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Characteristics of thermal water flow conditions and an analysis of changes in the main hydrodynamic parameters of the Jelenia Góra geothermal system hosted by the Karkonosze Granite Massif (Sudetes, SW Poland)

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Abstract
The Jelenia Góra thermal system is related to deep groundwater flow along fractures and faults, into the Upper Carboniferous Karkonosze granite massif that is an aquifer with the main tectonic dislocations identified having NW–SE and NE–SW strikes. Thermal waters occur in three explored deposits (Cieplice, Karpniki and Staniszów). They are deep circulation waters, whose flow time is over 10 kyr, and their recharge area lies at a considerable distance from the drainage zones. In contrast to more shallowly circulating cold waters, the thermal waters are characterized by higher concentrations of the fluoride ion and metasilicic acid. They are low-TDS waters of the Na-SO_4-HCO_3 or the Na-HCO_3- SO_4 type. Analysis of changes in the hydrodynamic parameters was conducted for the exploited flowing wells C-1 and KT-1, and the Basenowe Męskie spring. Our analysis takes into account parameters measured throughout the entire operational period, with particular emphasis on changes over the last 6 years. There are close correlations between the parameters studied in the Cieplice and Karpniki intakes. The characteristics include strong, almost immediate and simultaneous responses to extreme changes in exploitation conditions caused by deep drilling, hydrogeological surveying and changes in the amount of water abstraction.

Key words: thermal water; spring discharge; fissured granite, Sudetes Mts

Introduction

Thermal waters occurring in the Jelenia Góra Basin area have been explored and documented in three places: Cieplice, Karpniki and Staniszów (Fig. 1) that are part of a large Jelenia Góra geothermal system related to the Karkonosze granite massif (Dowgiałło and Fistek, 1995), for which better assessment of groundwater flow conditions may contribute to more sustainable management of thermal water resources. Waters from the Cieplice deposit have been utilized since the 13th century. Currently, the Cieplice Health Resort Ltd. of the PGU Group uses thermal waters for balneological purposes (as medicinal waters), while the nearby Cieplice Baths Ltd. organization exploits them for recreation, the Cieplice Baths comprising several sport-recreation pools. Although Cieplice has been a resort district of the city Jelenia Góra since 1976, the name 'Cieplice deposit' has remained unchanged. Therefore this name will be used in the rest of the article, especially when describing deposit conditions. In 2013-2014, two deep wells were drilled close (8 and 14 km away respectively) to Jelenia Góra-Cieplice: ST-1 in Staniszów and KT-1 in Karpniki. The drilling of these wells, capturing thermal waters in the area of the Jelenia Góra Basin, has contributed to better assessment of the hydrogeological and geothermal conditions of the Jelenia Góra geothermal system. These two wells enabled greater use of the thermal waters for recreation and heating purposes. However, deep drilling conducted nearby to capture similar thermal waters in Staniszów and Karpniki could threaten the extraction of medicinal thermal waters in Cieplice. Another threat is planned further deep drilling in the vicinity of Cieplice.

The mining area of Cieplice, established in 1968 in compliance with the rules applicable at that time, is small and covers only the drainage zone of the deposit, unlike the newer and much bigger mining areas set up for the Karpniki and Staniszów deposits. In order to increase the protection of medicinal thermal waters, expansion of the existing Cieplice mining area has been proposed (Fig. 1.; Liber-Makowska and Ciężkowski, 2018). In the Polish Geological and Mining Law, a mining area is the precisely defined space where an entrepreneur holds a concession and has the legal right to extract minerals as part of the activities of a mining plant. In this case, the extracted mineral from the deposit is thermal water.

In this article, we interpret and highlight the similar hydrogeological conditions under which the Cieplice, Karpniki and Staniszów deposits formed. The hydrogeological conditions for the Karpniki and Staniszów deposits have been less studied than those at Cieplice. Previous studies (Dobrzyński and al., 2016, 2023) highlighted the lack of data on changes in the hydrodynamic parameters of the Karpniki and Staniszów deposits, as well as for Cieplice, over the last few years. Therefore, this article describes the nature of these changes in the Karpniki and Staniszów deposits, along with updating such studies for the Cieplice deposit previously outlined by Liber-Makowska and Kiełczawa (2020). Currently, it is only possible to conduct such studies for the intakes exploited in Karpniki and Cieplice. We provide the first analysis of changes in the main parameters of the KT-1 well in Karpniki in the context of the current changes in these parameters in the C-1 well and the Basenowe Męskie spring in Cieplice. Identifying the causes of these changes and comparing their nature in the Cieplice and Karpniki deposits should confirm or rule out the existence of a common thermal water circulation system in the Karkonosze granite massif. Explaining the causes, and determining the nature, of the changes in the reservoir parameters analysed will contribute to better protection of the thermal water resources of the Jelenia Góra region. The hydrogeological studies carried out for the Karkonosze granite massif also contribute to the understanding of the conditions within thermal water deposits in similar crystalline massifs.

Geological and hydrogeological settings

Confirmed deposits of thermal waters in Cieplice, Staniszów and Karpniki are situated in the north-eastern part of the Karkonosze-Izera block, within the Karkonosze granite massif. The Karkonosze-Izera block is the largest tectonic unit within the Polish part of the Western Sudetes, the northern section of the Bohemian Massif. The Karkonosze massif is a Variscan intrusion comprising the Karkonosze ridge, the Jelenia Góra Valley, and the western slopes of the Rudawy Janowickie Mts. The location of the Cieplice, Karpniki and Staniszów thermal water deposits on a simplified hydrogeological sketch is shown in Figure 1.

The Karkonosze granite is a biotitic monzogranite (Borkowska, 1966; Mierzejewski, 2005), with associated vein rocks, mainly aplites, pegmatites and lamprophyres (Fistek and Dowgiałło, 2003). The estimated age of granite emplacement is from ~330 to ~310 Myr (Duthou et al., 1991; Marheine et al., 2002). In granite samples collected from the KT-1 well in Karpniki (from a depth interval between 1000 and 2000 m), concentrations of natural radioactive elements such as potassium K-40 (1026-1256 Bq/kg), radium Ra-226 (37-81 Bq/kg) and thorium Th-228 (45-67 Bq/kg) were determined (Łukaczyński and Polaczek, 2014a).

In the area of Cieplice, Staniszów and Karpniki, the Upper Carboniferous Karkonosze granite is overlain by Quaternary deposits (5-20 m thick) filling erosional depressions in the bedrock. These are mainly gravels and weathered granite detritus overlain by clays and tills. Holocene deposits comprise sands and clays of the floodplain river terraces.

The Upper Carboniferous Karkonosze granite is a fissured water-bearing rock with observed fracture systems and numerous tectonic dislocations. In the area of the Karkonosze massif, there are regional dislocation zones such as: the Intra-Sudetic Fault separating the massif from the Kaczawa Mts metamorphic complex (in the north); the Karkonosze Marginal Fault (Fig. 1) separating the massif from the Jelenia Góra basin (in the south); and the Rozdroże Izerskie Fault separating the massif from the Izera Mts metamorphic complex (in the west). In the granite, prevalent dislocations are those with NW–SE and NE–SW strikes, emphasized by the strike of veins, with large dip angles. A separate group are faults with a NNE–SSW or a N–S strike and faults with near-E–W strikes (Fistek and Dowgiałło, 2003; Cymerman, 2010). In the Cieplice, Staniszów and Karpnik areas, there are deep-circulating fissure thermal waters. The circulation paths of these waters in the granite massif are associated with tectonic zones, which usually form a network in the drainage zone of these deposits (Dowgiałło and Fistek, 1995, 1998; . Łukaczyński and Polaczek, 2014a, 2014b).

According to a regional hydrogeological division, the area of the Jelenia Góra basin lies in the Sudetic region (Paczyński, 2007), which is subdivided into the Izera-Karkonosze and the Kaczawa subregions (Marszałek, 2010). The area of the Jelenia Góra Basin is a hydrogeological depression containing two types of groundwater reservoir (Marszałek, 2010). These are: the porous reservoir of waters occurring in Pleistocene and Holocene cover deposits (waters of the Quaternary aquifer system) and the porous-fissured and fissured reservoir of waters occurring in crystalline rocks (waters of the Carboniferous aquifer system).

The groundwaters of the Carboniferous aquifer system comprise shallower waters circulating in the upper reaches of fractured granite (to a depth of 20-30 m) and deeper waters, related to zones of deep tectonic fracture zones. The boundary between the zones of cold (ordinary) and thermal groundwaters has been found in Cieplice (Dowgiałło and Fistek, 1998; Marszałek, 2010), at a depth of ~300 m. However, in other parts of the Jelenia Góra Basin, this boundary can occur at different depths.

Thermal waters often flow out to the surface naturally (Cieplice and Karpniki) due to increased hydrostatic pressure. Waters of infiltration origin enter the inner parts of the granite massif, then circulate through various fissures and faults and flow towards the ground surface, while becoming mineralized and increasing their temperature on the way. Occurrences of thermal groundwaters associated with regional flow along deep tectonic fractures commonly form local areas of hydrodynamic, hydrogeochemical and hydrogeothermal anomalies (Ciężkowski and Mroczkowska, 1985).

The depth range of the faults was assessed directly during deep drilling carried out in the area of thermal water occurrence in the Jelenia Góra geothermal system. In Cieplice, during the drilling of the C-1 well and its deepening to 2002.5 m, 11 fracture zones were drilled through and they were found to contain inflows of thermal waters (Dowgiałło and Fistek, 1998).

In Karpniki, during the drilling of the KT-1 well, more than 40 zones with water inflow to the well were identified at depths greater than 684 m bgl. These were mostly small inflows from fracture zones with thickness of several tens of centimetres to one metre. Most of the water flowing into this well comes from a drilled-through fault zone at a depth of ~1800 m (Łukaczyński and Polaczek, 2014a; Liber-Makowska and Łukaczyński, 2016). A similar pattern of fissures was found in the ST-1 well in Staniszów. To the depth of 1293 m, no water inflow to the well was observed. A tectonically disturbed zone was found at a depth of 1293-1405 m, and the largest inflows were observed at 1364-1405 m (Łukaczyński and Polaczek, 2014b).

Material and methods

Important roles in thermal water flow are attributed both to deep regional dislocation zones and to shallower faults in contact with them, associated with the occurrence of springs. The medicinal thermal waters of Cieplice are captured in six springs (1 – Marysieńka, 2 – Sobieski 3 – Antoni Wacław, 4 – Nowe, 5 – Basenowe Damskie, 6 – Basenowe Męskie) and two drilled wells (C-1 and C-2; Fig. 1). Shallow intakes have complex balneotechnological structures dating back to 1924-1930. These are four bell-type intakes (with depths of 4-4.9 m) and two dug wells (with depths of 37.5-48.4 m). The deep wells C-1 (with a depth of 661 m) and C-2 (with a depth of 750 m) were drilled in 1970-1971. The C-1 well was additionally deepened to 2002.5 m in 1997-1998.

The documented exploitable groundwater resources of the springs vary from 0.5 m^3/h (Sobieski) to 1.8 m^3/h (Basenowe Damskie), and for the C-1 and C-2 wells they are 45 m^3/h and 10 m^3/h respectively. The total exploitable reserves of all the intakes are 60.74 m^3/h (Liber-Makowska and Ciężkowski, 2018). Thermal waters from the C-1 well are extracted using a flowing well system under reservoir pressure, at a constant daily amount. Waters from the main C-1 well are used for balneotherapeutic and recreational purposes. Owing to the low discharge of springs, the disappearance of artesian flow in the C-2 well, and fluctuations in the quantitative and qualitative parameters, waters from these intakes are not utilized on a regular basis. The exploitable groundwater resources of the intakes and the chemical type of thermal waters from the Cieplice, Karpniki and Staniszów deposits are shown in Table 1.

In Karpniki, thermal waters are only captured from the 2010 m-deep KT-1 well (Fig. 1), drilled in 2013-2014. The exploitable resources for this intake have been determined to be 44 m^3/h (Łukaczyński and Polaczek, 2014a). Thermal waters from the KT-1 well, extracted using natural artesian flow, are currently being used for space heating purposes in Karpniki Castle.

One intake of thermal waters is also located in Staniszów. It is the 1500-m-deep ST-1 well drilled in 2013-2014 (Fig. 1). Its exploitable resources have been determined as 20.5 m^3/h, with a depression of 97.4 m (Łukaczyński and Polaczek, 2014b). The ST-1 well is currently unexploited.

An important hydrological role in the area of Cieplice is played by the Kamienna and the Wrzosówka faults with their respective ENE-WSW and NE-SW strikes. Additionally, there are other faults crossing the area, such as the Spring Fault, the Spa Park Northern Fault, the Spa Park Southern Fault, the Wojcieszyce Fault and the Goduszyn Fault (Fig. 1). Of paramount importance to deep circulation of the thermal waters is the regional Karkonosze Marginal Fault, whose branch running to the NE crosses Cieplice (Dowgiałło and Fistek, 1998; Mierzejewski, 2005).

In the area of Karpniki, there are two dislocation systems, with NW_SE and NE_SW strikes, which have been confirmed by magnetotelluric geophysical surveys (Ciężkowski et al., 2009). Similar surveys, conducted in the area of Staniszów, proved the existence of a deep dislocation zone with a NE–SW strike, situated ~300 m to the NW of the ST-1 well (Ciężkowski et al., 2011).

The thermal waters of the Karkonosze massif are low-TDS fluoride waters of Na-SO_4-HCO_3 or Na-HCO_3-SO_4 type (Tab. 1). The waters found in most intakes in Cieplice are classified as of (Ca)-Na-(Cl)-HCO_3-SO_4 +F+(Si) type, and waters from the Sobieski intake as of Ca-Na-(Cl)-SO_4-HCO_3 +F type. The TDS content in the water varies from ~490 mg/L for waters from the Antoni-Wacław intake to 1278 mg/L for waters from the Sobieski intake. The concentration of F^- ions in water varies from ~2 mg/L for the Sobieski intake to 13.7 mg/L for the C-2 intake. The concentration of metasilicic acid in water varies from ~36 mg/L for the Marysieńka spring to 136.5 mg/L for the Basenowe Damskie and the C-2 intakes (Liber-Makowska and Kiełczawa, 2020).

The Na-SO_4-HCO_3+F+Rn type water from the KT-1 well in Karpniki is characterised by a mean TDS content of 496.7 mg/L, significant concentrations of F^- ions (11.4-16.0 mg/L) and radon 222 (290.1 Bq/L), as well as an increased metasilicic acid content (59.6-68.3 mg/L) (Liber-Makowska and Łukaczyński, 2016). The ST-1 intake in Staniszów has Na-Cl-HCO_3-SO_4+F+Rn+H_2S type water, with a TDS content of 471 mg/L. Also, increased concentrations of the F^- ion (10.5-12.7 mg/L) and radon 222 (116.4-174 Bq/L) have been confirmed (Łukaczyński and Polaczek, 2014b).

Water temperatures measured at the outflows from the Cieplice intakes vary from 13.4°C for the Anotni-Wacław intake to 83°C for the C-1 well. The highest water temperature in the shallow intakes, i.e. 48.1°C, has been measured in the Basenowe Damskie spring (Liber-Makowska and Kiełczawa, 2020). The temperature of the water flowing out of the KT-1 well is 51.2°C, and that from the ST-1 well is 37.3°C (Łukaczyński and Polaczek, 2014b). The maximum water temperatures were recorded directly in the C-1 well (87.8°C at a depth of 2002.5 m; Dowgiałło and Fistek, 1998) and the KT-1 well (59.1°C at a depth of 1793.5 m; Łukaczyński and Polaczek, 2014a).

The thermal waters of the Karkonosze granite massif are of infiltration origin, and their temperature is related to an increased value of the geothermal gradient. The value of this parameter, estimated in the C-1 well, varies between 2.72 and 3°C/100m. The real value, however, is higher, as the gradient was determined during drilling and inflow of colder waters (Dowgiałło and Fistek, 1998; Bruszewska, 2000. Water temperatures obtained for the C-1 well from modelling using chemical geothermometers are 120℃ (Liber-Makowska and Kiełczawa, 2020).

The origin of the medicinal thermal waters is clearly indicated by the results of studies into stable oxygen and hydrogen isotopes.The values of $\delta^{18}O$ and δ^2H for waters from intakes in Cieplice are comparable and range between -10.55 and -10.2‰ and between -74 and -71‰ respectively. Such values indicate that infiltration took place either during the last Pleistocene glaciation, at much lower air temperatures than observed nowadays, or in the Holocene, but at elevations reaching 1000 m a.s.l. The results of determination of noble gases in waters, and low quantities of radiocarbon, support the first hypothesis. These results applies to the main system of the Cieplice waters. Their recharge area could be located to the SW, S or SE of the resort (Ciężkowski et al., 1992, 1996; Fig. 1).

Slightly different isotopic values of oxygen and hydrogen are characteristic of waters in the Sobieski intake (between -9.585 and -9.7‰ and between -69.7 and -68‰ respectively), which indicates that their infiltration takes place at heights of ~200 m above the outflow. It can be inferred that such infiltration takes place within the Karkonosze Foreland, in the entirely granite-underlain area of Sobieszów, and that the duration of underground flow of these waters is only ~5 yr (based on their tritium values, Ciężkowski et al., 1996).

The isotopic compositions of thermal waters from Karpniki and Staniszów are very close to those of the Cieplice waters (Łukaczyński and Polaczek, 2014a; Liber-Makowska and Łukaczyński, 2016;) The waters captured from the KT-1 and the ST-1 wells are recharged by inflows from the SE or the S, similarly to the case of Cieplice (Fig.1). Based on radiocarbon analyses, the time of thermal water flow from recharge areas to the ST-1 well was estimated as 17 900±1500 yr (Duliński, 2014).

Characteristics of variation in their operational parameters such as spring discharge, wellhead pressure and water temperature at the outflow from intakes have been described using measurements performed as a part of regular monitoring carried out for the Cieplice and Karpniki deposits.

The analysis of changes in hydrodynamic parameters was based on 20445 measurements carried out in 1956-2025 for the Cieplice intakes and in 2016-2025 for the Karpniki well. The data were verified and entered into a database created by the senior author (Liber, 2008; Liber-Makowska and Kiełczawa, 2020). In addition, verification measurements of basic operating parameters were performed for the Basenowe Męskie intake and the C-1 and KT-1 wells. For the first time, an analysis of changes in hydrodynamic parameters for the Karpniki deposit was performed, and changes occurring in the Cieplice intakes over the last six years were updated.

The majority of intakes of medicinal thermal waters in Cieplice are flowing wells. Thermal waters extracted from the main C-1 well are used for balneotherapeutic and recreational purposes. Additionally, waters from the Nowe and Marysieńka springs are used chiefly for industrial or utility purposes. Because of their low discharges, as well as fluctuations in their temperatures and qualitative and quantitative parameters, waters from the remaining springs are not being utilized. The C-2 well (with a depth of 750 m) is not being exploited due to the disappearance of its artesian flow caused by the start of the operation of the 2002.5 m deep C-1 well in 2012.

The operational parameters are monitored mainly for the intakes whose thermal waters are being utilized. In the C-1 well hydrostatic pressure, temperature and water abstraction volume are measured using a pressure gauge, an electronic thermometer and a flowmeter installed on the wellhead. These measurements are conducted once a week. The same frequency is applied to measuring temperature, water table level and water abstraction volume in the Nowe and Marysieńka intakes and, additionally, to measuring wellhead pressure in the C-2 well. For the Basenowe Męskie spring, discharge and water temperature are measured once a month. The analysis conducted took account of measurements made in 1956-2025 as part of regular monitoring of the Mining Plant of Cieplice Health Resort Ltd., affiliated with the Polish Health Resort Group operating as a part of the corporate group KGHM Polska Miedź JSC.

In the Karpniki deposit, thermal waters have been extracted from the KT-1 well since 2016 and used to heat the Karpniki Castle hotel. The well is subject to stationary observations including weekly measurements of water abstraction volume (using a flowmeter), wellhead pressure and water temperature. The measurements of operational parameters have been conducted as part of regular monitoring of the Mining Plant of Termy Zamek Karpniki Ltd.

The water abstraction volume from intakes C-1 and KT-1 was calculated as approximate average values from annual abstraction, therefore they were not shown in the graph as variables over time (Figs. 3 and 4) in the chapter on results.

In order to characterize the range of main changes in operational parameters such as well discharge, water temperature and wellhead pressure, the long-term mean, the minimum and the maximum, the standard deviation and the coefficient of variation defined as the ratio of the standard deviation to the arithmetic mean (expressed as a percentage) were determined. The coefficient, unlike standard deviation, better expresses variation in an analysed characteristic when it is being compared to various distributions.

Previous studies of variability in selected operational parameters (Liber, 2008) have indicated the need to separately analyse changes occurring throughout all the observation period and in selected periods characterized by stable and unstable operational conditions. Selecting these periods on the basis of statistical or hydrogeological variability indicators requires identifying the causes and the character of the changes occurring. It is particularly important in the case of analysing changes in operational parameters observed over a long period of time, such as over 60 years in the case of the Cieplice springs.

The discharge of the Cieplice springs is the most variable parameter. In order to quantify variation in this parameter, a hydrogeological long-term variability index R (Pazdro and Kozerski, 1990), understood as the ratio of the maximum to the minimum discharge, was additionally calculated. The calculations were performed for the Basenowe Męskie spring, for which regular discharge measurements have been conducted since 1956. In the other springs, no discharge measurements have been performed for at least twelve years.

Results and interpretation

Calculations of basic values characterizing the range of changes in operational parameters in 1956-2025 for the Cieplice intakes and in 2016–2025 for the KT-1 well are shown in Table 2.

The highest water temperature in the Cieplice intakes, oscillating between 57 and 83°C, was registered in the C-1 well in 2012-2025 (period of exploitation after reconstruction of the well). The calculated average water temperature in this well is 77.0°C. In springs, this parameter varied from 20.8°C in the Marysieńka spring to 42.8°C in the Basenowe Męskie spring. The calculated coefficient of variation, amounting to several percent for most of the intakes, indicates little variation in water temperature.

Discharge is a highly variable parameter in the Cieplice springs. In some of them, outflow of water has even completely disappeared, mostly as a result of hydrogeological surveys carried out during the deepening of the C-1 well (1997-1998) or during its reconstruction (in February 2011).

Wellhead pressure measured in the C-2 well (1973-2025) also shows significant variation. Like the spring discharge, this parameter displays considerable fluctuations (0-1.42 MPa). Extremely low values (0.34 MPa) were recorded in 1998, during deposit surveys conducted in the C-1 well. Pressure observed in the C-1 well throughout its exploitation period (2012-2025) has oscillated from 0.34 to 0.49 MPa (Tab. 2).

The temperature of water from the KT-1 well, measured in 2016-2025, has oscillated from 42°C to 55°C. This parameter shows little variation, indicated by a 2.9% coefficient of variation. Much greater variation is observed for wellhead pressure, varying from 0.016 to 0.1 MPa, with an average of 0.34 MPa (Tab.2). This variation is associated with the initial period of exploitation of this well, before the installation of a gas separator, which has contributed to a stabilization of the measurement conditions.

The range of changes described, in intake discharge, water temperature and wellhead pressure, as well as calculations of statistical characteristic values (the minimum, the maximum and the coefficient of variation) of these parameters for intakes in the Cieplice and Karpniki deposits point to their heterogeneity and changeability throughout the observation period. The largest variation is observed in the discharge of Cieplice spring (coefficient of variation 24.8%) and wellhead pressure in the KT-1 and C-2 wells (coefficient of variation 56.2-64.7%) in Karpniki and Cieplice. Variation in water temperature in the intakes surveyed is much smaller (with a coefficient of variation between 2.9 and 12%).

The calculated long-term variability index R for the Basenowe Męskie spring is 42.6 for all of the study period (1956-2025), and only 1.2 for a selected period of stable exploitation (1978-1993). According to Maillet's classification (Pazdro and Kozerski, 1990), an R index of over 10 points to significant variability in the discharge of a given intake. The cause of such large changes in the discharge of these thermal springs should be primarily sought in the changing conditions of their exploitation.

The character of changes in the discharge and water temperature in the Basenowe Męskie intake is shown in Figure 2. The selected exploitation periods, characterized by extreme discharge fluctuations, are similar to those in the remaining intakes of the Cieplice deposit. The chart shows changes in the discharge of the Basenowe Męskie spring in 1956-2025. This has been the longest period of regular discharge measurements of exploited springs of various medicinal waters in the Polish part of the Sudetes. The chart shows 4472 recharge measurements, and was updated as part of this research, and expanded to include the last six years of observations (Fig. 2).

A considerable drop in water temperature and spring discharge culminating in complete disappearance of outflows was caused by drilling and hydrogeological surveying conducted in connection with: the drilling of the C-1 and C-2 wells in 1973-1974 (period 2); the deepening of the C-1 well in 1997-1998 (period 5); and its reconstruction and preparation for extraction in 2011-2012 (period 6). A smaller drop in water temperature and spring discharge was related to the exploitation of wells C-2 (period 4) and C-1 (period 7) and increased water abstraction from these intakes (since 1994 and 2014 respectively). In the last highlighted period, 7 (Fig. 2), there was an increase in spring discharge between May 2020 and June 2021, which was related to lower water extraction from well C-1 (Fig. 3, period 3) during the Covid-19 pandemic. Such a rapid and clearly marked reaction indicates the existence of hydraulic connections between the Basenowe Męskie spring and well C-1.

After the reconstruction of the deepened C-1 well in 2011-2012, the Cieplice Health Resort started exploitation of this well while discontinuing extraction from the C-2 well. Thermal waters extracted from the C-1 well are used for balneotherapeutic purposes, and since 2014, also for recreational purposes in the pools of The Cieplice Baths Ltd. Since that year, the volume of thermal waters extracted for the needs of the Health Resort and the Cieplice Baths has increased (Liber, 2008; Liber-Makowska and Kiełczawa, 2020). The main intake exploited is the C-1 well, and additionally, waters from shallow Marysieńka and Nowe intakes are extracted.

The exploitation of the C-1 well caused a decline in wellhead pressure of the C-2 well until complete disappearance of its artesian flow, with a simultaneous drop in water temperature (from 62°C to 25°C). The character of changes in water temperature and wellhead pressure in the C-1 well observed in selected exploitation periods between 2012 and 2025 are shown in Figure 3. The selected exploitation periods are mainly related to the varying extraction volume in this well. For instance, increased water abstraction from the C-1 well after 2014 (from ~5.5 to ~17 m^3/h), related to the opening of the The Cieplice Baths Ltd, is the basis for delimiting a characteristic period (period 2). At the beginning of 2020, water abstraction volume dropped (from ~18 to ~12 m^3/h) due to a decreased demand for thermal water during the Covid-19 pandemic (period 3), and since 2021 the extraction increased again (to >16m^3/h; period 4). As extraction increases, a decrease in wellhead pressure accompanied by simultaneous increase in water temperature are observed. The observed increase in water temperature in conditions of higher extraction from the C-1 well could indicate a more intensive inflow of thermal waters to this intake.

An analysis of changes in the exploitation parameters of the KT-1 well in Karpniki has provided a basis for determining the character of correlation between water temperature and wellhead pressure in 2016-2025, in conditions of varying volumes of thermal water extracted for heating purposes. The character of changes in these parameters is shown in Figure 4. The chart shows two exploitation periods specified for the KT-1 well, connected with changes in the extraction volume since the beginning of its exploitation, i.e. since 2016 . At the initial stage of the exploitation, both of the observed parameters fluctuated until they stabilized after 2019. The average water temperature in this intake, calculated for the whole observation period, is 51.2°C, and the wellhead pressure 0.034 MPa (Tab. 2). In 2019-2025, an increase in water temperature was observed along with a drop in wellhead pressure. The recorded increase in water temperature in conditions of increased extraction could be related to an increased inflow of thermal water to the KT-1 well, as in the case of the previously analysed C-1 well in Cieplice.

To sum up, the dynamic changes studied in the operational parameters of the Cieplice deposit over more than 60 years have been linked to changing operational conditions caused by deep drilling and hydrogeological surveying carried out in wells. A particularly strong response to such changes in exploitation conditions is observed in springs. It is usually manifested by decreasing water temperatures and decline in intake discharge until complete disappearance of outflows. This poses a threat to the quality and quantity of the thermal waters extracted. These examples of extreme changes in thermal spring discharge in response to drilling and hydrogeological investigation or well exploitation point to the existence of a hydraulic connection between intakes within one deposit. A similar character of changes in deposit parameters was observed in the exploited KT-1 well in Karpniki.

Discussion

Based on the geological survey described above, conducted during deep drilling of the Cieplice-1, Staniszów-1 and Karpniki-1 wells, it can be concluded that the main routes of groundwater flow within the granite Karkonosze massif are systems of fractures and numerous faults, commonly having the character of regional dislocation zones and deep tectonic fractures. Furthermore, during the drilling, depth ranges of faults and fracture zones were identified. The largest inflows of thermal waters from tectonically disturbed zones were found at depths ranging from ~1400 m (in the ST-1 well) to 1800 m (in the KT-1 well). The upper limit of thermal water occurrence in the area of Cieplice is ~300 m. Apart from changing water temperature, vertical hydrochemical zoning is observed. In contrast to the more shallowly circulating cold waters, the thermal waters are characterized by higher fluoride ion content (>10 mg/L) and increased amounts of silica in the form of metasilicic acid (>35 ~~36-136~~ mg/L). The more detailed geochemical characteristics of the thermal waters of the Jelenia Góra geothermal system are described by Dobrzyński et al. (2016, 2023) and Liber-Makowska and Kiełczawa (2020). These hydrogeochemical or hydrogeothermal anomalies may occur along very deep circulation water outflows associated with deep tectonic fracture zones (Ciężkowski and Mroczkowska, 1985).

Based on the conditions of deposit exploitation described, it can be concluded that the thermal waters of the Jelenia Góra geothermal system are deep circulation waters, usually captured from flowing wells with high discharges (Cieplice and Karpniki). Research into the isotopic composition of the waters of the Jelenia Góra geothermal system indicates that these are deep circulation waters (over 1,000 m), with an average flow time of over 10 kyr, and the recharge area is located at a considerable distance from the drainage zone. Comparable concentrations of stable isotopes of oxygen and hydrogen, as well as noble gases and radiocarbon in the Cieplice, Karpniki and Staniszów waters corroborate their infiltration origin and long flow time. In drainage zones, these waters can mix with shallower circulation waters. The thermal waters in the main circulation system are recharged in the areas located towards the SE and S of the discharge areas. A different chemical and isotopic composition is characteristic of waters in the Sobieski spring (Cieplice), whose underground flow time is only ~5 yr (Ciężkowski and al., 1996).

An analysis of changes in the main hydrodynamic parameters of the Cieplice and Karpniki deposits indicates that the parameter with the lowest variability is the temperature of the thermal water flowing from the springs and wells.

Research indicates that extreme changes in the discharge of the springs are usually caused by drilling or changes in the amount of water extracted from wells within the deposit. This hydrodynamic parameter is characterised by the greatest variability. The largest fluctuations are observed for the discharge of the Cieplice springs, in particular the Basenowe Męskie spring, which have been observed since 1956. Changes in this parameter reflect the recent history of the development of the Cieplice health resort over the last 69 years.

An analysis of changes in the hydrodynamic parameters studied indicates that another hydrodynamic parameter showing significant fluctuations is the wellhead pressure in the C-1 and KT-1 wells.

A further hydrodynamic parameter showing significant variation is wellhead pressure in the C-1 and the KT-1 wells. These are exploited using a flowing well system under artesian pressure. The greatest wellhead pressure changes were observed at the start of their exploitation~~.~~ In both wells, increased water abstraction causes a rapid pressure drop and an increase in the temperature of the water flowing out of the well. The observed increase in water temperature accompanying higher extraction from the C-1 and the KT-1 wells may indicate a more intensive inflow of thermal waters to these intakes. These variations are dynamic and that they may be subject to change. A reduction in the abstraction of medicinal thermal water during the Covid-19 pandemic caused the opposite reaction, i.e. a rise in pressure and a simultaneous drop in water temperature.

Conclusions

The interdependencies between the hydrodynamic parameters studied in both the Cieplice and Karpniki deposits are very similar. A characteristic feature is a strong, almost immediate and simultaneous reaction (of spring discharge or wellhead pressure and temperature) to extreme changes in exploitation conditions. In the past, these were caused by deep drilling and hydrogeological surveying. Currently, they mainly related to change in thermal water abstraction volume from the C-1 and KT-1 production wells. The identical nature of changes in the hydrodynamic parameters studied in the Cieplice and Karpniki deposits confirms similar thermal water circulation conditions in the fissured granite massif of the Karkonosze. The existence of a common geothermal system is also indicated by the similar chemical and isotopic compositions of the thermal waters of Cieplice, Karpniki and Staniszów. The characteristic features of the waters found here are their low mineralisation and high content of fluoride ions and metasilicic acid. These are deep circulation waters with a similar long flow time (over 10 kyr) from recharge areas to their drainage zones. The results of this research are of fundamental importance in determining possible changes in reservoir parameters and the protection of thermal water resources in the Jelenia Góra region. From a broader perspective, the research can be used to explore, or better understand, the conditions of thermal water deposits in similar crystalline massifs in the Sudetes.

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Author contribution
Conceptualization, E.L-M.; methodology, E.L-M and M.S.; data preparation, E.L-M.; analysis, E.L-M.; investigation, E.L-M. and M.S.; writing—original draft preparation, E.L-M.; writing—review and editing, E.L-M. and M.S..; visualization, E.L-M..; project administration, E.L-M.

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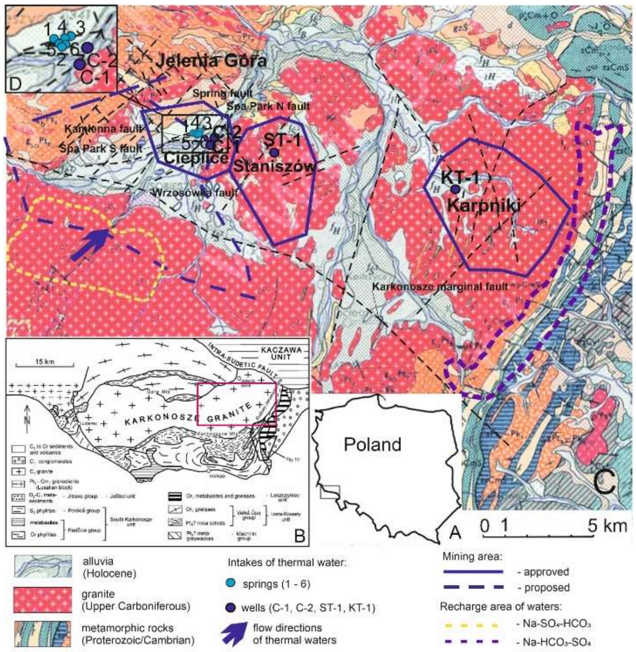

Fig. 1A – Location map, B – Geological sketch map of the Karkonosze-izera massif (after Mazur and Aleksandrowski, 2001), C – Simplified hydrogeological sketch of the Jelenia Góra Valley (background according to Milewicz et al., 1979; Liber-Makowska and Łukaczyński); proposed new mining area Cieplice according to Liber-Makowska and Ciężkowski (2018); recharge areas of waters according to Ciężkowski et al. (1996), D - Location of thermal water intakes in Cieplice.

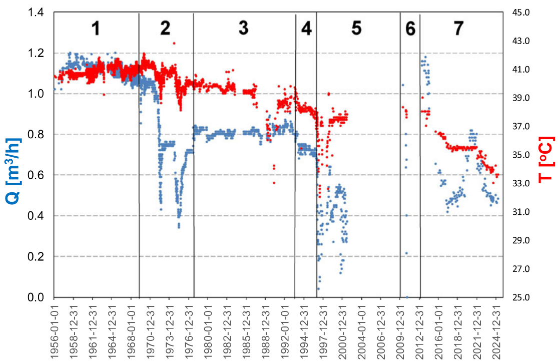

Fig. 2. Changes in water temperature (T) and discharge (Q) of the Basenowe Męskie intake in Cieplice in selected exploitation periods: 1 – start of exploitation (stabilization); 2 – drilling and examination of the C-1 and C-2 wells; 3 – stabilization; 4 – increased abstraction from well C-2; 5 – deepening and examination of the C-1 well, 6 – surveys during reconstruction of the C-1 well, 7 – exploitation of the C-1 well (according to Liber, 2008; Liber-Makowska and Kiełczawa, 2020, updated and modified).

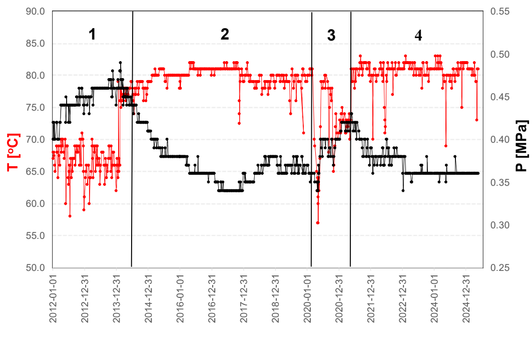

Fig. 3. Changes in water temperature (T) and wellhead pressure (P) in the C-1 well in Jelenia Góra-Cieplice in selected exploitation periods: 1 – start of exploitation, 2 – increased extraction, 3 – decreased extraction, 4 – recent exploitation period (according to Liber-Makowska and Kiełczawa, 2020, updated and modified).

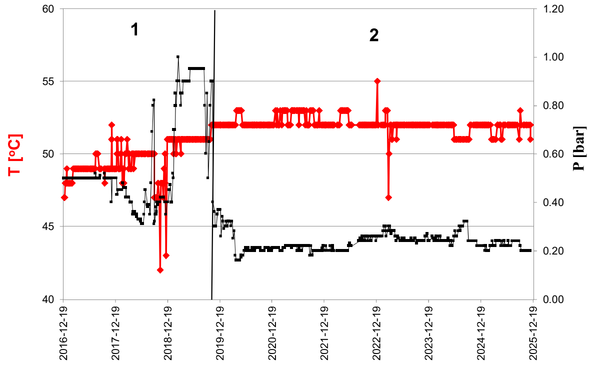

Fig. 4. Changes in water temperature (T) and wellhead pressure (P) in the KT-1 well in Karpniki in selected exploitation periods: 1 – start of exploitation, 2 – increased extraction.

Table 1
Exploitable groundwater resources of intakes and chemical types of the thermal waters in Cieplice, Karpniki, and Staniszów (based on (Dowgiałło and Fistek, 1998; Łukaczyński and Polaczek, 2014a, b; Liber-Makowska and Ciężkowski, 2018)

Name of spring* or well**	Exploitable groundwater resources [m^3/h]	Hydrochemical type of water	TDS [mg/L]
Marysieńka (No. 1)*	0.5	SO_4-HCO_3-Na +F	673.51
Sobieski (No. 2)*	0.04	HCO_3- SO_4-Na-Ca+F	1278.75
Antoni-Wacław (No. 3)*	1.2	SO_4-HCO_3-Na+F	678.88
Nowe (No. 4)*	1.0	SO_4-HCO_3-Na+F	635.89
Basenowe Damskie (No. 5)*	1.8	SO_4-HCO_3-Na+F	606.97
Basenowe Męskie (No. 6)*	1.2	SO_4-HCO_3-Na+F	652.97l
C-1 (Cieplice 1)**	45.0	SO_4-HCO_3-Na+F+S	635.89
C-2 (Cieplice 2)**	10.0	SO_4-HCO_3-Na+F	660.45
KT-1 (Karpniki 1)**	44.0	HCO_3- SO_4-Na+F+Rn	514.70
ST-1 (Staniszów 1)**	20.5	SO_4-HCO_3-Na+F+Rn+S	471.00

Table 2
Values characterising changes in the operational parameters of thermal water intakes in the Cieplice and Karpniki wells

Intake (spring* or well**)	Research period	Number of measu-rements	Mean	Minimum (date: y-m-d)	Maximum (date: y-m-d)	Standard deviation	Coefficient of variation (%)
	Water temperature [°C]						
Marysieńka*	1958-2025	3169	20.8	14.2 (1997-05-09)	27.4 (1959-10-29)	1.67	8.0
Nowe*	1956-2025	3396	31.4	20.0 (2012-08-23)	40.6 (1957-05-16)	3.9	12.0

Basenowe Męskie*	1956-2025	4426	40.2	32.0 (1997-07-25)	42.8 (1974-10-31)	1.40	3.5
C-1**	2012-2025	770	77.0	57.0 (2020-05-20)	83.0 (2024-03-11)	5.57	7.2
KT-1**	2016-2025	620	51.2	42.0 (2018-10-29)	55.0 (2022-12-27)	1.47	2.9
	Discharge [m^3/h]						
Basenowe Męskie*	1956-2025	4472	0.93	0 (2011-02-28)	1.70 (1961-10-21)	0.23	24.8
	Wellhead pressure [MPa]						
C-1**	2012-2025	770	0.390	0.340 (2017-12-20)	0.490 (2014-02-19)	0.04	10.0
C-2**	1973-2025	2203	0.170	0 (1998-03-02)	1.420 (1998-06-18)	0.11	64.7
KT-1**	2016-2025	619	0.034	0.016 (2020-05-11)	0.100 (2019-03-04)	0.19	56.2