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Characteristics and sustainable utilisation prospects of geothermal waters of the liassic formations in the Mogilno–Lodz Trough, Poland

Elzbieta Halaj[1]

Abstract

Mogilno–Lodz Trough is located in central Poland. It is structural basin filled with Triassic-to-Quaternary sediments. Lower Jurassic formations in Poland have one of the best conditions for the heating purposes. Presently, on the area of the Trough, no geothermal plant operates, which utilises geothermal waters from Lower Jurassic formations. Sustainable use of geothermal waters covers, e.g., effective use of thermal energy from waters, before they are injected back to the deposit. Such sustainable use can be achieved in cascaded systems, utilising thermal energy of waters, which gradually lose temperature at following stages of cascaded systems. Geothermal waters and energy occurring in Lower Jurassic formations in Mogilno–Lodz Trough have been analysed in terms of chemical composition and temperature parameters. A dominant type of water is chloride-sodium waters, with specific components contents, such as iodine, bromine, and iron. Lower Jurassic formations are deposited at different depths, which affects, to a high extent, water mineralization and temperature, as well as some elements contents. It has been demonstrated which parameters are decisive about a possibility of using them at particular stages of a cascaded system and where one should expect to find suitable conditions for particular applications.

Keywords Geothermal waters · Geothermal energy · Sustainable use · Mogilno–Lodz Trough

Introduction

Geothermal resources of Poland are considered low-temperature resources. Poland lies next to areas of present volcanic activity and surface geothermal activity. However, geothermal waters fill several sedimentary structural basins. Geothermal waters are currently used for heating, balneological (Kepinska 2013, 2015), and recreational purposes (Halaj 2015).

Disposable resources of the Lower Jurassic (Liassic) geothermal reservoir were estimated to be 14.23×10^6 [TOE], where 1 TOE (tonnes of oil equivalent) = 4.4×10^{10} [J] (Gorecki 2006), considered mostly for district heating and balneotherapy. Resources of geothermal waters from the Lower Jurassic (Liassic) in the Polish Lowlands were estimated in geothermal atlases (Gorecki 1995, 2006) and Gorecki 1996 (particularly in the Mogilno–Lodz Trough area).

Usually, the use of geothermal water resources was considered for district heating or balneological purposes. In general, other different uses of geothermal energy existing, in particular, the Ground Water Heat Pump Systems (GWHP): different applications in the urban context (Lo Russo et al. 2014; Verda et al. 2012; Lo Russo et al. 2011). In Mesozoic layers in Poland, a potential possibility of electricity generation has been taken into consideration recently (Wisniewski et al. 2011), together with enhanced geothermal system (EGS) (Sowizdzal 2016), in areas where Mesozoic layers of the Trough are located the deepest. Recreational centres using geothermal waters become more and more popular in Poland. The Lower Jurassic formations in the Polish Lowlands belong to formations having the most favourable hydrogeological and thermal conditions to use their waters for heating purposes (Bojarski et al. 1976; Gorecki 1995, 2006; Gorecki et al. 2015; Dowgiallo 2012; Dowgiallo et al. 2007). Waters from the Lower Jurassic formations are under Artesian pressure, allowing self-flowing extraction (Bojarski et al. 1976).

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The goal of this study is to demonstrate all possibilities of utilising geothermal waters and energy, taking into account water characteristics and the conditions of their occurrence, and also, drawing attention to a possibility of sustainable utilisation of resources from the Lower Jurassic formations which, so far, have been considered mainly in terms of heating.

In recent years, in the area under consideration, two new wells intended for geothermal purposes have been made, including the one that will exploit geothermal waters from the aquifer of the Lower Jurassic–Kleszczow GT-1. Specifically, in the area of the Mogilno–Lodz Trough, operating geothermal wells are located: three in Uniejow (one extraction well and two injection wells), two in Kleszczow (one extraction well and one injection well), exploiting the Lower Jurassic formations, and a one extraction well operating in Poddebice, which reaches fresh geothermal water. In the remaining part of the Polish Lowlands (ca. 80% of Poland's territory), six new wells have exploited the Lower Jurassic formations (Noga et al. 2013).

On the area of theMogilno–Lodz Trough, there is one geothermal centre (in Uniejow), where geothermal waters are extracted from Cretaceous formations, both for treatment and recreational purposes. Two geothermal heating plants, with the total capacity of 7 MW, use water from the Lower Cretaceous aquifers. Currently, no heating plant or swimming pool using geothermal water from the Lower Jurassic aquifers operates on the area of the Mogilno–Lodz Trough. It is planned to start a heating plant which will support sports facilities in the town of Kleszczow. Water from the well comes from the depth of 1620 m. Temperature measured at the outflow is 52 °C, while the mineralization value is 6 g/dm^3. Water discharge at the level of 150 m^3/h was obtained during a pumping test from a doublet. Power of the future heating plant is estimated at 2.5 MW (Noga et al. 2013).

Study area

The Mogilno–Lodz Trough is a structural unit (a paleodepression) located in the area of the Polish Lowlands in Central Poland. Location of the study area is shown in Fig. 1. The boundaries of the Mogilno–Lodz Trough are defined by the sill of the Lower Cretaceous. The resource area of the Lower Jurassic formations of the Trough (Fig. 2) is ca. 20,000 km^2. There are numerous salt structures, which penetrate the Mesozoic formations partially or completely.

Fig. 1 Location of the study area on a topographic map of Poland (based on Topographic map of Poland, CC-BY-SA-3.0)
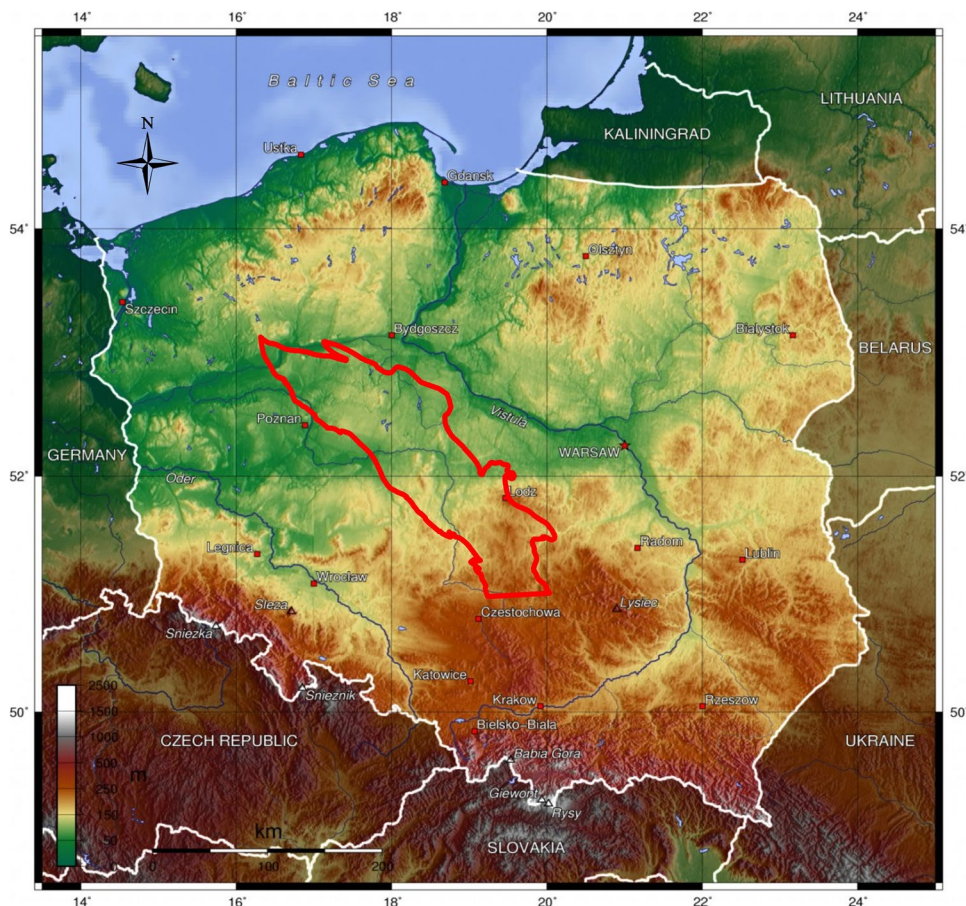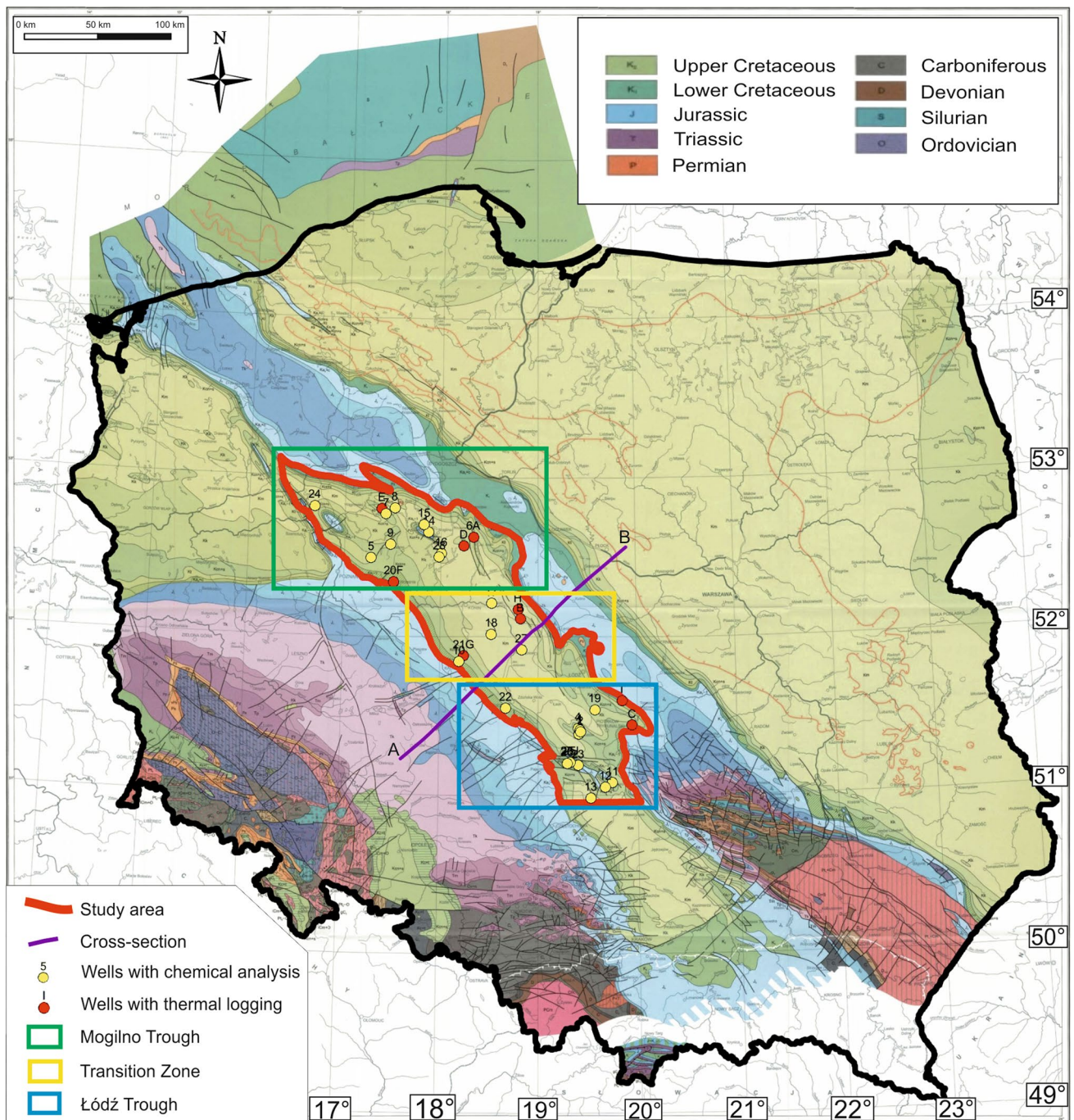
Fig. 2 Location of the study area on Poland's geological map, excluding Cenozoic formations (based on Dadlez et al. 2000)

Geological settings

The Mogilno–Lodz Trough is a middle basin of the three main sedimentary basins (Szczecin, Mogilno–Lodz and Miechow troughs) located from NW to SE Poland on the area of the Polish Lowlands. It used to be a part of a larger structure: the Central Polish Furrow (the Polish–Danish Furrow). Its recent structural arrangement was shaped by Laramide and Early-Kimmerian tectonic inversions. The Mogilno–Lodz Trough is a non-symmetrical structure—its eastern wing is steeper than the western wing. In some studies, Mogilno–Lodz Trough is divided into two smaller structures: a wider the Mogilno Trough and the Lodz Trough, which is narrower but elongated (Stupnicka 1997).

The Trough is filled with sediments of Triassic to Quaternary. One of the Trough's cross sections can be seen in

Fig. 3. The Lower Jurassic (Liassic) formation was deposited in a basin, whose ground was highly differentiated, and in which Zechstein salt structures development causes significant changes in subsidence speed. Deepening and shallowing of the basin bottom had an impact on the thickness and facies of the Liassic (Lower Jurassic) (Gorecki 2006). According to Gorecki (2006), the thickness of the Liassic formation from the Mogilno–Lodz Trough may reach from 150 to 230 m on average. Permeable rocks fill 60–80% of the Liassic lithological profile. The top of the Lower Jurassic is trough-shaped, with the axis in the NW-SE direction. The top is at the depth of about 500 m in zones of the western Trough boundary (minimum about 250 m in the southwestern zone, on the Trough edges) to more than 3000 m along the axis extending NW-SE in the central-eastern part: the transition zone.

The Liassic profile is built mainly of sands and sandstones interbedded with semi-permeable or impermeable claystones and mudstones. A geological profile can be seen in Fig. 3. Important Lower Jurassic reservoir's complexes are built of greywacke sandstones of the Upper Sinemurian

and Upper Pliensbachian sediments in the form of sand–clay and land layers of coarse-grain sandstones moving towards the ceiling into clay–mudstone sediments with coal inserts, as well as sands and fine-grain sandstones with inserts of clay formations and lignite of the Upper Triassic (Gorecki 1995).

Sediments of Zechstein salt formation occurred in two-thirds of the country area. This is the eastern province of the Central European Zechstein basin. The basement of the Zechstein Basin consists of three major tectonic units of varying degrees of consolidation, the impact of which influenced the development and evolution of the Zechstein Basin. The tectonic activity of the basement (the subsidence) and the plasticity of salt contributed to the salt structures origin (Bujakowski 2003). Concurrently, in the area of the Mogilno–Lodz Trough, there are numerous salt structures. These include salt chimneys which penetrate partially (Goplo, Ponetow) or completely (Wapno, Mogilno, Damaslawek) the Mesozoic formations, as well as pillows and salt shafts. These structures occur mainly in the eastern part of the Trough (especially in the Mogilno Trough) and continue
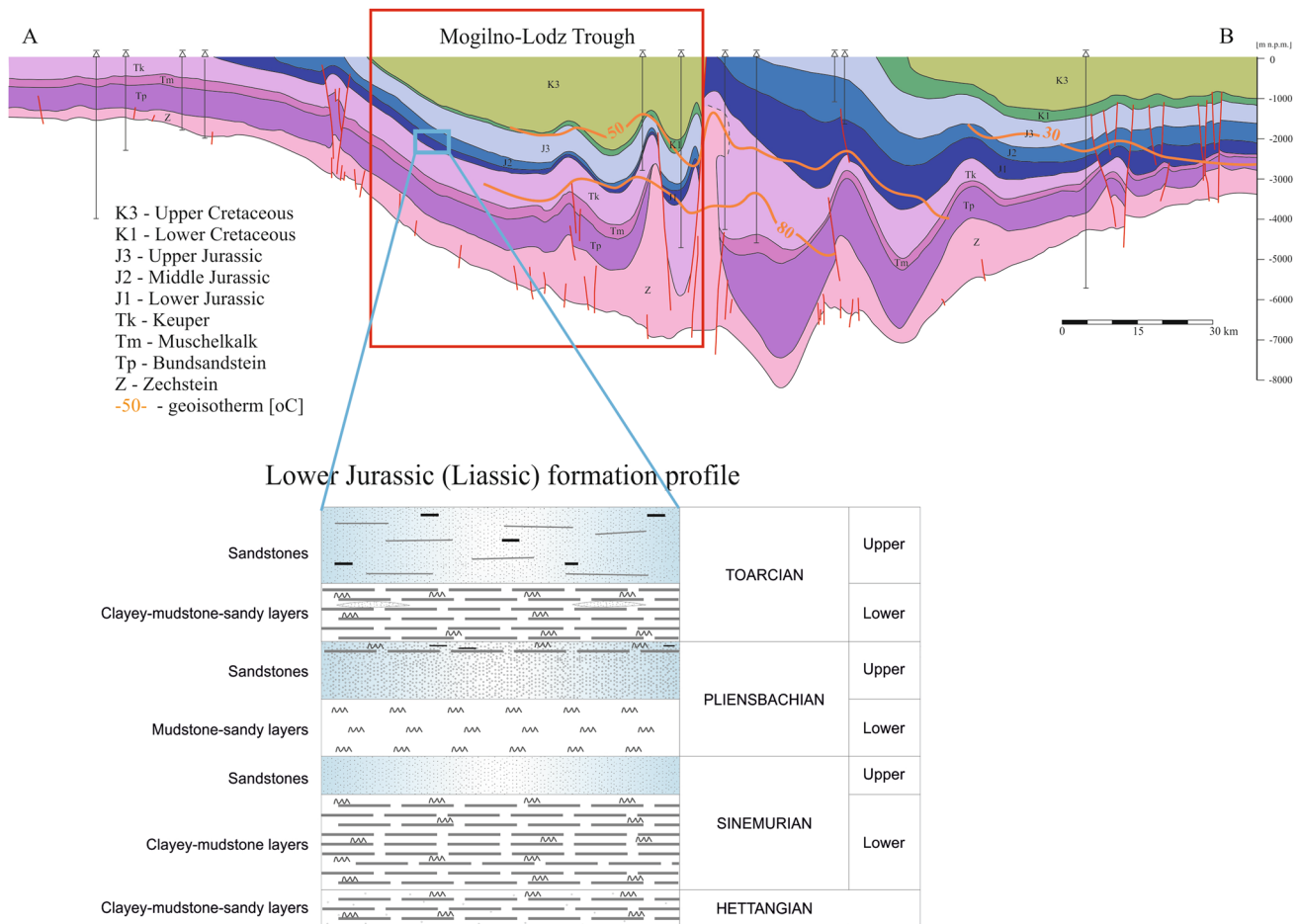

K3 - Upper Cretaceous
K1 - Lower Cretaceous
J3 - Upper Jurassic
J2 - Middle Jurassic
J1 - Lower Jurassic
Tk - Keuper
Tm - Muschelkalk
Tp - Bundsandstein
Z - Zechstein
-50- - geoisotherm [oC]

Fig. 3 Example of a cross-section (Gorecki 2006) and lithostratigraphic profile of the Lower Jurassic (Liassic) in the Mogilno–Lodz Trough

to the east (the Central Poland shaft–Kujawy)—the main areas of rock salt exploitation and northwest (area of the Szczecin Trough). The structures lie mainly in the NW-SE direction and sometimes in the SSE-NNW direction. Salt structures have an impact on a type of water and its mineral composition. An anomalous heat flow occurrence is observed over salt domes. Differences in thermal properties of salt structures and surrounding layers may cause a heat flow from inside of salt domes toward the Earth's surface and an increase in the temperature of rocks adjacent to salt structures (Petersen and Lerche 1995). In layers composed of the same type of rocks and laying at the same depth, but located in different areas, the temperature measured is lower than the temperature of layers surrounding the salt structures (Chylarecki 1990).

The depth at which the Lower Jurassic is laying influences temperature. The highest temperatures are observed in the deep deposition zones of the Lower Jurassic. According to Gorecki (2006), temperature ranges from about 40 °C (minimum: less than 30 °C is observed locally in the southern edge of the Trough) to about 120 °C in the central and eastern parts of the Trough (Gorecki 1995). The total thickness of the water-bearing sediments ranges from 50 m along the axis extending in the central part to ca. 200 m along the Trough edges (Gorecki 1996). Accordingly, with an increase of temperature and depth values, water mineralization increases. The mineralization ranges from a few g/dm^3 in the marginal southern part of the Trough, through 50 g/dm^3, to over 150 g/dm^3 in the areas of the deepest occurrence of the Lower Jurassic formations (more than 170 g/dm^3 in one analysed well). This phenomenon is unfavourable, particularly in case of using geothermal waters for, e.g., heating, other direct applications, or for energy storage (during water injection). On the other hand, an increased level of certain minerals (mineralization) may determine the use of geothermal waters of the region for balneotherapy and chemical elements production.

Materials and methods

Water analysis of samples taken from the Lower Jurassic formations on the Polish Lowlands is based on archival data collected from the National Geological Archives, the Department of Fossil Fuels and completed from the available materials. The Trough area was examined during deep drillings, mostly in search of hydrocarbons, as well as the exploration of other fuels and minerals (lignite, salt). For this reason, water temperature was not the key parameter during past examination. Hence, in some cases, fragmentary studies provided limited geothermal parameters of the area, i.e., pumping tests for the Lower Jurassic aquifer drillings were made only in four wells (Gorecki 1995). Similarly, usually chemical analyses of major

ions are available, excluding, e.g., microelements, rare metals, and base metals, etc. Moreover, most of the data come from 1960s and 1970s.

Within the research, data from the documentation of 100 wells reaching at least the top of the Lower Jurassic formations from the Trough area were analysed. Bottoms of deep drillings in the area range from about 1500 to 5000 m in depth. The top of the Lower Jurassic in the samples under discussion occurs at depths ranging from 579 to 3387 m. The number of wells being analysed narrows down to those where mineralization and major ions content are examined. Such examinations have been performed for 29 wells. Samples were collected from the depth ranging from 815 to 3364 m. The borehole temperature logging in the Lower Jurassic section was done in ten wells; however, in these wells, mineralization was examined rarely. One result of the borehole temperature logging exists in an analogue form, which reduces the reading precision.

The samples were divided into three groups, which gathered samples of similar distribution (Fig. 2). The groups correspond also to similar parameters. Depending on the location of the collection venue and parameters, the samples were divided into following zones: north-western (the Mogilno Trough), central (transition zone), and southern (Lodz Trough). Samples from particular zones are characterised by different parameters, e.g., mineralization and ion content, but they also have some common features, such as proportions of major ions contents.

The collected data were analysed in terms of the Lower Jurassic waters and reservoir temperature. Samples of the Lower Jurassic were considered in terms of main types of waters, water mineralization, and dependence of depth on mineralization and particular components (including some specific water components such as I, Br, Fe, Mg, Na, and Ca). Chemical composition of waters was compared on the Schoeller's diagram to find relationship between the chemical composition and the occurrence zone. Due to the fact that in older analyses, alkaline metals were specified jointly and converted into sodium, for the needs of a graphic presentation of element contents, such conversion was made in all analyses.

To draw temperature curves, geophysical profiling results were developed. In a few samples, water temperature was measured at the outflow from the well or in the ceiling of the sampled interval. Profiling results were compared in the section of the Lower Jurassic formations with the results of water temperature measurements and they were referred to the depth of the sampled interval.

The average value of temperature growth as a depth function, or the geothermal gradient, was calculated on the basis of the following formula (Plewa 1994):

$$G = \text{grad} T = \frac{T_2 - T_1}{h_2 - h_1} = q\xi = \frac{q}{\lambda}, \tag{1}$$

where T_1 and T_2 are the temperature at h_1 and h_2 depths, q is the density of Earth's surface heat flux, ξ is the rocks thermal resistance, and λ is the rocks thermal conductivity.

The gradient was calculated both for the whole temperature curve and for the Lower Jurassic section. Vertical gradient changeability was analysed by comparing the curves with a gradient of layers located under and over the Lower Jurassic formations.

Electric power of a model binary system with the assumption of using 1 kg/s of working medium was determined on the basis of Kaczmarek (2011). Isobutene was selected as low-boiling working medium and the following assumptions were adopted after the author: temperature of medium injected to the exchanger ($T_s = 30\ °C$), internal turbine-set performance ($\eta_i = 0.75$), mechanical performance ($\eta_m = 0.97$), electric generator performance ($\eta_g = 0.96$), and h_1, h_{2s}, h_3, and h_{4s} (thermodynamic cycle points).

Electric power was calculated according to the following formula (after Kaczmarek 2011):

$$N_{el} = N_{CR}\eta_i\eta_m\eta_g, \tag{2}$$

where

$$N_{CR} = \dot{m}_n\left[(h_1 - h_{2s}) - (h_{4s} - h_3)\right]. \tag{3}$$

To assess the possibility of ATES utilisation, an interpolation of initial parameters given in maps of top surface, thickness of the Lower Jurassic formation, surface potential discharge of wells, and hydraulic transmissivity (after Gorecki 2006) was done.

The relationships analysed allow specifying conditions of water and geothermal energy occurrence in the Lower Jurassic formations. Based on the conditions, particular stages of the cascaded system, using geothermal waters and reservoir of the formations, were proposed. On the basis of literature data, minimum temperature values for the selected geothermal applications were indicated. Then, water mineralisation values and the depth of the suitable reservoir were determined.

Results

Hydrogeological settings

For each sample, a chemical type of water was determined. The waters, apart from few samples, are of Na–Cl type. Some of them have also certain iodides, bromides, and iron components (Table 1). Sodium and chloride components constitute ca. 90%meq in most of the samples. Chloride and sodium content medians are 96.5 and 88.8%meq, respectively. Only, in two cases, calcium component exceeded 20%meq. Sodium and chloride concentration in the sample ranges from 104 to 60,685.1 mg/dm^3, and from 12 to

102,714.2 mg/dm^3, respectively. Sodium and chloride ions are dominant ions in waters from the majority of all zones, although in the Lodz Trough zone, they achieve lower concentrations. Na–Cl waters occurring on the area of the Polish Lowlands are regarded as originating from the process of halite solution or in relation to seawater evaporation and/ or chloride salts leaching by seawater (relict water) or by meteoric water (Dowgiallo et al. 2007).

Figure 4 shows the relationship between mineralization of water and the depth of occurrence of the sampled interval top. In general, mineralization increases along with depth. Moreover, the samples can be divided into three groups: blue, yellow, and green colours, according to their location and parameters (see Fig. 2). Waters from the southern part of the Trough (the Lodz Trough, blue marks), where samples are collected from the depth of less than 2000 m, have the lowest mineralization. In this group, mineralization increases directly with depth from a certain point, but generally, mineralisation stays very low, if compared to the same depths in other zones. The mineralization mostly does not exceed 20 g/dm3. The group of four samples between the southern and north-western part, the transition zone (yellow marks), is considered rather an intermediate zone, because of very few samples, which differ much one from another. However, the relationship between higher mineralisation and higher depth is also visible. Moreover, the area has better thermal examination. The north-western part (the Mogilno Trough, green marks) is represented by water samples with very high mineralization. The mineralization of one sample reaches up to 172 g/l. It is characteristic that the samples, which come from the depths between, for example, 1000 and 1500 m, have higher mineralization than the mineralization of samples from the southern part at the same depth and it can reach from 20 to ca. 87 g/l. It may be referred to be caused by the proximity of salt structures.

Main chemical components of waters from all three zones and an overview of samples were compared in Fig. 5 on semi-logarithmic Schoeller's diagrams (Schoeller 1962; Mazor 2004). The diagram of waters from Mogilno Trough (Fig. 5b) shows a similar chemical composition of those water samples and similar proportions of main ions. In the Lodz Trough (Fig. 5d), waters have similar chemical composition, but, due to a smaller depth of occurrence and mineralization, major ions content is lower. Those waters are also characterised with higher HCO$_3$- proportion ratio. In four cases, major ions do not correlate, which stems from the occurrence of other types of waters. Apart from the Na–Cl type, the following types also occur: Na–HCO$_3$, Na–HCO$_3$–SO$_4$–Cl and Na–Ca–SO$_4$, and Na–Cl–SO$_4$. Similarly, in the transition zone (Fig. 5c), major ions correlation trend can be seen. The comprehensive diagram presents the collected major ions contents for the whole area (Fig. 5a). Despite quantitative differences, there is a general

Table 1 Mineralization (TDS), water composition, and water type of the analysed samples

Well No.	TDS (g/dm^3)	Top surface depth (m bgl)	Water composition	Water type
1	7.6	1583	$Fe^{0.0035}M_{7.6}\frac{Cl^{93.3}}{Na^{94.2}}$	Na–Cl
2	9.3	1670	$Fe^{0.0049}M_{9.3}\frac{Cl^{94.7}}{Na^{92.2}}$	Na–Cl
3	15.2	1714	$Fe^{0.0112}M_{15.2}\frac{Cl^{97.4}}{Na^{91.6}}$	Na–Cl
4	3.1	1607	$Fe^{0.0053}M_{3.1}\frac{Cl^{83.4}}{Na^{96.6}}$	Na–Cl
5	8.5	1593	$Fe^{0.0042}M_{8.5}\frac{Cl^{93.5}}{Na^{94.8}}$	Na–Cl
6	13.6	1678	$Fe^{0.0103}M_{13.6}\frac{Cl^{96.4}}{Na^{75.7}}$	Na–Cl
7	16.7	1716	$Fe^{0.0178}M_{16.7}\frac{Cl^{96.5}}{Na^{90.8}}$	Na–Cl
8	30.9	1850	$I^{0.0007}Br^{0.0628}Fe^{0.0252}M_{30.9}\frac{Cl^{97.8}}{Na^{88.3}}$	Na–Cl
9	107.0	1820	$I^{0.0039}Br^{0.1023}Fe^{0.0018}M_{107}\frac{Cl^{98.3}}{Na^{89.6}}$	Na–Cl
10	172.0	3364	$Br^{0.1198}M_{172}\frac{Cl^{98.7}}{Na^{90.2}}$	Na–Cl
11	26.8	1046	$M_{26.8}\frac{Cl^{91.3}}{Na^{88.8}}$	Na–Cl
12	31.2	1446	$I^{0.003}Br^{0.07}Fe^{0.0032}M_{31.2}\frac{Cl^{96.2}}{Na^{83.1}}$	Na–Cl
13	0.4	1126	$Fe^{0.0069}M_{0.4}\frac{HCO_3^{84.9}}{Na^{80.7}}$	Na–HCO$_3$
14	1.8	1777	$Fe^{0.0075}M_{1.8}\frac{HCO_3^{37.2}SO_4^{32.2}Cl^{30.6}}{Na^{88.3}}$	Na–HCO$_3$–SO$_4$–Cl
15	114.7	2333	$I^{0.0042}Fe^{0.0469}M_{114.7}\frac{Cl^{97.7}}{Na^{93.6}}$	Na–Cl
16	99.8	2740	$M_{99.8}\frac{Cl^{97.3}}{Na^{92.3}}$	Na–Cl
17	124.7	2197	$Br^{0.1598}Fe^{0.2189}M_{124.7}\frac{Cl^{98.5}}{Na^{87.0}}$	Na–Cl
18	92.0	2901	$M_{92.0}\frac{Cl^{99.5}}{Na^{56.1}Mg^{25.8}}$	Na–Mg–Cl
19	100.5	2180	$Fe^{0.0696}M_{100.5}\frac{Cl^{89.3}}{Na^{97.9}}$	Na–Cl
20	36.0	2485	$I^{0.0032}Fe^{0.0203}M_{36.0}\frac{Cl^{82.5}}{Na^{98.1}}$	Na–Cl
21	63.2	1332	$I^{0.0041}Br^{0.0632}M_{63.2}\frac{Cl^{98.4}}{Ca^{36.4}Na^{35.6}Mg^{24.0}}$	Ca–Na–Mg–Cl
22	83.4	2580	$Fe^{0.0139}M_{83.4}\frac{Cl^{98.5}}{Na^{79.2}}$	Na–Cl
23	52.7	1620	$Fe^{0.0026}M_{52.7}\frac{Cl^{71.6}}{Na^{90.5}}$	Na–Cl
24	1.2	815	$M_{1.2}\frac{SO_4^{63.9}}{Na^{21.5}Ca^{74.2}}$	Na–Ca–SO$_4$
25	3.5	960	$M_{3.5}\frac{Cl^{57.5}SO_4^{39.1}}{Na^{86.1}}$	Na–Cl–SO$_4$
26	0.5	1275	$Br^{0.0533}M_{0.46}\frac{Cl^{98.0}}{Na^{82.1}}$	Na–Cl
27	86.9	1355	$Br^{0.075}M_{86.7}\frac{Cl^{98.6}}{Na^{91.6}}$	Na–Cl
28	4.6	1489	$F^{0.0005}Br^{0.0007}Fe^{0.0006}M_{4.60}\frac{Cl^{92.6}}{Na^{89.3}}$	Na–Cl
29	1.5	1060	$F^{0.0005}Fe^{0.0004}M_{1.53}\frac{Cl^{80.5}}{Na^{82.7}}$	Na–Cl

correlation between major ions contents. Most waters from all areas under consideration demonstrate similar proportions of major ions (similar peaks in the diagram).

The diagrams (Fig. 6) show the relationship between magnesium, sodium, and potassium, as well as some specific components in water down to the depth of sample collection. It can be seen in the diagram that there is a proportional relationship between an increase of the Na amount in samples according to depth, regardless of the place (zone) of occurrence. Such a tendency is less visible in case of Mg and Ca ions contents. In the zone of shallower sample occurrence (the Lodz Trough)—Mg, Na, and Ca concentrations increase proportionally to one another. At larger depths and in the remaining zones, such proportions are not preserved; cation exchange takes place.

Some samples showed the presence of I, Br, and Fe ions. It can be noted that iodides and bromides occur in samples collected from depths larger than 1300 and 1400 m, respectively. On the other hand, iron occurs (except for 1 case) in samples collected from depths greater than 1400 m and mostly in the Lodz Trough area. What can be also noticed is a certain increase in bromides with depth in the Mogilno Trough. Similarly, in the Lodz Trough, there is a clear tendency of iron ions contents growth, together with depth. In
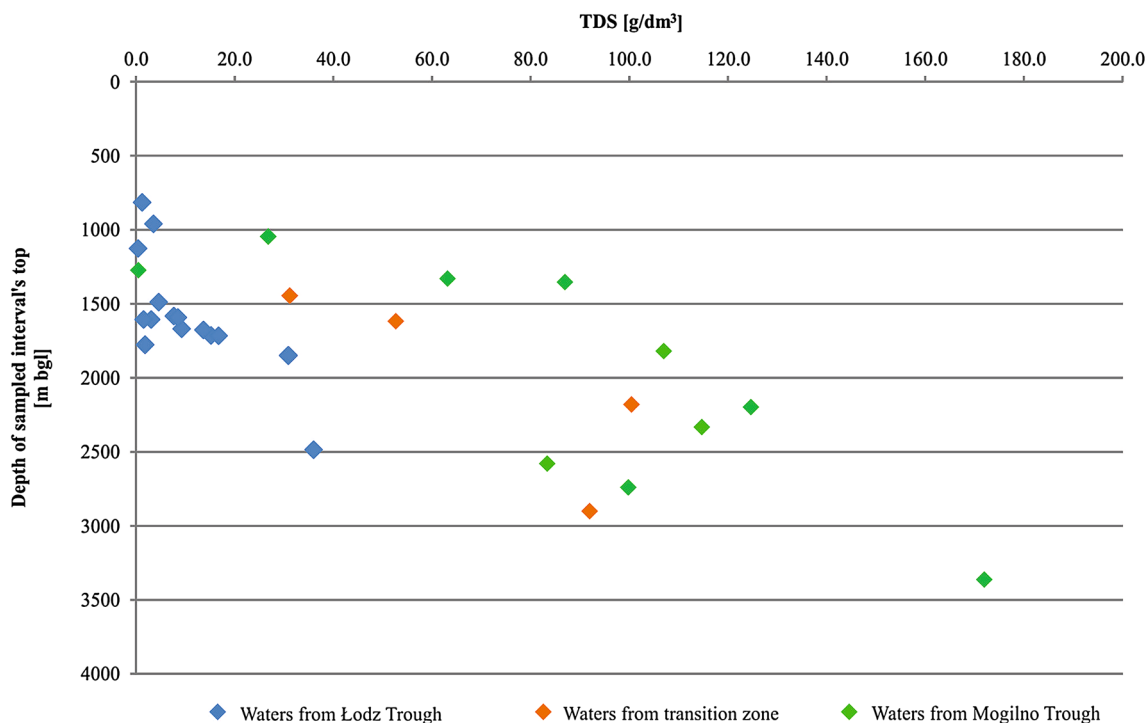
Fig. 4 Dependence of mineralization (TDS) on water from Lower Jurassic formations and the depth of the sampled interval top

other zones, it is difficult to evaluate such correlation, due to a small number of samples. Such correlation is not demonstrated by iodides contents in any of the zones.

Thermal parameters

There is not much data regarding water temperature at the outflow; hence, to determine the reservoir temperature, available borehole temperature logging data is shown. Temperature grows together with depth, depending on the local values of the geothermal gradient. Beside zones with fast water circulation (e.g., in supply zones), rock matrix (reservoir) temperatures are the same as liquids saturating them (Lapinkiewicz 1990). However, one should take into account a water temperature decrease when water is produced through a borehole.

In the boreholes, where thermal profiling was performed, the ceiling of the Lower Jurassic formations is located at the depths ranging from 678 to 3247 m. Data from water temperature measurements range from 31.1 °C at the depth of 966 m up to 105 °C at the depth of 3364 m. The highest temperatures are observed in deep deposition zones. A higher temperature growth, together with depth growth, was reported in the Mogilno Trough zone and in the transition zone rather than in the Lodz Trough zone (Fig. 7). Temperatures from the loggings in the Lower Jurassic section range from 32 °C in the marginal, southern part to about 103 °C in the central and eastern part of the Trough.

To be more visible, the Lower Jurassic sections in the curves are bold in Fig. 7. A curve in the diagram marked with a dashed line shows the features of sectional temperature measurement under non-stable thermal conditions. Values measured there are most probably disturbed. One temperature logging covered only a part of the Lower Jurassic section.

The geothermal gradient calculated using the Eq. (1) for the Lower Jurassic section ranges between 1.82 and 3.13 °C/100 m (Table 2). The average gradient value for the curves under consideration in the Lower Jurassic sections is 2.4 °C/100 m. This value is slightly lower than the average gradient value for the Polish Lowlands, which is 2.5 °C/100 m (Szewczyk and Hajto 2006).

The highest gradient value was reported in borehole A, in immediate proximity to the salt diapir. According to Plewa (1994), an elevated geothermal gradient is caused by the impact of the salt diapir on thermal parameters of neighbouring layers. The geothermal gradient shows vertical changeability. A higher geothermal gradient occurs in this borehole specifically for the Lower Jurassic layer. Furthermore, the gradient value for the Lower Jurassic section in this borehole exceeds considerably the geothermal gradient value calculated for the whole curve, and, what is important, for the gradient calculated for layers deposited under the Lower Jurassic. In no other borehole, were such gradient proportions reported. Geothermal gradients calculated for the Lower Jurassic sections in the remaining boreholes
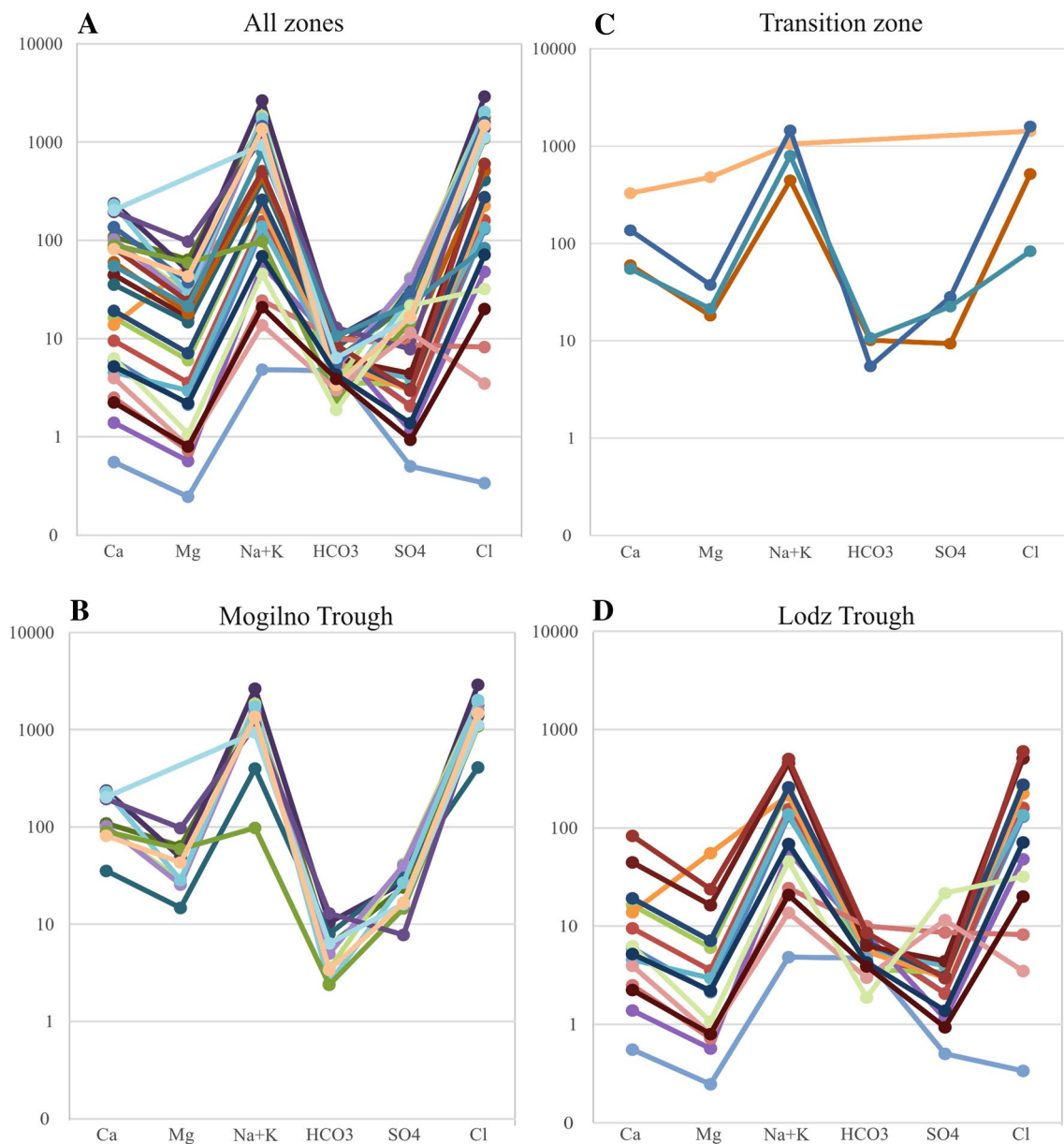
Fig. 5 Semi-logarithmic Schoeller's diagrams. Jointly for all zones (**a**) and for particular zones (**b, c, d**). Concentration of ions in (meq/dm^3)

present lower values than the gradient values calculated for the whole curves (except for samples A and G) and the Lower Jurassic overburden (except for samples A, C and G).

Sustainable use discussion

One of the issues of sustainable use of geothermal resources is balancing geothermal water extraction from the geothermal system. Overproduction and failure to inject geothermal water may relate to lowering its level in the aquifer and production decline in the future (Szanyi and Kovács 2010; Axelsson 2010; Buday et al. 2015). Another issue is

also maximum utilisation of available resources, e.g., using cascaded systems. Cascaded systems constitute an effective and sustainable way of using low- and medium-temperature geothermal resources. Utilising geothermal resources in cascaded systems is understood (after Rubio-Maya et al. 2015) as a way of sequential utilisation of geothermal heat by integrating different technologies for electricity production, transmission, and use of thermal energy, drying, and dehydration processes, application for recreational purposes, and other direct methods of using geothermal heat. During the process, geothermal waters gradually give away heat at subsequent levels, which causes that their temperature drops. Following system stages requires application of decreasing
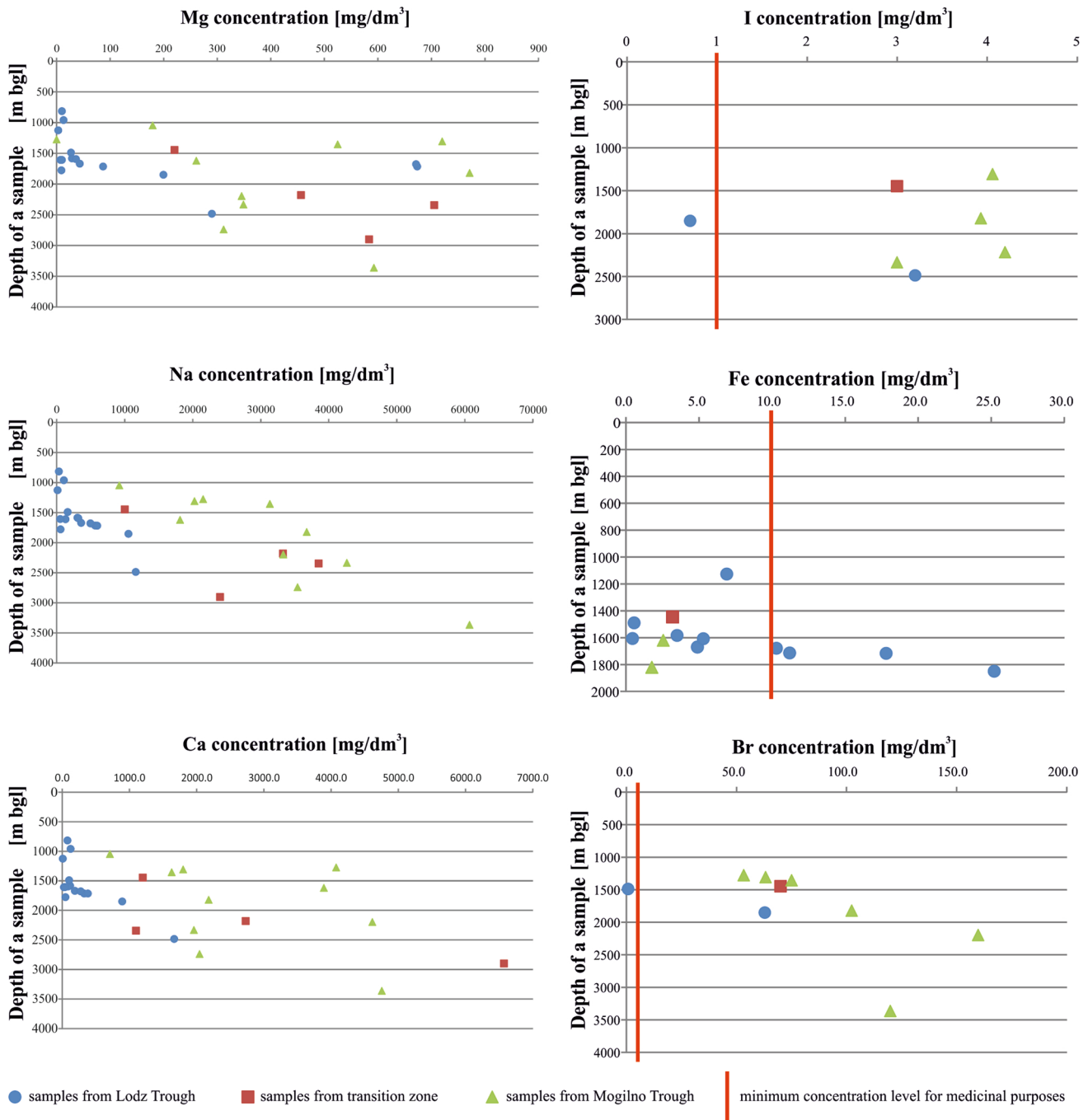
Fig. 6 Relations between Mg, Na, Ca, I, Fe, and Br concentrations depending on the occurrence depth and zone. A red line marks minimum specific components contents for medical purposes

temperature. The first stage of that process can be electricity production. To be able to apply electricity production in binary systems, it is assumed that water should have a temperature of minimum 93 °C, depending on the technology applied(Rubio-Maya et al. 2015), 80 °C (Kaczmarek 2011), or 73 °C (Taylor et al.. 2013). If there are no resources with suitable temperatures, a cascaded system may start with direct geothermal waters utilisation, as well as without any

of the stages. A combination of electricity production and direct application in cascaded systems may maximise the use of geothermal resources before water is injected back to the aquifer and increase economic profitability of a capital project (Lund and Boyd 2015). Figure 8 presents a schematic diagram of possibilities of utilising geothermal waters from the Lower Jurassic formations in a cascaded system, while specifying temperature requirements. Regardless of
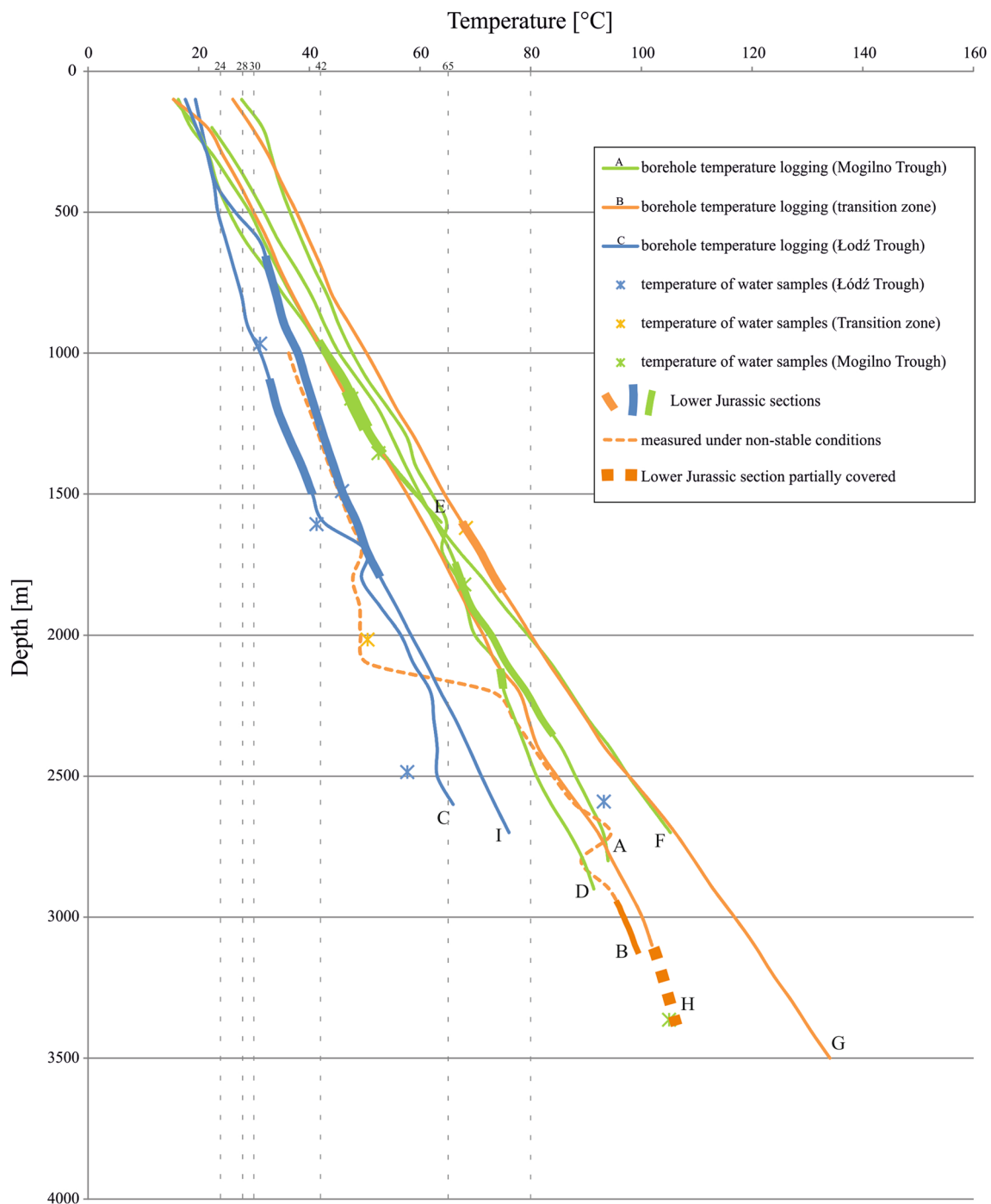
Fig. 7 Relationship between temperature logging curves prepared on the basis of geophysical data, water temperature, and depth of sampled interval for three zones (the Mogilno Trough, the transition zone, and the Lodz Trough)

technical and engineering issues at particular stages, focus was given to the indication of geothermal parameters of the aquifer, enabling selection of suitable conditions for water and/or energy utilisation in a cascaded system.

Geothermal energy with the highest temperature of more than 80 °C can be transferred into electricity in binary systems, then water can be used in the most popular way: in space heating/direct use as well as for bathing and therapeutic purposes. Once discharged, water may be the source of certain minerals and the material for cosmetics production. Furthermore, some aquifers may be used for energy storage for additional waste heat, not consumed in summer to be used in winter time.

Table 2 Geothermal gradient calculated for the Mogilno–Lodz Trough according to borehole temperature logging data

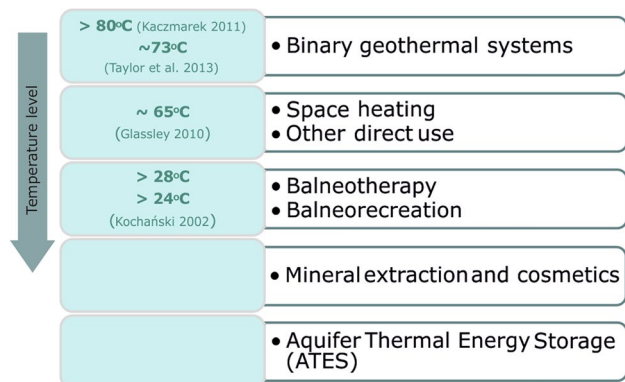| Section	Wells									
	A	B	C	D	E	F	G	H	I	J
Overburden of the Lower Jurassic	2.95	2.96	1.37	2.27	3.03	2.98	2.76	n.m	2.56	n.m
The Lower Jurassic	3.13	2.54	1.82	1.58	2.27	2.73	2.94	2.88	1.82	n.m
Bed of the Lower Jurassic	1.72	n.m	2.35	2.23	3.84	2.96	2.96	n.m	2.63	n.m
For the whole logging curve	2.77	2.87	1.88	2.25	3.19	2.95	2.89	2.88	2.28	2.28

n.m not measured

Fig. 8 Diagram of a cascaded system use, proposed for geothermal waters and energy from the Lower Jurassic formations, together with temperature requirements for particular stages

Binary systems

Electricity from geothermal energy or/and waters can be produced, in principle, in three different ways:

1. The cheapest and the simplest method is electricity production from geothermal steam (high-temperature resources, over 150 °C), supplied to a turbine directly from a borehole, which—after cooling down—is released to the atmosphere as waste. A power plant of this kind, having access to superheated steam, needs much less fluid than binary power plants with an intermediate fluid (Barbier 2002). It is not taken into account in the Mogilno–Lodz Trough, due to the lack of high-temperature resources.

2. In case of low-temperature resources (when geothermal water temperature does not exceed 150 °C), binary systems are used, which utilise working medium circulation in a closed system (organic rankine cycles, kalina cycles). Geothermal water is transported to an exchanger, where heat is given away to working medium. Next, it is injected back to the aquifer. However, geothermal binary power plants are usually characterised by lower efficiency (DiPippo 2004). Despite that, binary systems are considered, from the technical and environmental point of view, the best method of energy conver-

sion, while using low-temperature resources (Franco and Villani 2009).

3. Another kind of binary installation is an installation with direct evaporation of fluid in the exchanger (underground closed geothermic heat exchanger). Such an installation does not need geothermal water circulation, since fluid collects heat in a geothermal exchanger and, at the same time, it is working medium in the power plant. Such a system eliminates heat losses in intermediate exchangers and it allows using waters with lower temperatures (Kaczmarek 2011).

When analysing distribution and parameters of geothermal waters and the reservoir (Figs. 4, 7), which correspond to the temperature values over 80 °C, one may state that they are most frequently located at large depths, over 2000 m. It regards, first of all, the Mogilno Trough zone and the transition zone, where the Lower Jurassic formations are deposited at the greatest depth. It relates to the occurrence of high mineralization, usually over 80 g/dm^3. In the Mogilno Trough and in the transition zone, mineralization of water samples collected at the depth ranging from 2000 to 2500 m is from 83.4 to 124.7 g/dm^3, and in the extreme case, it is 172 g/dm^3. In the Lodz Trough, where lower water mineralisation occur at similar depths, temperatures are even ca. 20° lower; and to achieve similar parameters, it would be necessary to increase borehole depth, which leads to incurring higher costs.

An example of applying a binary power plant for low-temperature geothermal waters is Chena—a binary geothermal plant, where water with the temperature of 73.33 °C was utilised (Aneke et al. 2011). Yet, geothermal water comes from much shallower depth, ca. 200 m (Erkan et al. 2008), which is a ten times lower value, compared to waters with similar temperature occurring in the Mogilno–Lodz Trough.

The impact of highly mineralized water with suitably high temperatures can be reduced by applying an Underground Closed Geothermic Heat Exchanger, which does not require higher geothermal water flow and injection later on. However, electric power calculated on the basis of formulas (2) and (3) and Kaczmarek (2011) for working medium evaporation temperatures: 80 or 100 °C are 31.62 and 41.56 kW, respectively, which is a quite low value, compared to the

expected expenditures. Such expenditures may be reduced by installing geothermal exchangers in old, earlier drilled boreholes.

Space heating and other direct utilisation

Thermal modernization of buildings in Poland changed the type of heating systems to those with a larger surface and a decreased input temperature from 90/70 to 60/45, or even 35/28, which makes it possible to utilise energy of water previously used for electricity production in binary systems, especially from the transition zone. Moreover, district heating systems are rather popular in Poland. According to Glassey, there are three main geothermal sources for space heating, depending on temperature (Table 3). The temperature of about 65 °C is available at depths of 1600 m, which must be expected to have mineralization at the level beginning with 3 g/dm^3, and more.

Partially, geothermal waters with such temperature can be used for direct applications in the form of, e.g., greenhouse or aquaculture pond heating. However, these are not popular uses of geothermal waters in Poland yet.

Balneotherapy and balneorecreation

After decreasing a geothermal water temperature within electricity production and/or space heating, water or part of water stream may still have a temperature enabling it to be used for different therapies, bathing, or for other recreational purposes. Geothermal waters used for treatment and recreational purposes have to demonstrate specific parameters. According to Kochanski (2002), waters used for medicinal baths are required to have temperatures ranging from 28 to 42 °C, while mineralization should not exceed 60 g/dm^3. For recreational bathing purposes, temperature and mineralization values at 24–30 °C and up to 35 g/dm^3, respectively, are required. In addition, if water is used partially also for medicinal purposes, the required values are up to 32 °C and 40 g/dm^3, accordingly.

If we consider balneotherapy and balneorecreation as a following stage of the cascaded system, especially water, temperature parameters will depend on return water temperature from the previous stage. If we consider the application of water directly produced from a borehole (for example, as

the first stage of the cascaded system), we need to take into account minimum parameters values of geothermal waters occurring in the aquifer. We can notice that temperatures above 24–28 °C occur at the depth from ca. 500 m and deeper, where mineralization is ca. 0.3 g/dm^3. Although the temperature of water produced from the aquifer corresponds to the minimum required temperature, it may turn out to be insufficient, due to transmission losses and losses during heat exchange. However, the Lower Jurassic formations are usually located below that depth, and what is more, the temperature will be also higher. It regards particularly the transition zone. Higher water temperatures can be used for space and hot domestic water heating, e.g., directly or by means of heat pumps. That is why, the upper temperature limit was not considered for the first stage of a cascade. At the same time, at higher depths, mineralization is also higher.

In accordance with the available data, the Lower Jurassic formations in the Lodz Trough at the depth of ca. 1000–2000 m, where temperature exceeds minimum limits and mineralization does not exceed the upper limit of 35 g/dm^3, are characterised by the best parameters, useful particularly for recreational purposes. Specific components contents, permitting to use waters for some therapeutic purposes, are the highest in the Mogilno Trough area (I) and the Lodz Trough area (Fe) (cf. Fig. 6).

According to the Polish law, natural water must have some specific biologically active components to be called medicinal waters. A specific minimum concentration level of components occurring in the Mogilno–Lodz Trough is given in Table 4. I, Fe, and Br ions occur in those waters. In Fig. 6, the red line shows the minimum content of the ions defined by law. There are several wells where these components are documented, sometimes with amounts high enough for mineral extraction from geothermal waters.

Among the available results, presented in Fig. 6, iodides and bromides occur in concentrations exceeding minimum concentration given in Table 4 at depths exceeding 1000 m. Exceptionally, high iodides and bromides concentration occurs especially in the Mogilno Trough and it may be due to the presence of salt structures or the occurrence of crude oil deposits (Witczak et al. 2013). Iron occurs in the Lower Jurassic formations waters most frequently in the Lodz Trough. Values above the minimum concentration level occur at depth exceeding ca. 1600–1800 m.

Table 3 Sources of geothermal heating according to Glassley (2010)

> 65 °C	50–65 °C	< 40–50 °C
Hot springs (shallow) wells	Moderate temperature of waters and depths	Shallow wells
(small) Geothermal systems supplying geothermal water directly to the consumer or heat exchanger needed (e.g., Poland)	Heat of geothermal water is transferred via heat exchanger; possible cascade use	Require use of heat pumps
useful in further cascade use		

Table 4 List of specific medicinal components' concentration classifying waters as specific mineral waters, which can be regarded as waters for therapeutic purposes (based on App. 4, Dz.U.06.80.565)

Specific medicinal components	Minimum component concentration	Unit	Name of water
Iodides	1	mg/dm^3	Iodide water
Sulphides or other sulphur compounds (II)	1	mg/dm^3	Sulphide water
Fluorides	2	mg/dm^3	Fluoride water
Iron (II)	10	mg/dm^3	Ferrugineous water
Silicic acid	70	mg/dm^3	Silica water
Unbound carbon dioxide	1000	mg/dm^3	*Szczawa*
Unbound carbon dioxide	250–999	mg/dm^3	Acid and carbonic water
Temperature at the outflow from the intake	20	°C	Thermal water
Radioactivity	74	Bq/dm^3	Radon water
Bromides[a]	5[a]	mg/dm^3	Bromine water

[a]In accordance with the previous legislation

Table 5 Minimum elements contents in waters, which may be of industrial significance, based on Dzieniewicz (1990) and their occurrence in the Mogilno–Lodz Trough

Component name	Minimum content	Unit	Component occurrence in the Trough (mg/dm^3)
Br	250	mg/dm^3	< 161
I	18	mg/dm^3	< 5
K	350	mg/dm^3	3 wells: 392–480
Mg	2000	mg/dm^3	1 well: 5800

Mineral extraction and cosmetics production

Before injection of geothermal waters, some minerals can be extracted from water. Minerals can be extracted for several industrial purposes, bathing, and therapeutic salt or for cosmetics formulas. Chemical composition of geothermal waters (brine) differs. Depending on a type of geothermal waters and extraction depth, one can recover minerals on an industrial scale, including such valuable minerals as platinum group metals, gold or silver, as well as other base elements: zinc, lead, copper, manganese, rare earths, silica, lithium, arsenic, antimony, boron, bromine, iodine, strontium and barium sulphate, precipitated calcium carbonate, calcium chloride, potassium, magnesium, table salt, sodium sulphate, and others (Bourcier et al. 2005; Gallup 1998; Harper et al. 1992). However, among the above-mentioned elements, geothermal waters from the Mogilno–Lodz Trough include only the following ones being significant on an industrial scale: bromine, iodine, potassium, and magnesium. Minimum contents of ions which can be effectively recovered from geothermal waters for industrial purposes have been presented in Table 5, together with their concentrations in the Mogilno–Lodz Trough waters.

Despite high mineralization values and water origin from high depths, the occurrence of minerals in the amount sufficient for industrial applications was confirmed only in four wells. It regards potassium contents (two wells in the Mogilno Trough and one in the transition zone) and magnesium contents (one well in the transition zone). Lithium occurs in one sample and strontium in two samples. The contents of those elements are lower than threshold values, i.e., 1.6; 3; and 45.1 mg/dm^3, respectively. Those contents do not meet the minimum condition of contents, which are 10 and 300 mg/dm^3, respectively (Svalova 2015).

Highly mineralized sodium-chloride waters contain iodides and bromides ions. Bromides and iodides contents are not high enough to be used for industrial extraction; however, they are sufficient for the production of salts added to fresh waters and for bathing or other therapeutic purposes. Such waters can be also used as a base for cosmetics formula.

Aquifer thermal energy storage

Aquifer thermal energy storage is a technology of seasonal heat/cold storage in aquifers. To transfer thermal energy in and out of an aquifer in ATES systems groundwater is used. Low-grade energy is used to heat/chill water. Water is then injected into an aquifer for storage and pumped from the aquifer for heating/cooling in the building, when needed. Thermal and flow properties of the aquifer affect the process efficiency (Lee 2013). The heat source may be heat pumps cooling rooms in the summer, industrial cogeneration installations, solar collector installations, etc., which give away the surplus of heat in summer. (Paksoy et al. 2009). The most popular is the use of aquifers not exceeding 200 m in depth. Most frequent are low-temperature ATES, where storage temperature is 5–30 °C and sometimes medium-temperature systems, where temperature is 30–60 °C (Schout et al. 2014). Two high-temperature systems operate in Germany and they store waters with temperatures of 70 and 80 °C at the depth of ca. 1200–1300 m (Kabus et al. 2005, 2009). In high-temperature systems, some issues have been reported

with regard to minerals precipitation, corrosion, and low heat storage performance co-efficient (Schout et al. 2014).

Because the Lower Jurassic formations in the Mogilno–Lodz Trough are located at greater depths, some requirements need to be considered. These requirements are as follows: aquifer depth not exceeding 1500 m, the flow rate between 10 and 100 m^3/h (200 m^3/h is also possible like in Neubrandenburg installation), confined groundwater-bearing bed, reservoir thickness at the level of ca. 30 m, avoiding interference with groundwater catchment areas (after Seibt and Kabus 2006).

Some assessments of possible locations were done in the area of the Trough according to initial parameters based on Gorecki (2006). Good conditions for ATES would be at the edge of the Lodz Trough, as shown in Fig. 9.

Conclusions

According to available data, waters occurring in the area of the Mogilno–Lodz Trough, in the Lower Jurassic formations, are mostly of Na–Cl type, with some content of specific components (I, Br, and Fe). Waters in the Mogilno–Lodz Trough demonstrate similar proportions of major ions contained in them, regardless of the occurrence zone.

In the Trough, dependence between mineralisation and depth can be noted very clearly. The highest mineralization, reported in the Mogilno Trough, most probably relates to the proximity of the salt structures occurrence. The lowest mineralization can be seen in the Lodz Trough, where the Lower Jurassic deposition depth is lower.

A geothermal gradient in the Lower Jurassic formations ranges from 1.82 to 3.13 °C/100 m, with 2.4 °C/100 m on average. The highest value is connected with positive thermal anomalies in the proximity of salt dome structures. At certain depths, the reservoir temperature exceeds 100 °C. The highest temperature growth, together with depth, can be

Fig. 9 Map of the most prospective areas for applying aquifer thermal energy storage (ATES) on the layer showing temperatures in the Lower Jurassic formations' tops. A temperature layer based on Gorecki (2006)
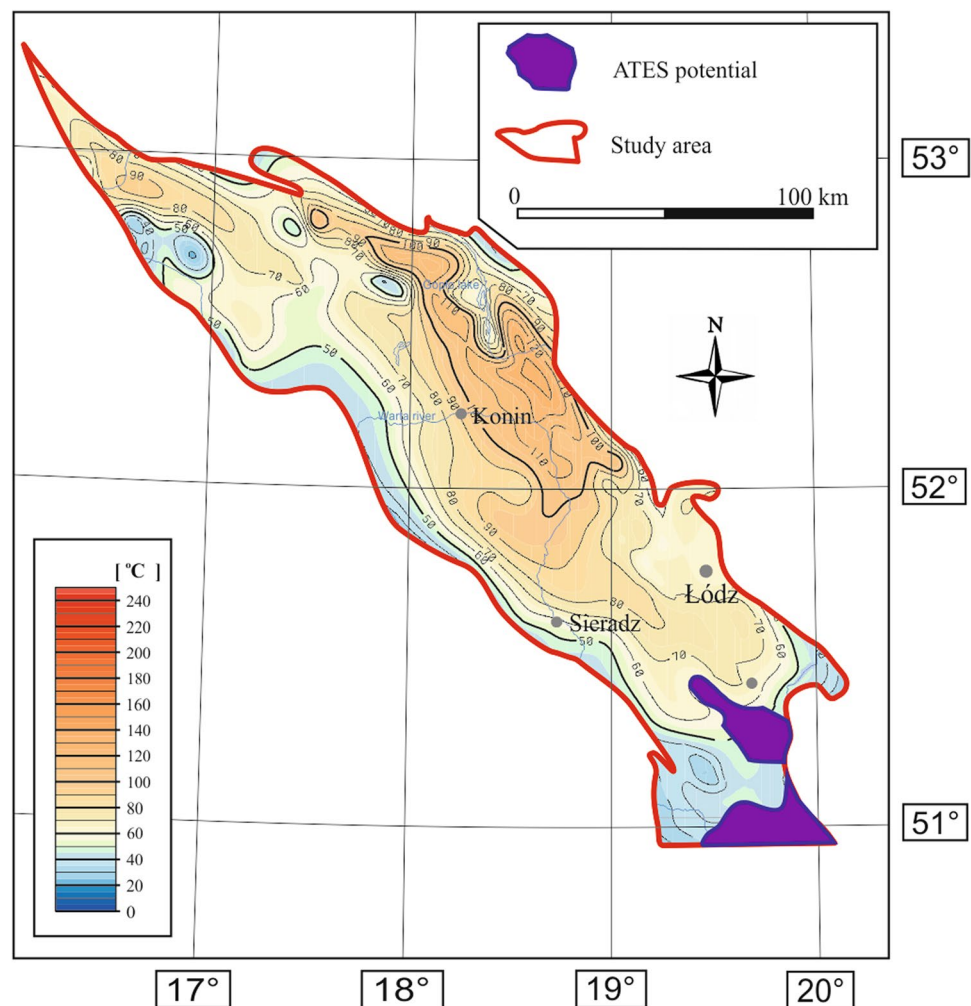
seen in the northern and central part of the Mogilno–Lodz Trough (in the Mogilno Trough and in the transition zone).

Geothermal waters from the Mogilno–Lodz Trough should be used in a cascaded system, which guarantees the optimal utilisation of available temperatures and specific components. It is possible to produce electricity in the area from geothermal energy at given temperatures in amounts of tens kW/1 kg/s of working medium, which is a relatively low value. The best location of a binary power plant would be the transition zone, where the Lower Jurassic formations are located at the highest depth. Waters with temperatures possible to be used in the heating sector are located at depths about 1600 m. The best parameters, especially for recreational purposes, are reported in the Lower Jurassic formations in the Lodz Trough, at the depth around 1000–2000 m. Specific components useful for therapeutic applications occur particularly in the area of the Mogilno Trough. In four wells, the occurrence of minerals in the amounts allowing industrial utilisation was recognised in the Mogilno Trough and in the transition zone. For the purposes of aquifer thermal energy storage, the Lower Jurassic formations were indicated only at the southern edge of theMogilno–Lodz Trough.

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