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The verification of forecasts of temperature and mineralization of the Lower Jurassic And Lower Cretaceous geothermal waters of the Polish Lowlands Based on data from new drillings performed in the years 2000–2023

Introduction

As of April 19, 2024, the Central Geological Database (CBDG) which collects detailed information on boreholes, archival geological documentation, and various types of geophysical research, contains data from 181,443 geochemical analyses for 4,708 wells. Thus far,

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in the Polish Lowlands, thirty-six wells have been made for geothermal reconnaissance (CBDG 2024). In the years 2000–2023, within the Polish Lowlands, resources were documented in twenty-eight boreholes drilled for geothermal exploration.

The basic resources of geothermal waters in the Polish Lowlands are associated with Mesozoic aquifers. Geothermal waters accumulate in sandy formations of the Lower Cretaceous (K1) and Lower Jurassic (J1) (Górecki ed. 1990; Górecki 2010; Hajto and Górecki 2010). The J1 aquifers are characterized by the largest available resources among geothermal water reservoirs in the Polish Lowlands analyzed in geothermal atlases (Górecki ed. 2006a, b; Górecki et al. 2010). Sandy-mudstone-clay formations of the J1 cover an area of 160,400 km^2 in the Polish Lowlands. While, the area of the K1 geothermal water reservoir is about 127,900 km^2, which is 41% of the territory of Poland (Górecki et al. 2007, 2010). Gorecki et al. (2010) indicated that in the coming years, the use of energy for heating, technological and balneological purposes, and also recreational activities, will be based on J1 and K1 hydrogeothermal reservoirs in the Polish Lowlands. These recommendations are confirmed by the currently implemented new investments.

Geothermal waters with a temperature exceeding 60°C and mineralization below 100 g/dm^3 were, among others, found in the Koło GT-1 wellbore. Heating, balneology, medicine and recreation are the main directions for the use of geothermal water resources in Poland. These waters are mainly used for recreational purposes in the Polish Lowlands and the Podhale Basin, with several centers operating in each of them. They use different types of water with different parameters (mineralization and temperature) (Tomaszewska and Szczepański 2014; Hałaj 2015; Kępińska 2021).

The presented work aims to show the potential of using geothermal resources in the Polish Lowlands for heating purposes. In the first part of the work, entitled *Verification of the geothermal conditions in the Polish Lowlands based on data from new drillings performed in the years 2000–2022* (Bujakowski et al. 2023), an analysis of geothermal conditions was presented, while this paper focuses on geothermal water temperature and mineralization. For this purpose, data from the CBDG (Central Geological Database) and data included in the works of, among other academics, Sokołowski (2021), Felter et al. (2021), Sokołowski (2021), and Górecki ed. (2006), were collected. The novelty of this work is the identification of changes that have occurred in forecasting the values of temperature and water minerali-

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zation in the top surface of deposits in various places as a result of performing new drilling operations, obtaining the actual values in these wells (Górecki ed. 2006; Sokołowski 2021; CBDG 2024).

1. Hydrogeothermal data sources

In Poland, since 1 January 2002, the state hydrogeological service has been performed by the Polish Geological Institute – National Research Institute (PIG-NRI). The Polish Geological Survey (PGS) actively participates in promoting activities relating to the management of geothermal waters. PGI-NRI publishes periodical studies on geothermal water resources and their utilization (PGS 2024).

PGI-NRI has been collecting and sharing geological and hydrogeological data and values of resources and abstractions in the database, commonly known under the name: Data Bank of Groundwater Classified as Minerals. The database is operated using the MINERALNE web application. This system also supports other databases of PGS – the Central Bank of Hydrogeological Data – HYDRO Bank (Bank HYDRO 2024), Groundwater Monitoring (MWP), and the Pobory database (Gryszkiewicz et al. 2021). The Data Bank of Groundwater Classified as Minerals – the Bank of Mineral Waters (DBGCM 2024), is a database that collects information on hydrogeological objects – springs, exploitation, research and observation wells – located in the territory of the country, incorporating medicinal, geothermal and brine waters (waters included in minerals), as well as mineralized and therapeutic waters, which, due to their physical and chemical properties, may in the future be classified as minerals.

The Data Bank of Groundwater database Classified as Minerals contains information on over 2,300 hydrogeological objects, including sixty-two geothermal water intakes, which are part of thirty-six geothermal water deposits. In addition to the indicated intakes, water with a temperature exceeding 20°C was documented in 283 objects, but due to insufficient research, they were not classified as mines (Gryszkiewicz et al. 2021; DBGCM 2024). One of its components is a database called the Central Bank of Hydrogeological Data – HYDRO Bank, which contains basic information about groundwater intakes, including their hydrogeologic parameters, water chemistry, and licenses (Ciężkowski et al. 2010; Bank HYDRO 2024). The scope of information stored in the database includes the location of the hydrogeological object, measurement, and the calculation of hydrogeological data, basic drilling and lithostratigraphic data, and physicochemical data of groundwater samples. The Bank HYDRO application makes it possible to provide up-to-date information on hydrogeological data in the basic scope and in the extended scope about data for which the applicant has obtained permission to access. Currently, the database contains documentation data on about 144,000 hydrogeological objects from all over the country. The database is constantly updated. About 1,700 new hydrogeological objects are added to the database annually. The owner of the information collected in Bank HYDRO is the State Treasury (PGS) (Bank HYDRO 2024).

Recognition, the determination of resources, balancing, and protection of medicinal, geothermal and brine waters are conducted by the PGS, which is performed by PGI-NRI. Information on the exploitation and disposal of resources of underground therapeutic and geothermal waters and brines are presented annually in the publication *Balance of Mineral Deposit Resources in Poland* (Szuflicki et al. ed. 2023). The latest, from the 2023 *Balance of Mineral Deposit Resources in Poland* contains data on 14,780 domestic mineral deposits. Therein it was indicated that up to the year 2022, the number of underground water deposits classified as minerals were 147, including 111 medicinal water deposits (twenty-six deposits in the Polish Lowlands), thirty-five geothermal water deposits (twenty-one deposits in the Polish Lowlands), and one brine deposit. Each deposit is recognized by one or more boreholes (Sokołowski et al. 2021; Sokołowski and Skrzypczyk 2023; Szuflicki et al. ed. 2023).

Information on medicinal, geothermal, and brine waters has been presented since 2015 in annual cycles in the publication entitled *Map of the Management of underground waters classified as minerals in Poland* (MAP OF MINERAL WATERS 2024), developed by the (currently the last edition from the end of 2021). Each edition of the map contains information on the occurrence of medicinal, geothermal, and brine waters, their physicochemical properties, exploitation resources, the method and intensity of development, and planned investments related to their intake. Data on areas particularly predisposed to exploration and intake of this type of water are also presented. The study includes a map board on a scale of 1: 1,000,000 and text explanations (Felter et al. 2019, 2021). The main content of the map board consists of points representing the location of documented underground water deposits classified as minerals (146 objects as of the end of 2020) and selected mineralized and therapeutic water intakes (215 objects as of the end of 2020), along with descriptive information such as stratigraphy of the captured aquifer, water mineralization and the total exploitable resources of all intakes, as well as water temperature at the outflow, as long as it is at least 20°C (Felter et al. 2019, 2021).

2. The management of geothermal investments performed in the years 2000–2023 in the context of the hydrogeochemical parameters of water

Between 2000 and 2023, twenty-four boreholes deeper than 1,000 meters below sea level have been drilled in the Polish Lowlands, providing information on the temperature and mineralization of waters extracted from J1 and K1 formations. The main use of geothermal wells in the range of J1 and K1 is presented in Figure 1. Figure 2 presents water mineralization documented in newly drilled boreholes. Table 1 provides more details on geothermal water data, such as water mineralization and outflow temperature from new drillings performed in 2000–2023. The boreholes are ordered from the most recent documented resources to the oldest. The documentation for the Piastów GT-1 and Wągrowiec GT-1 wells has not been approved, there is no accurate data available.

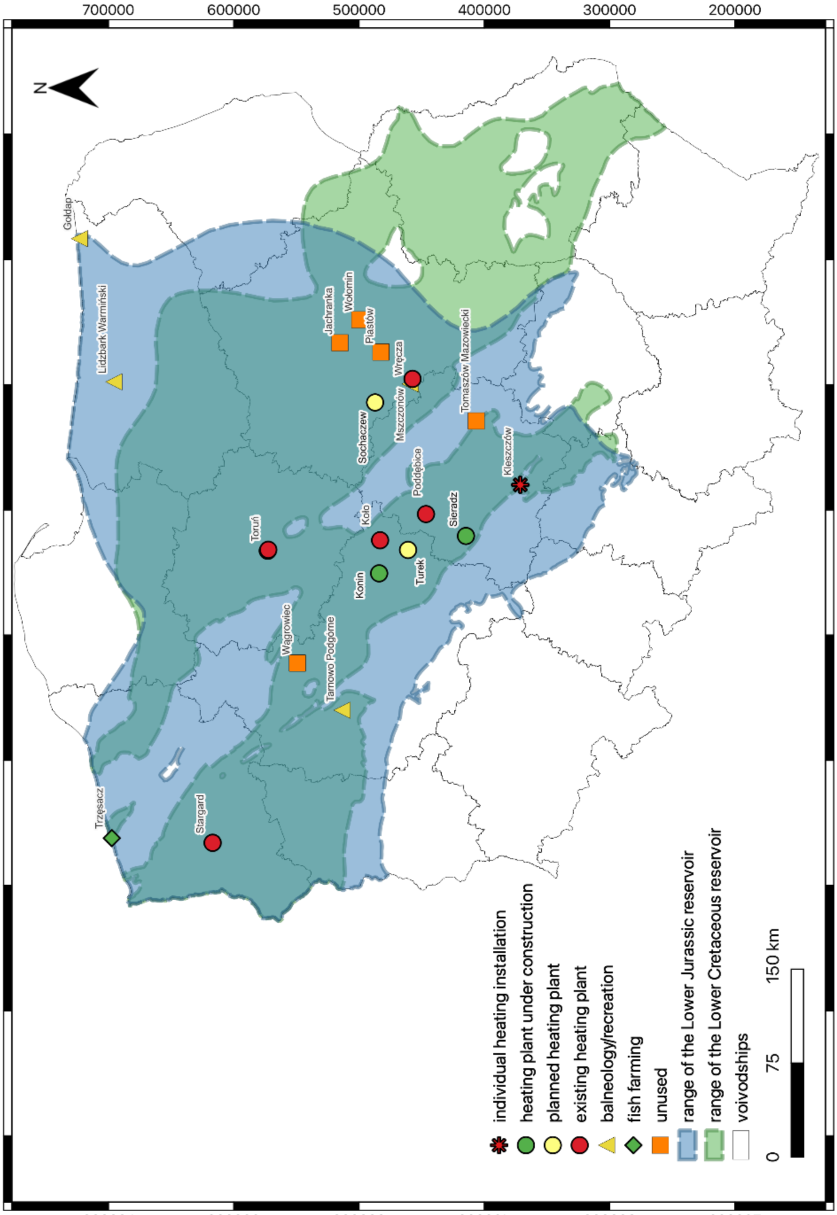

Fig. 1. The main use of geothermal wells in the Polish Lowlands within the range of the Lower Jurassic and Lower Cretaceous reservoirs (based on: Górecki ed. 2006; CBDH 2024)

Rys. 1. Główne wykorzystanie otworów wiertniczych w obrębie Niżu Polskiego w zasięgu zbiorników dolnej jury i dolnej kredy

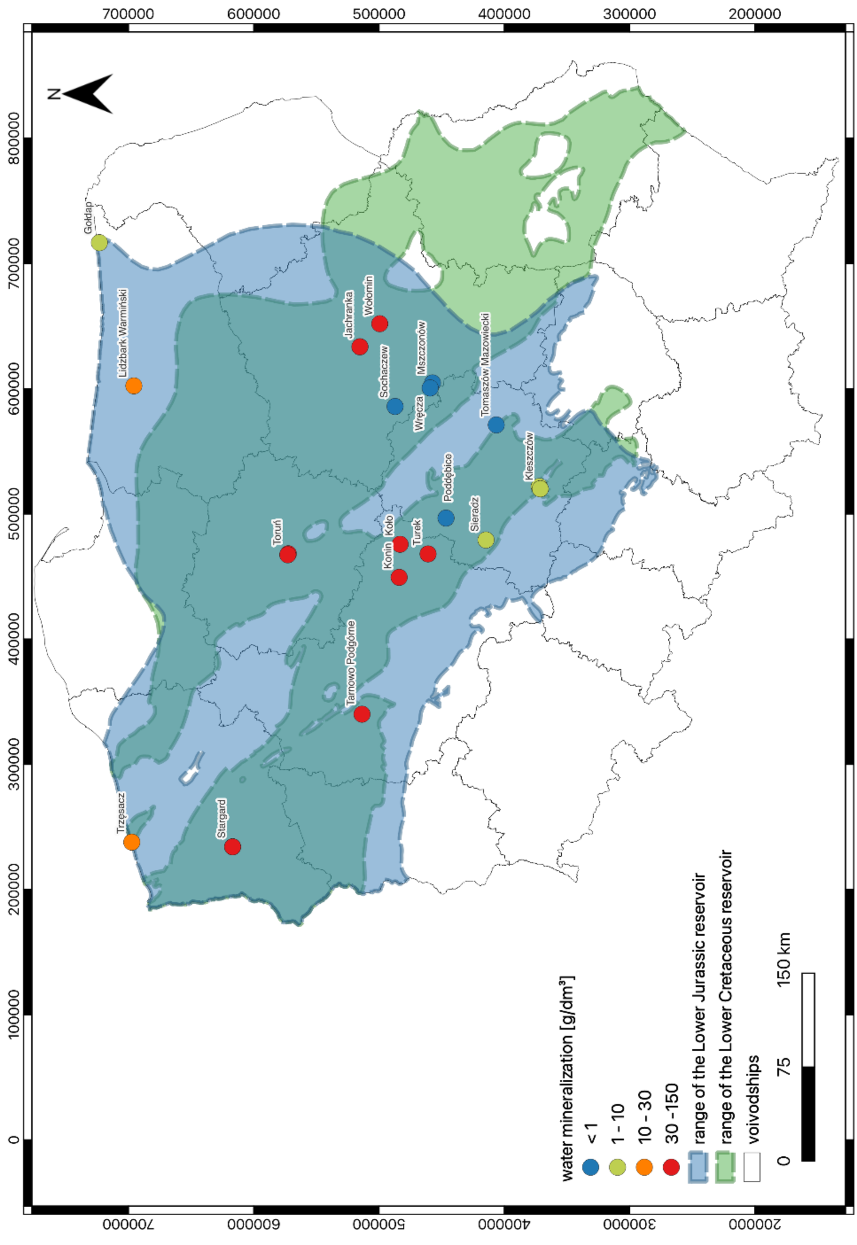

Fig. 2. Water mineralization in boreholes provided new geological information within the range of the Lower Jurassic and Lower Cretaceous reservoirs (based on Górecki, ed. 2006)

Rys. 2. Mineralizacja wód w otworach wiertniczych, które dostarczyły nowych informacji geologicznych w zasięgu zbiornika dolnej jury i dolnej kredy

Geothermal waters occurring and exploited by geothermal boreholes in Poland are fresh, low, medium, and highly mineralized waters, with mineralization from below 1 g/dm^3 to over 100 g/dm^3. They are divided into four groups according to the classification of geothermal waters commonly used in Poland in relation to their mineralization (Tomaszewska and Szczepański 2014):

- brines – highly mineralized waters (30 – 200 g/dm^3);
- salty waters – moderately mineralized waters (10 – 30 g/dm^3);
- brackish waters – low mineralized waters (1 – 10 g/dm^3);
- freshwater with mineralization <1 g/dm^3.

Brines – highly mineralized waters (30–200 g/dm^3)

Lower Jurassic (J1) reservoir

Boreholes Stargard GT-1, Stargard GT-2, Stargard GT-3, Toruń TG-1, Toruń TG-2 (wellbore has been abolished), and Toruń TG-2A are used in the existing two heating plants. The geothermal doublet consisting of the Stargard GT-1 and Stargard GT-2 wells was drilled in 2001–2003. In Stargard, additionally, Stargard GT-3 was drilled in 2016. The Stargard GT-2 well exploits Cl-Na, I, F, and Fe waters with a mineralization of 114-133 g/dm^3 and an outflow temperature of over 68°C. Currently, the Stargard GT-1 and Stragard GT-3 wells are of the injection type. Before 2008, the Stargard GT-1 operated as a production well and the Stargard GT-2 well as an injection well. Geothermal waters are used in the district heating plant to produce heat. The license for their extraction was granted to G-Term Energia sp. z o.o.

In 2009, drilling of the Toruń TG-1 (exploitation) and Toruń TG-2 (injection) wells were performed in Toruń. Geothermal waters of Cl-Na/Cl-Na, I type with mineralization of 97–120 g/dm^3 and a temperature at the outflow from the intake of 60°C were obtained in both wells. The Toruń TG-2 well is intended for the injection of used water. In 2013, Geotermia Toruń sp. z o.o. obtained a license for geothermal water extraction. In 2021, due to damage to the casing pipe column, the Toruń TG-2 well was abolished. At the same time, hydrogeological studies were underway to document the exploitable resources of the newly drilled Toruń TG-2A replacement well. The construction of the geothermal heating plant started in January 2019. The geothermal heat plant in Toruń was connected to the PGE Toruń district heating network in 2022 (Felter et al. 2021).

A geothermal heating plant is under construction in the Polish Lowlands based on the geothermal borehole Konin GT-1 (production) and Konin GT-3 ST (injection), in which highly mineralized J1 waters were captured. On Pociejewo Island in Konin, the Konin GT-1 (drilled in 2015) and Konin GT-3 ST (drilled in 2023) exploited water at the outflow temperature of 92°C, Cl-Na/SO_4-F-Na type, and mineralization of 150 g/dm^3. This is the highest water temperature at the outflow from the intake documented in Poland. Initially, the intake remained undeveloped, but currently, a geothermal heating plant is being built by Miejskie Przedsiebiorstwo Energetyki Cieplnej in Konin. It is planned that the investment will be commissioned in June 2024 (Felter et al. 2021; Sokołowski 2021; CBDG 2024; Bank HYDRO 2024).

Table 1. Geothermal boreholes within Lower Jurassic and Lower Cretaceous reservoirs in the Polish Lowlands delivered new geological information on water mineralization and temperature

Tabela 1. Odwierty geotermalne w zasięgu jury dolnej i kredy dolnej Niżu Polskiego, które dostarczyły nowych informacji geologicznych w zakresie mineralizacji i temperatury wód

No.	Borehole name	Borehole drilling date	Year of documenting resources	Total borehole depth (m)	Final object depth (m)	Aquifer stratigraphy	Water temp. [°C]	Water mineralization (g/dm^3)	Water type	Borehole purpose
1	Konin GT-3 ST	2023	nd	2,933	2,933	J1	92	150	Cl-Na/SO_4-F-Na	injection
2	Mszczonów GT-1	2023	2023	1,750	1,750	K1	41	0.5	HCO_3-Cl-Na-Ca	production
3	Piastów GT-1	2023	nd	2,035	2,035	nd	nd	nd	nd	nd
4	Wągrowiec GT-1	2023	nd	2,248	2,248	nd	nd	nd	nd	nd
5	Wołomin GT-1	2023	2023	1,450	1,450	J1	36.7	51.4–54.9	nd	nd
6	Jachranka GT-1	2019	2020	1,780.5	1,780.5	J1	43.2	77.4	Cl-Na(I+Fe)	injection
7	Jachranka GT-2K	2019	2020	1,775.4 (2,150 m MD)	1,775.4	J1	42.5	76.3	Cl-Na(I+Fe)	production
8	Tomaszów Mazowiecki GT-1	2019	2020	1,672	1,577	J1	41.7	0.5	Cl-HCO_3-Na	production
9	Turek GT-1	2019	2019	2,169	2,151	J1	77.9	132.9	Cl-Na(I)	production
10	Koło GT-1	2018	2019	3,905	2,815	K1	84.3	94.9	Cl-Na(I+Fe)	production
11	Sochaczew GT-1	2018	2019	1,540	1,540	K1	44.3	0.6	Cl-HCO_3-Ca-Na	production
12	Wręcza GT-1	2018	2019	1,688	1,688	K1	40.15	0.42	HCO_3-Ca	production
13	Sieradz GT-1	2018	2018	1,505	1,505	J1	51.8	2.6	Cl-Na	production
14	Konin GT-1	2015	2016	2,660	2,660	J1	92	150	Cl-Na/SO_4-F-Na	production

No.	Borehole name	Borehole drilling date	Year of documenting resources	Total borehole depth (m)	Final object depth (m)	Aquifer stratigraphy	Water temp. [°C]	Water mineralization (g/dm^3)	Water type	Borehole purpose
15	Trzęsacz GT-1	2012	2012	1,224.5	1,215.5	J1	25.4	13.5	Cl-Na	production
16	Lidzbark Warmiński GT-1	2011	2012	1,035	1,035	J1	21	21	Cl-Na(I)	production
17	Tarnowo Podgórne GT-1	2011	2012	1,200	1,200	J1	43.46	81.3	Cl-Na(I)	production
18	Gołdap GZ-1	2010	2012	851	646.5	J1, J2	22	6.3	Cl-Na	production
19	Toruń TG-1	2009	2012	2,925	2,925	J1	60.5	120	Cl-Na/Cl-Na(I)	production
20	Kleszczów GT-2 (Chłonny)	2011	2011	1,725	1,725	J1, J2	45.9	2.5	Cl-Na	injection
21	Poddębice GT-2	2010	2011	2,101	2,101	K1	68.4	0.46	HCO_3-Na-Ca$(Si)_2$)/ /HCO_3-Cl-Na-Ca	production
22	Kleszczów GT-1	2009	2011	1,620	1,620	J1	52.2	4.7	Cl-Na	production
23	Toruń TG-2 (Chłonny)	2009	2011	2,362	2,362	J1	–	97	Cl-Na	injection
24	Stargard GT-2	2003	2006	3,080	3,080	J1	68.9	133	Cl-Na(I+F+F)	production

K1 – Lower Cretaceous; J1 – Lower Jurassic; J2 – Middle Jurassic; nd – no data.
Based on: Sokołowski 2021, Felter et al. 2021; CBDH 2024, CBDG 2024; DBGCM 2024.

In the Polish Lowlands, it is planned to build a heating plant based on the Turek GT-1 geothermal borehole (and a new one planned to be drilled in this area), which captured J1 waters. From the Turek GT1 well (drilled in 2019), an inflow of Cl-Na, I type water was obtained with an outflow temperature of almost 78°C and mineralization of almost 133 g/dm^3. The Turek GT-1 well remains closed; however, the Turek Municipal and Housing Company plans to drill the Turek GT-2 well and build a geothermal heating plant and a pipeline between the Turek GT-1 and the Turek GT-2 well to use these geothermal waters for heating purposes.

Tarnowo Podgórne GT-1 borehole, which captured J1 waters, was developed for balneological and recreational purposes. Tarnowska Gospodarka Komunalna TP-KOM sp. z o.o. exploits the Tarnowo Podgórne GT-1 deposit through a Tarnowo Podgórne GT-1 well drilled in 2011 to supply the Tarnowskie Termy resort (since 2015). It is a complex of indoor and outdoor swimming pools with a total area of approx. 1,110 m^2 and a depth of 0.4–1.8 m, including one pool with geothermal water. The Tarnowskie Termy recreational swimming pool complex is supplied with Cl-Na, I water with a mineralization of over 81 g/dm^3 and a temperature of over 43°C (Felter et al. 2021).

The Jachranka GT-1 borehole (injection) and Jachranka GT-2K directional borehole (production) are intended to constitute a geothermal doublet in the future. The inflow of Cl-Na, I, and Fe J1 waters with the mineralization of 76–77 g/dm^3 and outflow temperature of 42–43°C was obtained. Jachranka GT-1 and Jachranka GT-2K boreholes remain unused. After obtaining the license, the investor plans to use the captured geothermal waters in the recreational complex in Jachranka (Felter et al. 2021; Sokołowski 2021; Bank HYDRO 2022; CBDG 2024).

Wołomin GT-1 well was drilled in 2023 in Wołomin city. The borehole obtained J1 waters with a mineralization of 51.4–54.9 g/dm^3 and an outflow temperature of 36.7°C. The construction works have recently been completed. The well is set to be developed in the future (CBDG 2024).

Lower Cretaceous (K1) reservoir

In the Polish Lowlands, one heating plant is operated based on the Koło GT-1 and Koło GT-2 boreholes, in which K1 waters are captured. The Koło GT-1 well (drilled in 2018 in the Koło area) exploits Cl-Na, I, and Fe geothermal waters with an outflow temperature above 84°C and mineralization of almost 95 g/dm^3. In 2022, the Koło GT-2 well was drilled. Opened in 2024, the geothermal heating plant operates based on the work of a geothermal doublet – two geothermal boreholes: the Koło GT-1 (injection) well and the Koło GT-2 (production) well.

Salty waters – moderately mineralized waters (10–30 g/dm^3)

Lower Jurassic (J1) reservoir

Since 2015, geothermal waters (mineralization 13.5 g/dm^3, type Cl-Na) from the Trzęsacz GT-1 well, with a temperature of 25°C at the outflow, have been used in the breeding of thermophilic fish at the Zakładzie Chowu i Hodowli Ryb Jurassic Salmon sp. z o.o. in Dreżewo near Trzęsacz. In 2021, the water withdrawal from the Trzęsacz GT-1 deposit was significantly lower than in previous years. This is due to the technological changes applied in the plant. The Trzęsacz GT-1 well was drilled in 2012. Initially, the obtained geothermal waters were to be used to heat the Pałac Trzęsacz recreation and leisure complex. Due to the very good physicochemical parameters and water temperature, the construction of a complex of thermal pools was also consideredin which water would be used in recreation and medicine. The investment was abandoned due to the high costs and, as mentioned, the water is used in the salmon farming process (Felter et al. 2021; Sokołowski 2021; CBDG 2024; Bank HYDRO 2024).

Moderately mineralized J1 waters were captured in the Lidzbark Warmiński GT-1borehole. These are used for balneological and recreational purposes. In 2016, the Termy Warmińskie sp. z o.o. obtained a license for the extraction of geothermal waters from the Lidzbark Warmiński GT-1 mining area. In the same year, a recreational complex was opened in Lidzbark Warmiński. The leisure and recreation complex include a hotel, SPA rooms, an indoor pool connected to an outdoor pool, a therapeutic saline pool, and a hyperthermal pool. From the Lidzbark Warmiński GT-1 well, Cl-Na, I water with a mineralization of 21 g/dm^3 and an outflow temperature of 21°C was exploited. In 2021, the intake remained closed. Lidzbark Warmiński has the status of a health resort (Felter et al. 2021; Sokołowski 2021; Bank HYDRO 2024).

Brackish waters – low mineralized waters (1–10 g/dm^3)

Lower Jurassic (J1) reservoir

In 2009–2011, the Kleszczów GT-1 production well and the Kleszczów GT-2 injection well were drilled in the Kleszczów area. The production borehole exploits Cl-Na waters with a mineralization of 4.7 g/dm^3 and a temperature of 52°C at the outflow. In 2015, the Kleszczów GT-1 mining area was established for water exploitation. The concessionaire is Zakład Komunalny Kleszczów sp. z o.o (Tomaszewska et al., 2010). These waters were used to heat the recreation and sports center and to fill the swimming pools therein; but both wells are currently closed due to unfavorable geological conditions (Felter et al. 2021; Sokołowski 2021; CBDG 2024; Bank HYDRO 2024).

Low mineralized J1 waters were captured in the Gołdap GZ-1borehole. These are used for balneological and recreational purposes. In the village of Gołdap, the Gołdap GZ-1 borehole exploited medicinal waters with mineralization of 6.3 g/dm^3 and a temperature of 22°C at the outflow. The license for extracting water used for therapeutic purposes was granted to Przedsiębiorstwo Wodociągów i Kanalizacja sp. z o.o. in Gołdap (Felter et al. 2021; Sokołowski 2021; Bank HYDRO 2024).

In the Polish Lowlands, a geothermal heating plant is under construction based on the Sieradz GT-1geothermal borehole, in which low mineralized J1 waters are captured. The Sieradz GT-1 well (drilled in 2018 in Sieradz) exploited geothermal waters of the Cl-Na type with a mineralization of 2.6 g/dm^3 and an outflow temperature of almost 52°C. Currently, the Sieradz GT-1 well remains unused; however, Geotermia Sieradz is building a geothermal-biomass heating plant in Sieradz, together with the Sieradz GT-2 injection well, and a 0.9 MWe and 1.1 MWt cogeneration module supporting the operation of the heating plant in Sieradz. A geothermal-biomass heating plant in Sieradz is planned to be put into operation in 2024 (Felter et al. 2021; Sokołowski 2021; CBDG 2024; Bank HYDRO 2024).

Fresh water with mineralization <1 g/dm^3

Lower Jurassic (J1) reservoir

In the Tomaszów Mazowiecki GT-1 well (drilled in Tomaszów Mazowiecki), an inflow of Cl-HCO_3-Na water with a mineralization of 0.5 g/dm^3 and an outflow temperature of 41.7°C was obtained. However, the deposit has not been developed. The Tomaszów Mazowiecki GT-1 boreholes remain unused (Felter et al. 2021; Sokołowski 2021; Bank HYDRO 2024; CBDG 2024).

Lower Cretaceous (K1) reservoir

The Poddębice GT-2 wellbore is used in existing heating plant. The Poddębice GT-2 well (drilled in 2010 in Poddębice) exploits geothermal waters of the HCO_3-Na-SiO_2-Ca (HCO_3-Cl-Na-Ca) type with an outflow temperature of 68°C and mineralization of less than 0.5 g/dm^3. In 2016, Geotermia Poddębice obtained a license for geothermal water extraction within the Poddębice I mining area. In 2021, the water from the intake was used for heating purposes by the municipal heating plant, and additionally for balneotherapy treatments (healing treatments) at the Poddębice Health Center as well as for the production of cosmetics (Dermedic dermo-cosmetics). In 2021, the thermal pools were not functioning due to ongoing revitalization works (transformation into the Hydrotherapy and Recreation Centre), but water from the intake was used for heating purposes by the municipal heating plant (Felter et al. 2021; Sokołowski 2021; CBDG 2024; Bank HYDRO 2024).

Mszczonów GT-1 (drilled and documented in 2023) exploited fresh geothermal waters with mineralization below 0.5 g/dm^3, HCO_3-Cl-Na-Ca type and with a water temperature at the outflow from the intake reaching 41°C. Together with the Mszczonów IG-1 well, it will constitute a doublet, Mszczonów GT-1 will be a production well, and Mszczonów IG-1 will be an injection well in the local geothermal heating plant.

Freshwaters from K1 deposits were captured in the borehole Wręcza GT-1. They are used for balneological and recreational purposes. In the town of Wręcza, the Wręcza GT-1 borehole was drilled to obtain fresh geothermal waters with mineralization below 0.5 g/dm^3. Since obtaining the license in 2021, the investor has used the waters for recreational purposes in the Suntago Wodny Świat Aquapark (Felter et al. 2021; Sokołowski 2021; Bank HYDRO 2022).

In the Polish Lowlands, the geothermal heating plant is under construction based on the geothermal borehole Sochaczew GT-1, in which fresh waters were captured. The Sochaczew GT-1 borehole (drilled in 2018 in Sochaczew) exploited geothermal waters of the Cl-HCO_3-Ca-Na type with a water temperature at the outflow from the intake reaching 44°C and a mineralization of below 1 g/dm^3. Currently, the Sochaczew GT-1 well remains unused. However, as in the case of Turek, in Sochaczew Przedsiębiorstwo Energetyki Cieplnej Sochaczew plans to drill a second geothermal well and connect it with a pipeline to the existing borehole, and will also build a geothermal heating plant equipped with two injection heat pumps together with the necessary heating devices to ensure the proper operation of the entire installation (Felter et al. 2021; Sokołowski 2021; CBDG 2024; Bank HYDRO 2024).

3. Research methodology

Maps of temperature and water mineralization at the top of the J1 and K1 formations, as included in *Atlas of geothermal resources of the Mesozoic formation in the Polish Lowlands* Górecki ed. (2006), were used to identify possible changes that should be introduced in the course of forecasting as a result of performing new drilling operations, due to obtaining the actual values in these wells (Table 1). As in the aforementioned work, the hydrogeological conditions were also slightly updated using the QGIS Desktop 3.24.1 software. The analysis was based on the results of drilling geothermal boreholes, which provided new hydrogeological information, such as water mineralization and outflow water temperature (Table 1) (Data Bank of Groundwater Classified as Minerals – the Bank of Mineral Waters PGI-NRI 2022; CBDG 2024). In this work, the indicated maps (water mineralization and temperature at the top surface of formations) from the Atlas of geothermal resources of the Mesozoic formation in the Polish Lowlands (Górecki ed. 2006) were imported into the QGIS Desktop 3.24.1 software application in the form of jpeg images. Based on imported raster maps with georeferences, shapefile isolines of water mineralization and temperature were then created. Hydrogeological information from the new geothermal wells was used to check the course of the isoline and, where necessary, based on this data, the courses of the isolines were changed based on new data using the forecasting tools available in the QGIS program.

The maps of potential temperature in the top surface of the hydrogeothermal reservoirs included in the Geothermal Atlas (Górecki ed. 2006) were made from the superposition of four maps according to the following formula (Szczepański et al. 2006):

$$T_s = G_T \cdot \frac{Z_p - Z_s}{100} + T_p \quad (°C)$$

- T_s – the temperature in the top part of a given aquifer (°C);
- G_T – geothermal gradient for the given aquifer (°C/100 m);
- Z_p – altitude of the measurement site (m a.s.l.);
- Z_s – altitude of the top surface of the given aquifer (m a.s.l.);
- T_p – mean annual temperature at the measurement site (at 0.5 m depth) (°C).

The maps of water mineralization in the top surface of the hydrogeothermal reservoirs included in the Geothermal Atlas (Górecki ed. 2006) were made from the superposition of three maps according to the formula (Szczepański et al. 2006):

$$M_s = G_M \cdot \frac{Z_p - Z_s}{100} \ (\mathrm{kg/m^3})$$

↳ M_s – mineralization of groundwaters in the top part of the given aquifer (kg/m^3);
G_M – hydrogeochemical gradient of the given aquifer (kg/m^3/100 m);
Z_p – altitude of the measurement site (m a.s.l.);
Z_s – altitude of the top surface of the given aquifer (m a.s.l.).

In this work, actual data from newly drilled geothermal boreholes, water mineralization, and outflow water temperature (documented exploitation resources) were used to update the map of potential water mineralization and temperature in the top surface of J1 and K1 reservoir formations. The borehole data (water temperature and mineralization) were converted to data in the top surface of the J1 and K1 aquifers.

4. Results

4.1. Water temperature in the top of Lower Jurassic and Lower Cretaceous formations (Polish Lowlands)

The potential water temperature in the top of the J1 formation in the Polish Lowlands ranges from 20°C to 130°C (Figure 3), while for the K1 formation, it ranges from 25°C to 90°C (Figure 4). It was identified that only in the boundary parts of the K1 formation, this value is about 20°C. Within the entire J1 reservoir, a general trend of temperature increase is visible as we approach the central parts of the reservoir (Górecki ed. 2006). In the north-western part of the reservoir, the isoline temperatures in the top of the J1 reservoir formations of 30, 70, and 80°C were corrected based on data from wells, where water temperatures were found at 25.4°C and 68.9°C, respectively. Changes were also introduced within the isoline of 40°C in the central and south-eastern part of the reservoir, where the water temperature of the reservoir of this age in the wells were 43.46°C and 41.7°C, respectively. In the southern part, the course of the 50°C isoline was updated based on data from the well in which the water temperature of the Lower Jurassic reservoir is 51.8°C. In the central and northeastern parts of the reservoir, corrections were made to the isolines of 20, 30, and 60°C. In the central part of the reservoir (data from the well – 77.9°C), an isoline correction of 80°C was introduced. Additionally, based on data from the wells, 52.2°C and 45.9°C, an isoline of 50°C was introduced in the southern part of the Lower Jurassic reservoir.

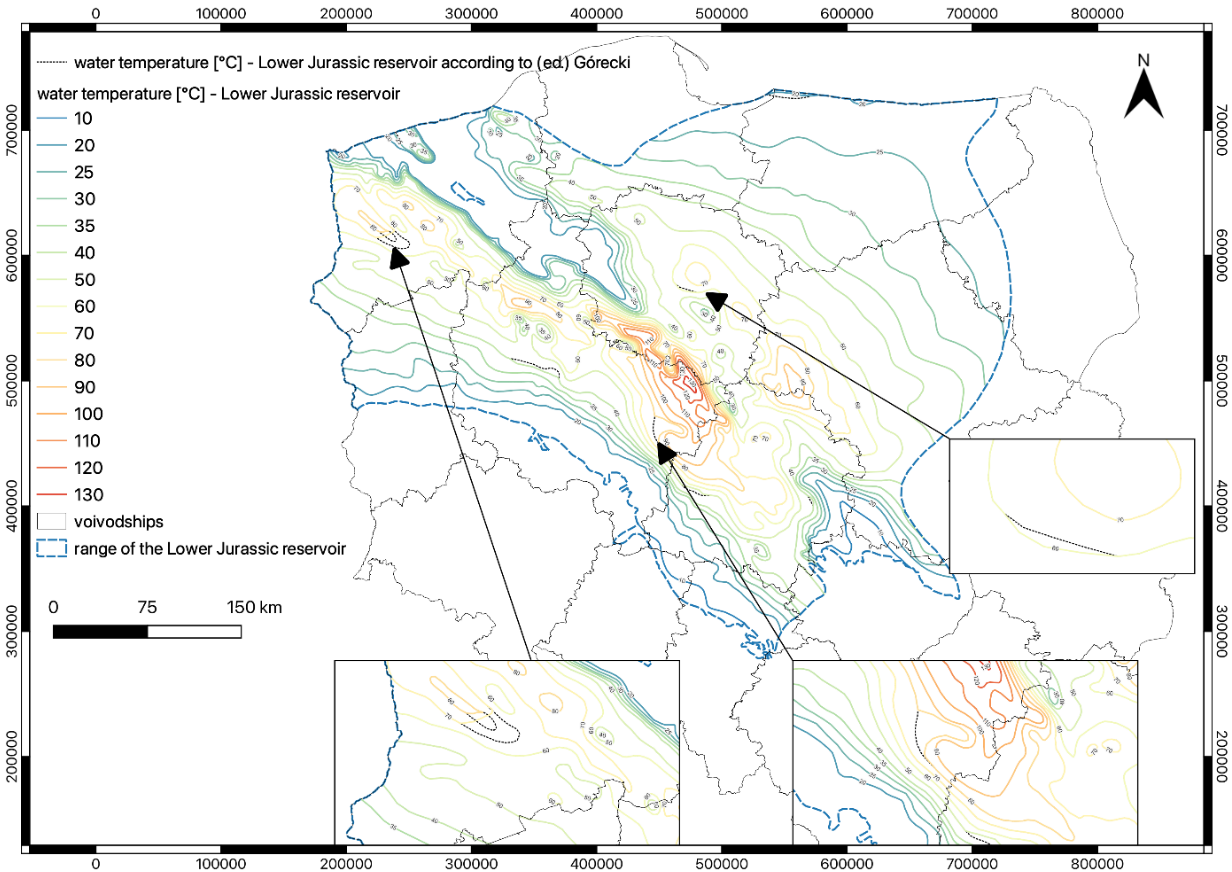

Fig. 3. Map of the potential temperature in the top of the Lower Jurassic formation in the Polish Lowlands (based on Górecki ed, 2006) with introduced changes

Rys. 3. Mapa potencjalnych temperatur w stropie utworów zbiornika dolnej jury na Niżu Polskim (na podstawie Górecki red, 2006) z wprowadzonymi zmianami

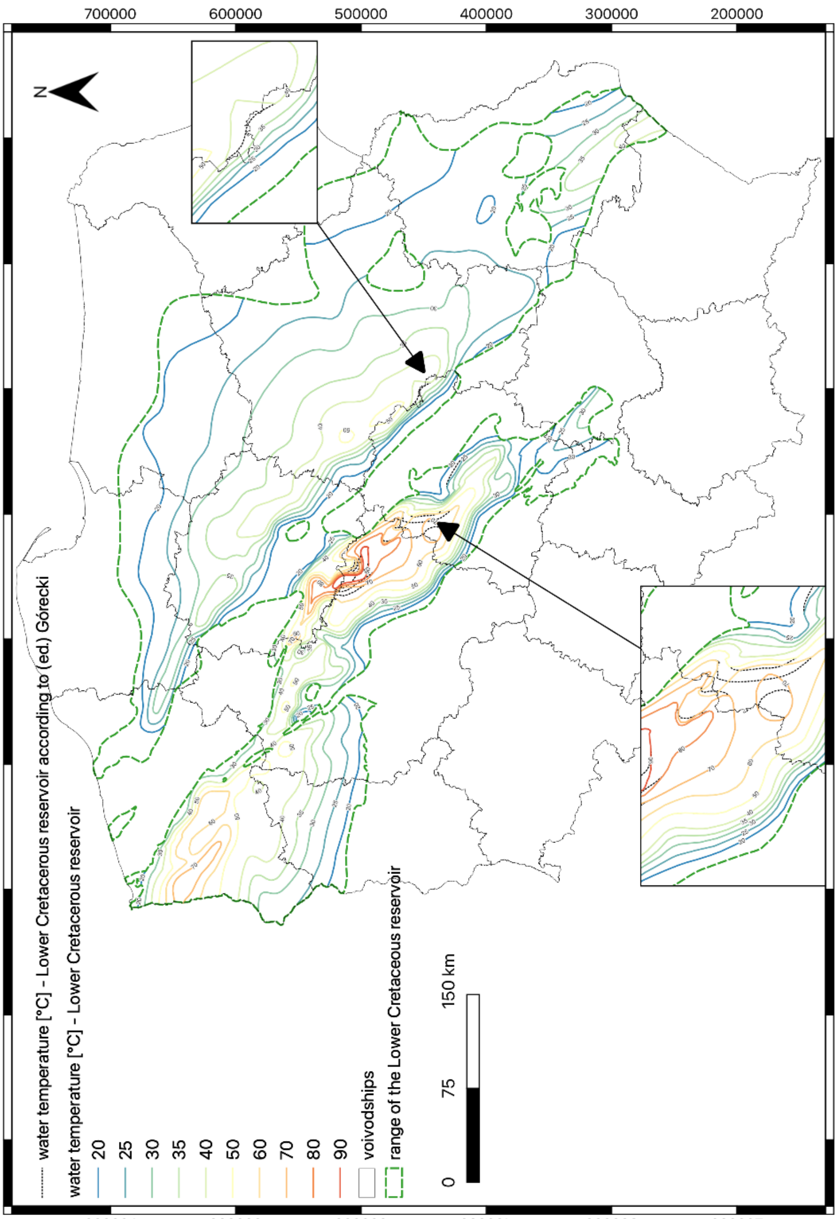

Fig. 4. Map of the potential temperature at the top of the Lower Cretaceous formations in the Polish Lowlands (based on Górecki ed. 2006) with introduced changes

Rys. 4. Mapa potencjalnych temperatur w stropie utworów zbiornika dolnej kredy na Niżu Polskim (na podstawie Górecki red, 2006) z wprowadzonymi zmianami

For K1, changes in the course of the isoline lie in a strip from the southeast to the northwest, in the central part of the reservoir. In the central-eastern part, the temperature isoline in the top of the K1 reservoir formations with a value of 40°C was corrected based on data from the 2 wells (40.15°C and 41°C). In the central part, in the western wing of the reservoir, based on data from 2 wells (68.4°C and 84.3°C), corrections were made to the isolines with values of 90, 80, 70, 60, and 50°C. The corrections were made based on new hydrogeological data from nine geothermal boreholes: Trzęsacz GT-1, Stargard GT-2, Tarnowo Podgórne GT-1, Tomaszów Mazowiecki GT-1, Sieradz GT-1, Toruń TG-1, Turek GT-1, Kleszczów GT-1, and Kleszczów GT-2 for the J1 reservoir and 4 wells: Wręcza GT-1, Mszczonów GT-1, Poddębice GT-2, and Koło GT-1 for the K1 reservoir.

4.2. Water mineralization in the top of Lower Jurassic and Lower Cretaceous formations (Polish Lowlands)

The forecasted values of water mineralization at the top of the J1 formation in the Polish Lowlands range from 10 to 200 g/dm^3 (only in the boundary parts of the reservoir is this value below 2 g/dm^3) (Figure 5), while for Lower Cretaceous, this value ranges from below 2 to 100 g/dm^3 (Figure 6) (Górecki ed. 2006). Corrections to the isolines include a strip from the southeast to the northwest, in the central part of the J1 reservoir. In the south-central part, the course of the water mineralization isoline with a value of 150 g/dm^3 was corrected based on data from wells in which water with mineralization of 150 and 94.9 g/dm^3 was found. Changes were also introduced within the isoline with a value of 50 g/dm^3 due to the water mineralization identified in the wells amounting to 81.3, 77.4, 76.3 g/dm^3, and 54.9 g/dm^3. In the southern part of the reservoir, based on the results of water tests from three wells (4.7, 2.5, 0.5 g/dm^3), corrections were made in the course of the isoline with values of 2, 5 and 10 g/dm^3. Additionally, based on data from three further wells (133, 2.6, 120 g/dm^3), isolines were introduced with a value of 150 g/dm^3 in the north-western part of the country, 5 g/dm^3 in the south and 100 g/dm^3 in the central part of the J1 reservoir. Changes in the course of the K1 isolines range from the southeast to the northwest in the central part of the reservoir. In the eastern central part of the reservoir, the mineralization isolines of the water in the K1 reservoir with values of 2, 5, and 10 g/dm^3 were corrected based on data from the well in which water with mineralization of 0.96 g/dm^3 was found. Changes were also introduced within the isoline with a value of 2.5 g/dm^3 (data from the well: 0.46 g/dm^3). In the central part of K1, the course of the 50 and 100 g/dm^3 isolines was updated based on data from wells in which water mineralization was 94.9 and 150 g/dm^3. The corrections were made based on new hydrogeological data from thirteen geothermal boreholes (Konin GT-1, Konin GT-3 ST, Koło GT-1, Tarnowo Podgórne GT-1, Jachranka GT-1, Jachranka GT-2K, Wołomin GT-1, Kleszczów GT-1, Kleszczów GT-2, Tomaszów Mazowiecki GT-1, Stargard GT-2, Sieradz GT-1, and Toruń TG-1) for the J1 reservoir and 5 wells (Sochaczew GT-1, Poddębice GT-2, Konin GT-1, Konin GT-3 ST, and Koło GT-1 for the K1 reservoir).

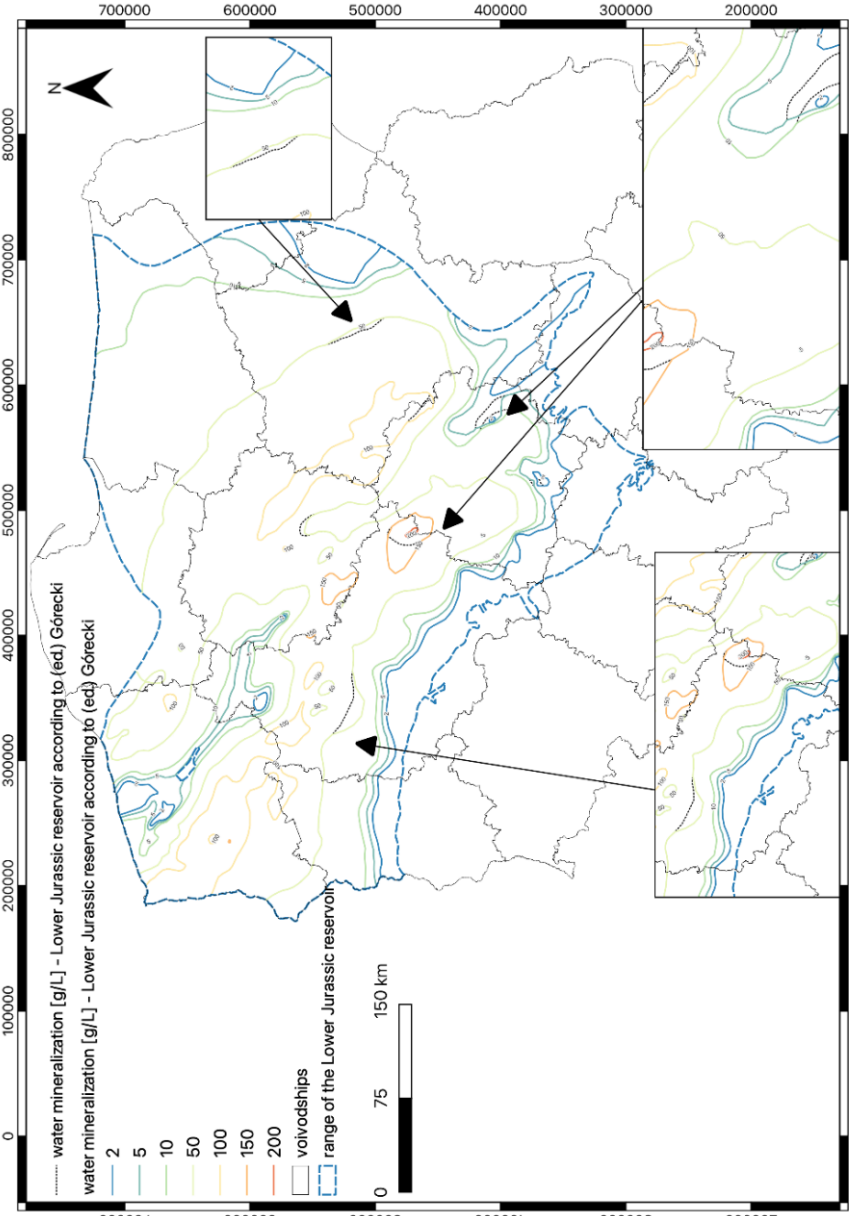

Fig. 5. Map of the potential geothermal water mineralization of the Lower Jurassic formation in the Polish Lowlands (based on Górecki ed, 2006) with introduced corrections

Rys. 5. Mapa potencjalnych mineralizacji wód geotermalnych zbiornika dolnej jury na Niżu Polskim (na podstawie Górecki red., 2006) z wprowadzonymi poprawkami

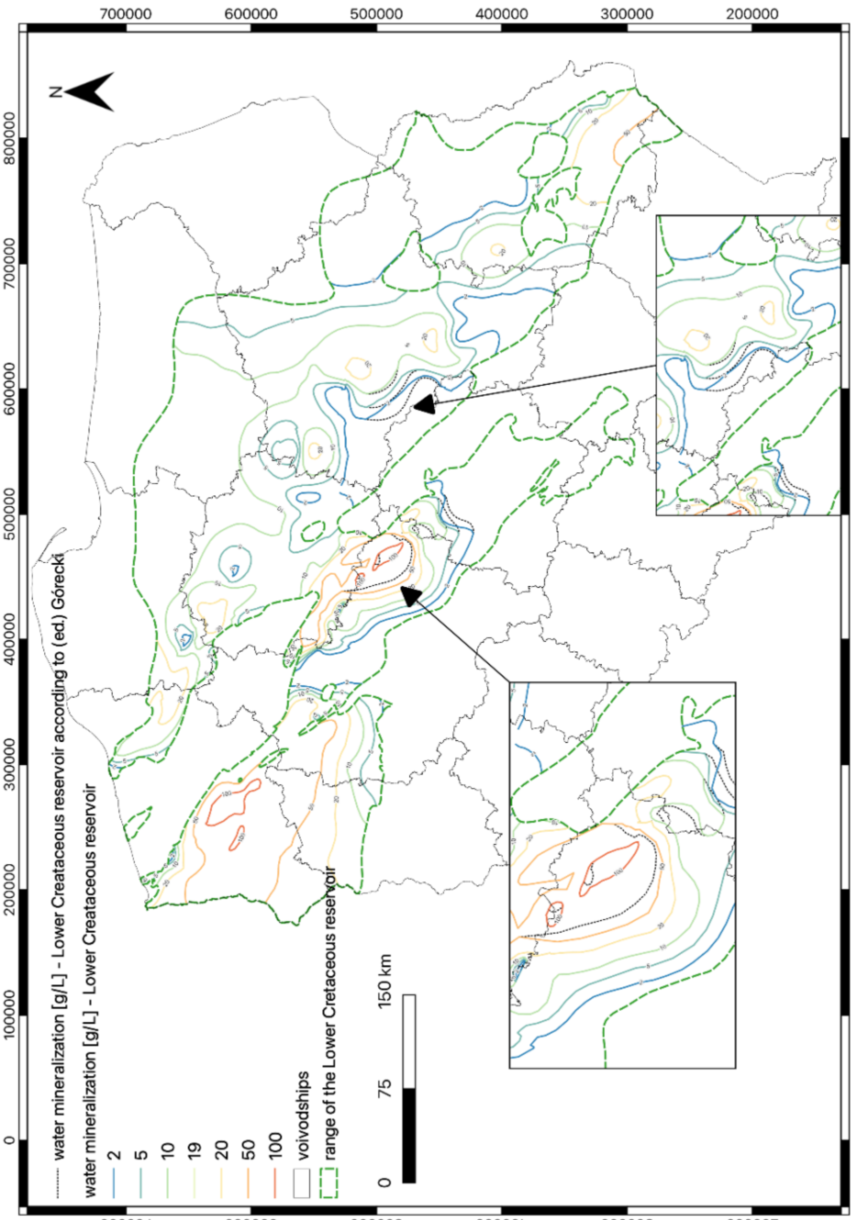

Fig. 6. Map of the potential geothermal water mineralization of the Lower Cretaceous formation in the Polish Lowlands (based on Górecki ed. 2006) with introduced changes

Rys. 6. Mapa potencjalnych mineralizacji wód zbiornika dolnej kredy na Niżu Polskim (na podstawie Górecki red., 2006) z wprowadzonymi poprawkami

Conclusions

The conducted research enabled the point-based updating of commonly used maps presenting thermal conditions and water mineralization in the top surface of the hydrogeothermal reservoirs of the Polish Lowlands, which are particularly favorable for geothermal use. Based on geological information from nineteen wells drilled from 2000 to 2022, the following points were found:

1. In relation to the J1 reservoir:
   - In the boundary (southwest strip) and central parts of the reservoir, the temperature values, the predicted and confirmed in boreholes, differ on average by about less than 5°C, by approximately 5–7.5% from the values predicted in the atlases.
   - Corrections cover the belt from the south-east to the north-west and in the central part of the reservoir.
   - The values of the mineralization, predicted and confirmed in boreholes, differ from the maps on average from less than 1 g/dm^3 in the boundary parts to up to a dozen g/dm^3 in places of great mineralization by approximately 1–30% from the values predicted in the atlases.
2. In relation to the K1 reservoir:
   - In the central part, the temperature values, the predicted and confirmed in boreholes, differ on average by less than about 8°C. These values differ by approximately 8–11% from the values predicted in the atlases; these values are both overestimated and underestimated concerning the values in the atlases.
   - The corrections of the course of the isolines cover the belt from the southeast to the northwest and in the central part of the reservoir.
   - The values of the mineralization, the predicted and confirmed in boreholes, differ from the maps on average from less than 1 g/dm^3 to a couple or so g/dm^3 (higher mineralization value). These values differ by approximately 1–18% from the values predicted in the atlases; these values are both overestimated and underestimated concerning the values in the atlases.

The corrections introduced are larger in the case of forecasts of mineralization values in both the J1 and K1 reservoirs; they usually concern the underestimation of mineralization values in the corrected areas (changes amount to up to 30% for J1 and 18% for K1 compared to the values predicted in the atlases). The corrections made increase the precision of the prediction of local geothermal conditions and indicate the need to constantly update the maps after drilling new wells.

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THE VERIFICATION OF FORECASTS OF TEMPERATURE AND MINERALIZATION OF THE LOWER JURASSIC AND LOWER CRETACEOUS GEOTHERMAL WATERS OF THE POLISH LOWLANDS BASED ON DATA FROM NEW DRILLINGS PERFORMED IN THE YEARS 2000–2023

Keywords

Polish Lowlands, geothermal water, water mineralization, water temperature, geothermal wells

Abstract

This work aimed to verify forecasts of temperature and mineralization of the Lower Jurassic and Lower Cretaceous waters in the Polish Lowlands, based on new geological information. In the first part of the articles series, entitled *Verification of geothermal conditions in the Polish Lowlands based on data from new drilling performed in the years 2000–2022*, an analysis of geothermal conditions is presented, while this work focuses on hydrogeochemical parameters, such as temperature in the top of formations and water mineralization. For this purpose, data from the Central Geological Database (CBDG), the Central Bank of Hydrogeological Data – HYDRO Bank, and from previously published scientific and research works were used. In the years 2000–2023, twenty-four exploration wells with a depth exceeding 1000 m below ground level were drilled and documented in the Polish Lowlands, providing information on the temperature and mineralization of waters taken from the Lower Jurassic or Lower Cretaceous formations. The assessment of spatial changes, as in the first part of the work,

was performed with the use of QGIS Desktop 3.24.1 software, which is geoinformation software (GIS) that allows viewing, editing, and analyzing spatial data and the creation of maps. The presented analysis made it possible to make a spot, local correction of the projected course of the isoline in relation to the maps published earlier in the *Atlas of geothermal resources in the Polish Lowlands. Mesozoic Formations* developed in 2006, edited by Wojciech Górecki.

WERYFIKACJA PROGNOZ TEMPERATURY I MINERALIZACJI WÓD GEOTERMALNYCH JURY DOLNEJ I KREDY DOLNEJ NIŻU POLSKIEGO NA PODSTAWIE DANYCH Z NOWYCH WIERCEŃ ZREALIZOWANYCH W LATACH 2000–2023

Słowa kluczowe

Niż Polski, woda geotermalna, mineralizacja wód, temperatura wód, otwory geotermalne

Streszczenie

Celem pracy była weryfikacja prognoz temperatury i mineralizacji wód dolnej jury i dolnej kredy na Niżu Polskim, na podstawie nowej informacji geologicznej. W pierwszym z serii artykułów, pt. *Weryfikacja uwarunkowań geotermalnych na Niżu Polskim na podstawie danych z nowych wierceń zrealizowanych w latach 2000–2022*, przedstawiono analizę warunków geotermalnych, natomiast w niniejszej pracy zwrócono uwagę na parametry mające wpływ na warunki hydrogeochemiczne, tj. temperaturę w stropie utworów oraz mineralizację wód. W tym celu wykorzystano dane z Centralnej Bazy Danych Geologicznych (CBDG), Centralnego Banku Danych Hydrogeologicznych – Bank HYDRO oraz z dotychczas opublikowanych prac naukowo-badawczych. W latach 2000–2023 wykonano i udokumentowano na obszarze Niżu Polskiego 24 otwory poszukiwawcze o głębokości przekraczającej 1000 m p.p.t dostarczające informacji o temperaturze i mineralizacji wód ujmowanych z utworów dolnej jury lub dolnej kredy. Ocenę zmian przestrzennych, tak jak w przypadku pierwszej części pracy, wykonano z wykorzystaniem oprogramowania QGIS Desktop 3.24.1, oprogramowania geoinformacyjnego (GIS) umożliwiającego przeglądanie, edytowanie i analizowanie danych przestrzennych oraz tworzenie map. Zaprezentowane analizy pozwoliły na dokonanie punktowej, lokalnej korekty prognozowanego przebiegu izolinii w odniesieniu do publikowanych wcześniej map w *Atlasie zasobów geotermalnych na Niżu Polskim. Formacje mezozoiku* opracowanym w 2006 r., pod redakcja naukową Wojciecha Góreckiego.