–61 mg/l. According to Varsányi (2001) the waters are of paleometeoric origin and were recharged during the last ice age as well as in the previous warmer period.

There was no significant difference in the chemical composition at the time of drilling and of measured data from 1972. Only a few hundred mg/l concentration differences were observed at the *K-60* well and at the *K-578* well (Korim and Liebe 1973). In these cases the increase of concentration associated with reservoir and wellhead pressure increase over time due to the cleaning of the well after drilling and renewing of production from the perforated sections.

Based on the available water chemistry, the newest measured data were collected and the total dissolved solid content was presented as a function of depth (Fig. 10). It shows that in the entire geothermal field the thermal waters are not very different at a given depth in total dissolved solids. In the case of the upper and middle aquifer layer groups it is generally true that the total dissolved solid content increases with depth, while in the lower aquifer layer group more dilute thermal waters can be found in the Szentes town and Szegvár areas than in the shallower wells in the same area. There is also one exception in the Szentes outskirts area: the *K-560* well producing from the upper aquifer layer group has 3200 mg/l total dissolved solid content, which exceeds by 700 mg/l the neighboring *K-503* well perforated to the middle aquifer layer group.

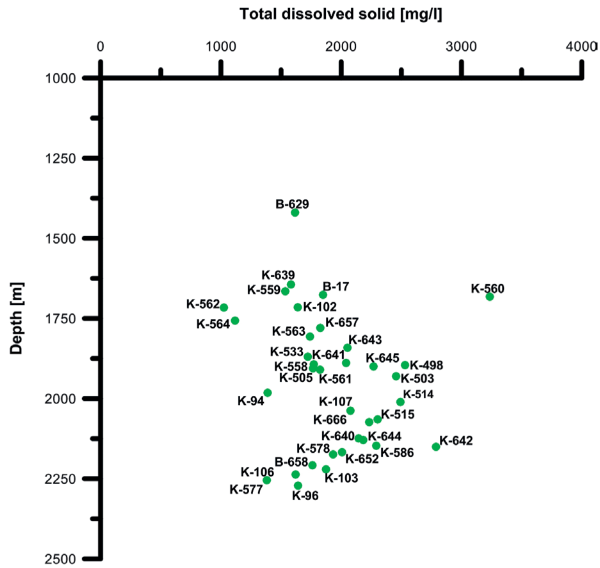

Fig. 10
Total dissolved solid data as function of depth

The newer water chemical analyses confirmed the former observations made by Korim and Liebe (1973), namely that the water chemistry suggests heterogeneity in the geologic structure. However, whether the concentration increases from west to east (Korim 1991) cannot be conclusively proved.

Deep-well pressure build-up curves

Deep-well pressure build-up curves provide information about the reservoir parameters, well completion properties and reservoir energy conditions. The first, rapidly increasing part of the curves shows the near-wellbore properties, the second – usually straight – part shows the reservoir permeability, porosity and type of reservoir, while the third part provides information about reservoir extension and boundary conditions (Kassai 1960; Gyenese 2013).

The analysis of the deep-well pressure build-up curves of the Szentes geothermal field have a general problem, which means that we have less measured data than the deep-well capacity curves; the measurements were usually not longer than for 100–120 minutes, which results in the absence of the third part of the deep-well pressure curves. What also makes the analysis difficult is that the old and new measurements were mostly taken at different depth. Due to the difficulties mentioned above, deep-well pressure build-up curves were used primarily to define permeability, but their long-term change over time also provides valuable information about reservoir energy conditions.

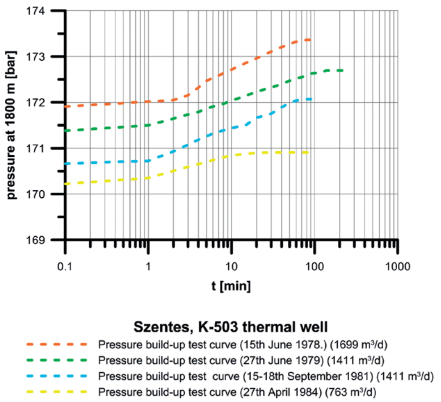

Fig. 11
Pressure build-up curves of the K-503 thermal well

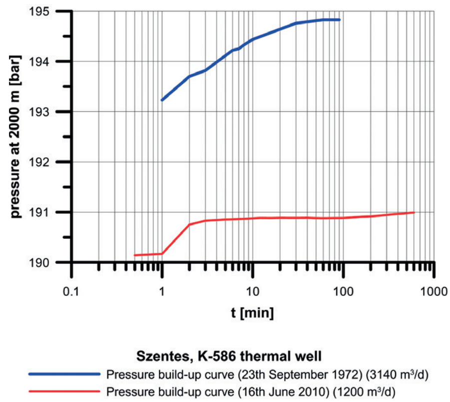

Fig. 12
Pressure build-up curves of the K-586 thermal well

Deep-well pressure build-up curves show not only the pressure decrease, but also the smaller yields from year to year, resulting in even greater pressure decrease; despite the smaller yields, static pressure cannot reach the former levels after shutting down the well. In the case of the *K-503* well the produced yield decreased by half between 1978 and 1984, but over the same time span after well shut-down, the static pressures were 2.5 bar lower (Fig. 11). Similar results can be observed at the *K-586* well, where in 1972 the maximal available yield was 3,140 m^3/d with 194.83 bar, while in 2010 it was only 191 bar with a production of 1,200 m^3/d (Fig. 12).

Deep-well capacity curves

The preferred way of investigating the actual pressure conditions is the analysis of deep-well capacity curves. Although the old and new capacity curves were not measured at the same depth, by applying the equation below (Bobok and Tóth 2007) the measured data were converted to the same depth (usually the difference is not more than 100–200 m):

$$P_x = P_z \pm \rho_{x-z} \times g \times \left(\left|H_x - H_z\right|\right) \pm \Delta p'$$

$$\Delta p' = \frac{\left[8 \times \lambda \times m^2 \left(\left|H_x - H_z\right|\right)\right]}{\left(\rho_{x-z} \times \pi^2 \times D^5\right)}$$

where:

P_x: pressure at the calculated point [Pa]
P_z: pressure at the measuring point [Pa]
ρ_{x-z}: density of the water column between the calculated and measured point [kg/m^3]
g: gravity acceleration [m/s^2]

H_x: depth of the calculated point [m]
H_z: depth of the measuring point [m]
$\Delta p'$: friction pressure loss [Pa]
λ: friction coefficient [-]
m: mass flow rate [kg/s]
D: casing diameter [m]

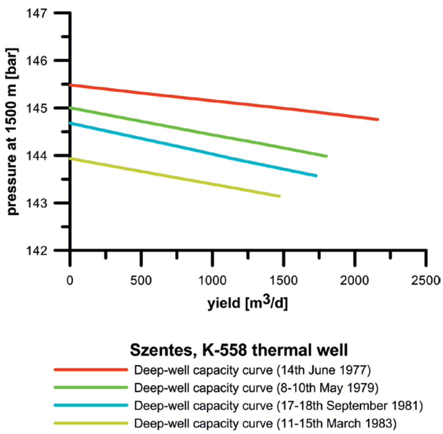

Fig. 13
Deep-well capacity curves of the K-558 thermal well

Both the converted and the non-converted capacity curves show good synergy with deep-well pressure build-up curves and that long-term annual production without reinjection results in reservoir pressure decrease; shutting in the wells in the summer period is not sufficient to allow full regeneration of the producing wells (Figs 13–15 – *K-558, K-652, K-503*).

Among the wells included in the 2009–2010 hydraulic test series, in most cases there are only 2 data series (usually the data after the well establishment and the new ones). With the exception of the *K-639* well, depending on the location and depth of the measurements,

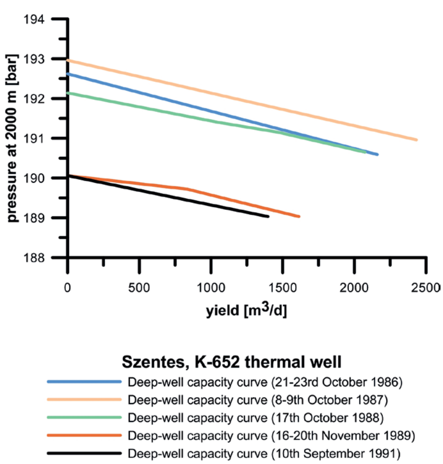

Fig. 14
Deep-well capacity curves of the K-652 thermal well

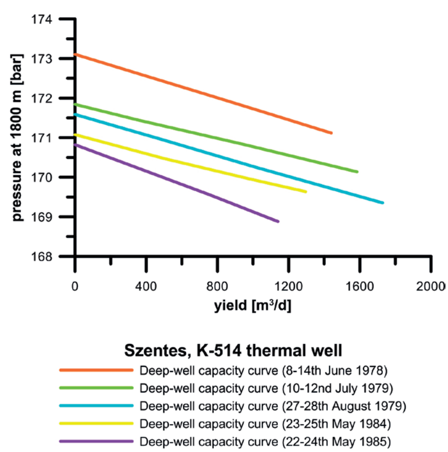

Fig. 15
Deep-well capacity curves of the K-514 thermal well

1.5–4 bar pressure decreases were experienced. The most significant decrease was in the area of the Árpád Agricultural Company in the lower and middle aquifer layer groups. At the Szegvár area there was a 2–3 bar pressure decrease, independent of the reservoirs' depth.

Surface pressure curves

Analyzing and comparing the surface pressure curves of deep thermal wells should only be done with great caution. The well-head pressure changes are influenced by temperature decrease and gas content of thermal water as well as the date and other conditions of the measurement (Gruber 2002; Gyenese 2013). In the case of comparing the static well-head pressures the greatest problem is that there is no clear definition for a thermal well's static well-head pressure. Some experts suggest waiting until the water column fully cools after production, while others recommend considering the almost steady pressure within 5–10 minutes after closing the well. In the first case, the problem is that usually the complete cooling time of the water column is not awaited and the obtained well-head pressure not properly reflecting the reservoir energy conditions. In contrast the latter case represents a better estimation of the reservoir energy conditions, compared with the deep-well pressure build-up curves, the increase of deep-well pressure can be experienced while the well-head pressures begin decreasing after 20–30 minutes, due to the cooling. Another problem is, that neither the measuring conditions, nor the registration time after shutting-in, are usually noted in the well test reports.

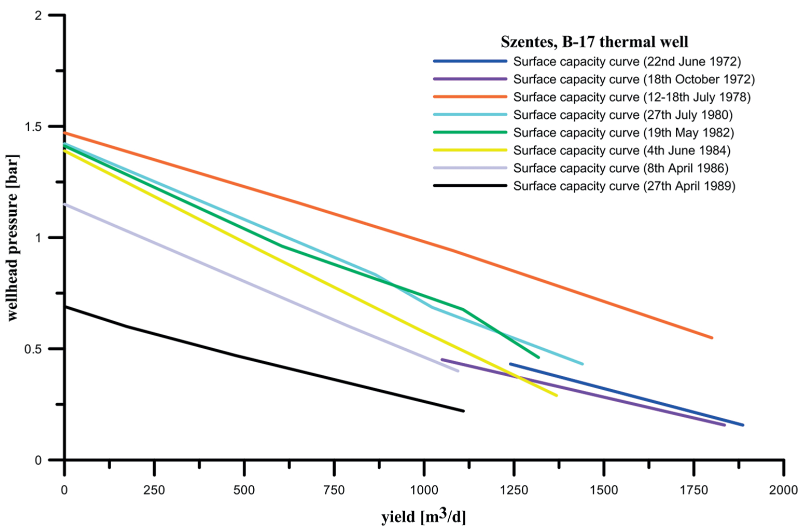

Fig. 16
Surface capacity curves of the B-17 thermal well

Despite the difficulties mentioned above the surface pressure measurements are very important. However, after the 90s deep well pressure measurements ceased in the entire Szentes geothermal field until 2009–2010. Fortunately the surface pressure measurements were continued in case of a few wells.

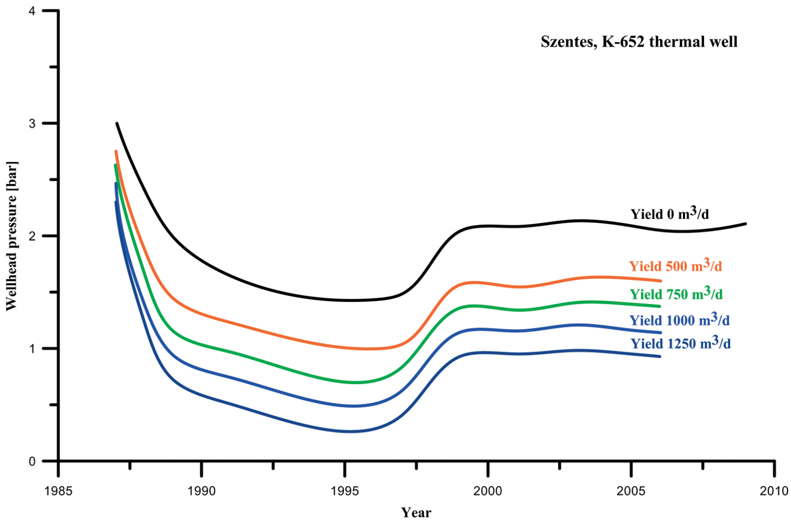

Fig. 17
Time–wellhead pressure curves of the K-652 thermal well

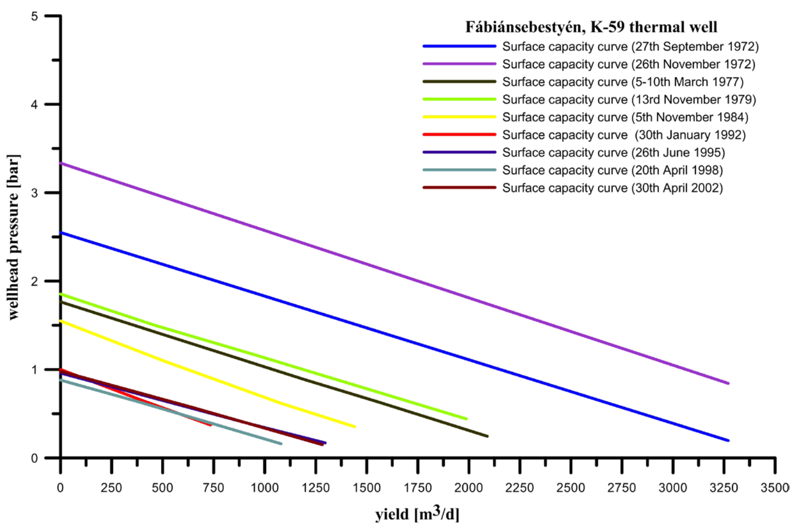

Fig. 18
Surface capacity curves of the K-59 thermal well

Measured data were presented as surface capacity curves and pressure-time curves. This showed the same tendency as for deep well capacity curves, which means that pressure decreased by 1.5–4 bar in almost every case. Changes can be easily followed from year to year thanks to the relatively many data series. The *B-17* well, with measured data up to 1989, shows continuous decrease (Fig. 16), while the *K-652* and *K-59* wells show pressure stabilization and a slight (0.5–1 bar) pressure increase (Figs 17–18).

The drastic effect of long-term production is illustrated by the wellhead pressure-time diagram of the *K-498* well (Fig. 19). Despite the decades-long data gaps, Fig. 19 shows that while in 1965 a 1,000 m^3/d yield could be produced at 2.4 bar, by 2010 this was only possible with 0.5 bar well-head pressure.

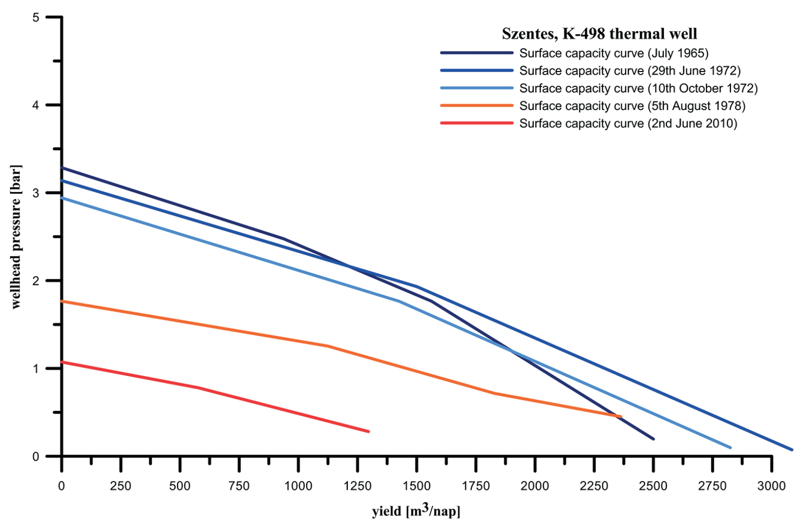

Fig. 19
Surface capacity curves of the K-498 thermal well

Summary

The Szentes geothermal field, with nearly a half century of production, is of great importance, both scientifically and practically. On a national scale it has an unmatched well density and the widespread usage experiences can serve as guidance for the operation of other deep porous reservoirs. However, the lack of systematic measurements of operating and yield data, as well as the extremely heterogeneous geologic properties, render the evaluation process very difficult.

By analyzing the well hydraulic tests made in 2009–2010, and comparing them with the previous measurements and reports, the following statements can be made:

- Due to the horizontal and vertical heterogeneity of the thermal water-bearing layers the correlation is very uncertain, even if the distance between wells is only 1–1.5 km. As long as the calculated permeability values are within a narrow interval, the permeability values in the middle and upper layer groups can differ by more than 1,000 mD;
- The geothermal gradient is between 4–5 °C/100 m; it decreases slightly in the direction of Szegvár due to the increasing thickness of sediments;
- Waters are of sodium bicarbonate type; the total dissolved solid content was practically unchanged during production. In the upper and middle aquifer layer group the total dissolved solid content increases with depth; however, the solids content of the lower aquifer group is smaller in the Szentes town and Szegvár areas than in the shallower wells of the same area;
- The long-term production of thermal water reservoirs resulted in a 1.5–4 bar decrease from natural conditions;
- The most important pressure decrease occurred in the most intensively produced lower layer group. More than 100 l/m^3 reduction of gas content also participated in the established pressure decrease;
- Lower maximal yields are also associated with the reservoirs' pressure decrease;
- Surface pressure curves show that the former continuous pressure decrease up to the early 90s changed to stagnation and then moderate increase in the mid-90s. The reservoir pressure stabilization resulted from decreased thermal water production;
- Shutting in the wells in the summer months is not sufficient to allow for full regeneration of the disturbed reservoir energy conditions.

The example of the Szentes geothermal reservoir proves that long-term production without reinjection results in regional pressure decrease in the Upper Pannonian layers. The negative wells with decreased pressure can only provide limited production compared to the natural state.

Although the rational use of water and long shutting-in of some wells resulted in stabilization and a moderate increase of reservoir pressure, in the case of further development and more intensive production reinjection of used thermal water is essential.

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