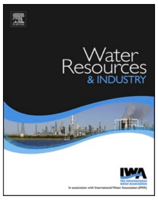
Water Resources and Industry 31 (2024) 100233

Contents lists available at ScienceDirect

Water Resources and Industry

journal homepage: www.elsevier.com/locate/wri



Stability of geothermal waters parameters as a major factor guaranteeing the possibility of its use and discharge into the environment

Agnieszka Operacz [a,*], Agnieszka Zachora-Buławska [a,b], Zuzanna Gonek [a], Barbara Tomaszewska [c], Bogusław Bielec [d], Tomasz Operacz [e], Jochen Bundschuh [f]

[a] *University of Agriculture in Kraków, Mickiewicza Av. 21, 31-120, Krakow, Poland*
[b] *Chochołowskie Termy Sp. z o.o., Chochołow 400, 34-513, Chochołow, Poland*
[c] *AGH University of Science and Technology, Mickiewicza Av. 30, 30-059, Krakow, Poland*
[d] *Mineral and Energy Economy Research Institute of the Polish Academy of Sciences, Wybickiego 7A str., 31-261, Krakow, Poland*
[e] *Polish Geological Institute - National Research Institute, Carpathian Branch in Krakow, Skrzatów 1 str., 31-560, Krakow, Poland*
[f] *University of Southern Queensland, West Street, Toowoomba, Queensland, Australia*

ARTICLE INFO

Keywords:
Geothermal waters
Hydrogeochemical characteristics
Temporal variations
Stability

ABSTRACT

Geothermal waters are considered a type of renewable energy source. Waters with elevated temperatures are also used in balneotherapy. In each type of use, the stability of the basic parameters guarantees the reliable operation of the plant. On the other hand, useable geothermal waters, which in legal terms are usually wastewater, are discharged into a surface water reservoir or injected into the rock. The diversity of geothermal waters use options creates the need to assess stability. Low and known variability of the basic parameters is extremely important for the protection of the receiving environment or the reliability of the injection process. This paper identifies the basic parameters, the relationships between them and a methodology for assessing their stability, which has not been widely used to date. The approach presented is universal and can be successfully applied to other geothermal installations anywhere in the world.

1. Introduction

For several decades, geothermal waters and geothermal energy contain have been of particular interest worldwide for their potential use in electricity generation as an alternative energy source [1], also as a means to decarbonise the energy mix of megacities [2]. GEE for electricity generation has reached its peak in recent years, representing one element of RES, but it is also used for heating [3], balneological uses [4] and recreational purposes [5,6] among others. The Lindal diagram [7] is commonly used to classify the potential uses of geothermal waters showing examples of potential uses of geothermal resources as a function of the temperatures required for the process. The development of renewable energy sources including geothermal energy, not only enables countries to meet their energy needs and become independent of energy imports, but also, above all, to reduce the level of greenhouse gas emissions [8] and slow down climate change [9]. Geothermal waters in Poland are subject to the Geological and Mining Act [10], which defines them as groundwaters with a temperature of not less than 20 °C at the point of extraction. However, the use of geothermal waters resources

---

[*] Corresponding author. Mickiewicza Av. 24/28, 30-059, Krakow, Poland.
E-mail address: a.operacz@urk.edu.pl (A. Operacz).

https://doi.org/10.1016/j.wri.2023.100233
Received 3 September 2023; Received in revised form 15 November 2023; Accepted 19 November 2023

Abbreviations:

RES -	Renewable Energy Sources
GW	Geothermal Water
GEE	Geothermal Energy Exploitation
MaxEnt	Maximum Entropy
MCDA	Multi-Criteria Decision Analysis
GP	Geothermal Potential

Nomenclature

EC -	electrical conductivity [μS/cm]
S -	standard deviation
$\bar{x}$	arithmetic mean

must be technically possible and economically justified [11]. It is very difficult to reliably identify and document geothermal waters resources and to decide whether or not to use or develop them. GP assessments are often carried out at a country level, such as in Iran [12], Croatia [13] or Poland [14], for both deep and shallow GPs [15]. Increasingly, newer methods and specialised software are being used, such as the MaxEnt method and MCDA [16], among others. On the other hand, the investor often needs easily accessible and inexpensive information at the preliminary stage of the investment, where the relationship between the depth of the intake and the expected water temperatures at that depth becomes an important parameter, simply to find the optimal location for the investment. For this purpose, for example, geothermal degree/gradient isoline maps are developed [17,18]. The use of geothermal waters with optimal parameters also requires an analysis of the environmental impact of the investment and the management of the waters used [19,20], and even the impact on living conditions [21]. Whatever the purpose of using geothermal water, whether low or high temperature for energy production, it is essential to know the temporal variability of its parameters such as mainly temperature, yield and physical and chemical composition. Such analyses are commonly carried out in the world literature. However, an assessment of the stability of these parameters, taking into account the natural variability of geothermal waters, is relatively rare. Analyses that can provide a basis for identifying correlations between individual parameters and assessing the strength of these correlations are also rarely undertaken. Such an attempt has been made in previous studies where the independent variable was the temperature of the extracted water [22]. A full understanding of the natural variability and expected stability of geothermal waters parameters is essential to assess the feasibility of both the use of geothermal waters and the environmentally safe management of used geothermal waters.

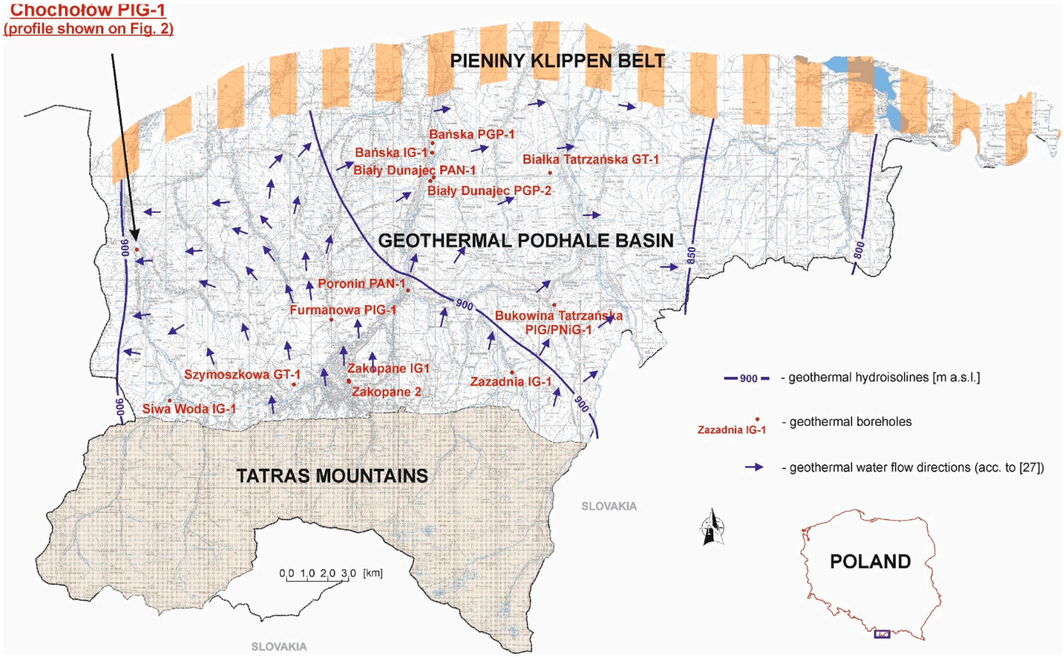


Fig. 1. Geothermal waters of the Podhale Basin (color online).

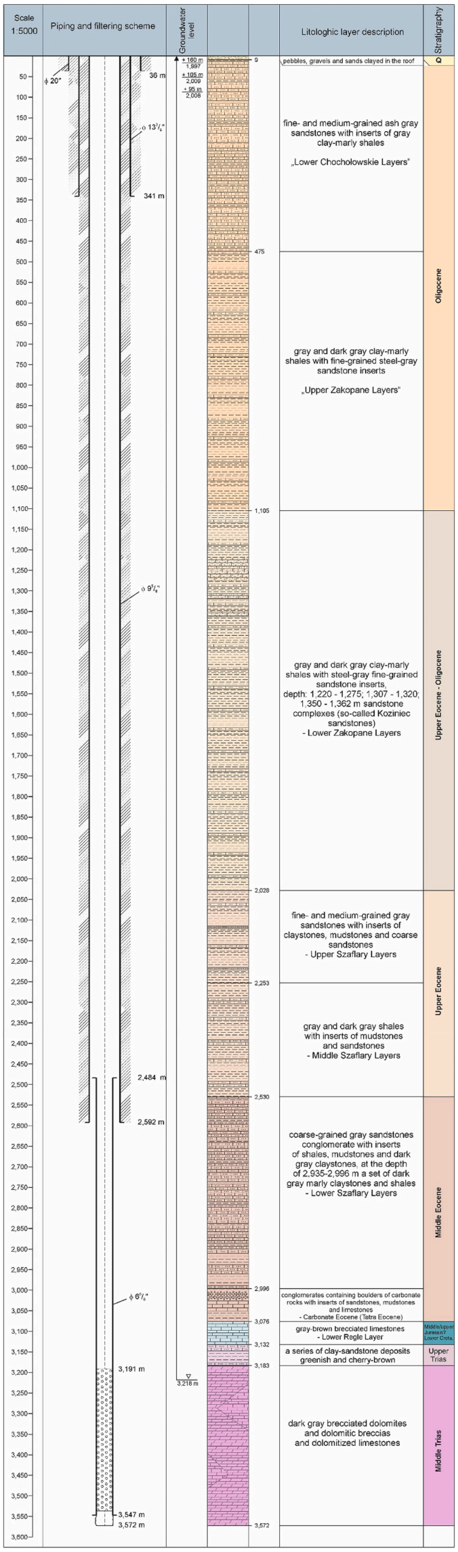


Fig. 2. Hydrogeological and structural profile of the Chochołów PIG-1 borehole (own work based on [31], modified) (color online).

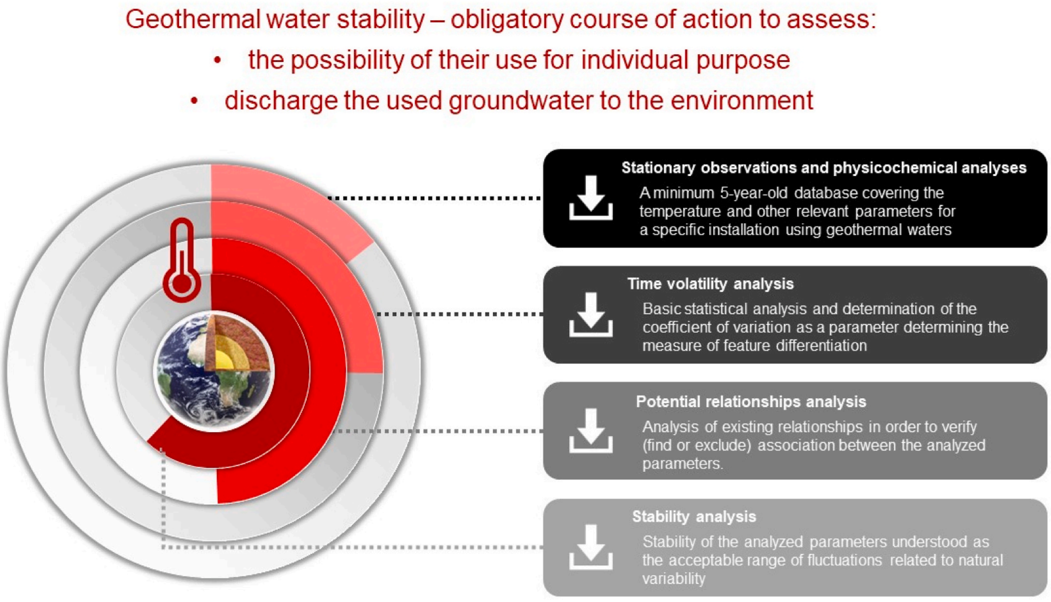
2. Characteristics of the area under study

The rich deposits of geothermal waters in Poland are associated with three major tectonic units: Western European Palaeozoic Platform and Sudety and the Carpathian Mountains with their foothills [23]. The Podhale Basin - one of the most valuable geothermal areas in Poland - is the best known region in Poland for the occurrence of geothermal waters and their extraction [17,24]. Podhale is considered to be the best reservoir of GWs in Poland, Central Europe [2,25]. High temperatures reaching almost 90 °C at the outflow, low mineralisation of the waters with a maximum of 3 g/L, high yields from individual wells and good renewability of the reservoir are favourable conditions for the exploitation of geothermal waters in this area [26]. The area of the basin within the borders of Poland is about 490 km^2 and extends in latitudinal direction from W to E, with a belt about 40 km long (Fig. 1).

The presence of geothermal waters in the study area is related to the exposure of fractured and cracked Mesozoic and Eocene carbonate rocks in the area of the Tatra Mountains, where they are fed by meteoric waters. Rainwater infiltrating this area moves northwards through a system of fractures and karst cavities towards the collapse of the Tatra Mountains (Fig. 1). These waters have a relatively short circulation, as it appears at the surface in the form of springs or is discharged in the valleys. The remaining part of the waters penetrates to the depths and then, under the influence of the dense barrier formed by the formations of the Pieniny Klippen Belt spreads out to the E and W beyond the state border [27]. Most probably, the flow velocity in the northern part of the basin is significantly lower than in the southern part, which causes more pronounced changes in the hydrogeochemical composition of the water due to the longer contact time of the waters with the rocks [28]. The mineralisation of the waters flowing down from the Tatra Mountains to the north increases and their hydrogeochemical type changes from HCO_3–Ca–Mg and HCO_3–Ca–Na to SO_4–Cl–Na–Ca. This is mainly due to the fact that the depth of the reservoirs increases towards the north, as well as the direction of the water flow. As one moves away from the Tatra Mountains, the area of water supply, the flow velocity decreases, so that the contact between water and rock is prolonged [29]. There is a high intensity of water exchange in the Podhale Basin, which has been confirmed by isotopic studies indicating its young age, i.e. between 100 and 2000 years [30].

In the area of the Podhale Basin, geothermal waters are extracted from a number of deep boreholes (Fig. 1). Some of the extracted geothermal waters are the basis for supplying recreational complexes, and thus there is an additional need to dispose of the used water, which legally constitutes wastewater. The Chochołowskie Termy complex analysed in this paper is one of the largest geothermal complexes in the Podhale region. The Chochołów PIG-1 borehole used here is located in the western part of the Podhale basin (Fig. 1). The borehole is 3572 m deep (Fig. 2) and provides access to Middle Triassic geothermal waters from the 3218–3572 m level [31].

In 2016, the permanent use of geothermal waters for the Chochołowskie Termy recreational centre began. It is one of the largest recreational centres in Poland using geothermal water. Geothermal waters are used for the thermal needs of the building: central heating, domestic hot water, mechanical ventilation and primarily for the needs of swimming pool technology: heating and partial replenishment of water in swimming pools. In addition, the Chochołowskie Termy complex is currently implementing the modernisation and expansion of the existing energy generation sources provided by a geothermal power plant, as well as the construction of a power plant based on a photovoltaic system and energy and heat storage [32]. The geothermal waters extracted from the Chochołów PIG-1 borehole is 0.11 % SO_4–Ca–Mg–Na water [33]. Currently, according to the water permit, the used geothermal waters are discharged into a surface watercourse: the Czarny Dunajec stream. In this way, its quality is controlled, which is largely determined by the physical and chemical composition of the raw waters taken from the borehole. According to the legal definition [10], geothermal



Geothermal water stability – obligatory course of action to assess:

- the possibility of their use for individual purpose
- discharge the used groundwater to the environment

Stationary observations and physicochemical analyses
A minimum 5-year-old database covering the temperature and other relevant parameters for a specific installation using geothermal waters

Time volatility analysis
Basic statistical analysis and determination of the coefficient of variation as a parameter determining the measure of feature differentiation

Potential relationships analysis
Analysis of existing relationships in order to verify (find or exclude) association between the analyzed parameters.

Stability analysis
Stability of the analyzed parameters understood as the acceptable range of fluctuations related to natural variability

Fig. 3. Proposed approach to assessing the stability of geothermal waters (color online).

waters are groundwaters that are chemically and microbiologically uncontaminated and characterised by natural variability of physical and chemical properties. However, low variability, understood as high stability, determines both its suitability for use according to the purpose of its exploitation and the safety of discharging used geothermal waters into the environment.

3. Proposed approach for assessing stability

In order to monitor the quality and composition of the geothermal waters extracted, each of these installations will be monitored by keeping the intake in full working order and by carrying out stationary observations of the basic operational, physical and chemical parameters. As part of this approach, it is proposed that the input database should cover a period of at least 5 years in order to assess the stability of geothermal waters parameters.

In the Chochołów PIG-1 intake, the results of the 2017–2021 multi-year study were used for this analysis including the following parameters: temperature of the geothermal waters intake, EC, pH and determination of the main ions: HCO_3-, SO_4^2-, Cl-, Na+, K+, Mg^2+, Ca^2+. The analyses were carried out in an accredited laboratory.

The first step in the proposed procedure (Fig. 3) is the analysis of the temporal variability and the determination of the coefficient of variation as a parameter that determines the measure of variation of the characteristic. In this way, the possible preliminary hypothesis of low variability of the hydrogeological parameters of the collected geothermal waters can be verified. The coefficient of variation V was calculated using equation (1):

$$V = \frac{S}{\bar{x}} \bullet \ 100[\%] \tag{1}$$

where:

S - standard deviation,

- arithmetic mean.

The interpretation of the coefficient is related to its size according to a conventional distribution.

$V < 25$ % - low variability,
$25\ \% \leq V \leq 45$ % - medium variability,
$45\ \% \leq V \leq 100$ % - high variability,
V > 100 % - very high variability.

Basic statistical analysis of the variation in the observed parameters was performed using Statistica software version 8.0. Single outlying observations were excluded from the analysis. The exploratory procedure of the Shapiro-Wilk test [34] was used to check the distribution of the data. Significance values greater than 0.05 indicate a normal distribution.

To verify relationships between the parameters analysed, an analysis of correlations was performed using Statistica software. Associations were determined using Pearson's linear correlation. The correlation coefficients were interpreted using the scale proposed by Stanisz [35]. The knowledge of the correlations allows, among other things, to react in an emergency situation when a parameter is not measured, knowing its correlation with another measured parameter.

Both the basic parameter of geothermal waters, i.e. temperature, and other parameters important for their use, such as the content of major ions or specific components in the case of balneotherapy, should be characterised by stable values as a function of time. The stability of the analysed parameters over time was determined by taking as a range the permissible range of fluctuations associated with natural variability [36]:

$$-2 \bullet \mathrm{S} \leq \bar{x} \leq 2 \bullet \mathrm{S} \tag{2}$$

The values of parameters considered stable, i.e. with only natural variability, should fall within the above range. It is proposed that a parameter should also be considered stable if a maximum of 10 % of the results from a multi-year database (at least 5 years) are outside the range.

4. Results and discussion

The proposed approach shown in Fig. 3 is one that is commonly used in GW analyses worldwide. For the efficient use of geothermal resources, the stability of their basic parameters is important, as it guarantees the reliable operation of a warm/hot water plant. On the other hand, a comprehensive assessment of the use of geothermal waters cannot ignore the aspect of the treatment of the used water, i.e. its discharge into a surface water receiver or its injection into the rock mass through an absorption borehole. Here, too, the low variability of the raw water parameters and their initial physical and chemical composition make it possible to minimise the need for treatment and increase the safety of the water environment of the surface water receiver or the trouble-free operation of the absorption borehole injection system.

4.1. Temporal variation of temperature, EC and pH

According to the proposed procedure in Fig. 3, the first step should be to analyse the temporal variability of the parameters under

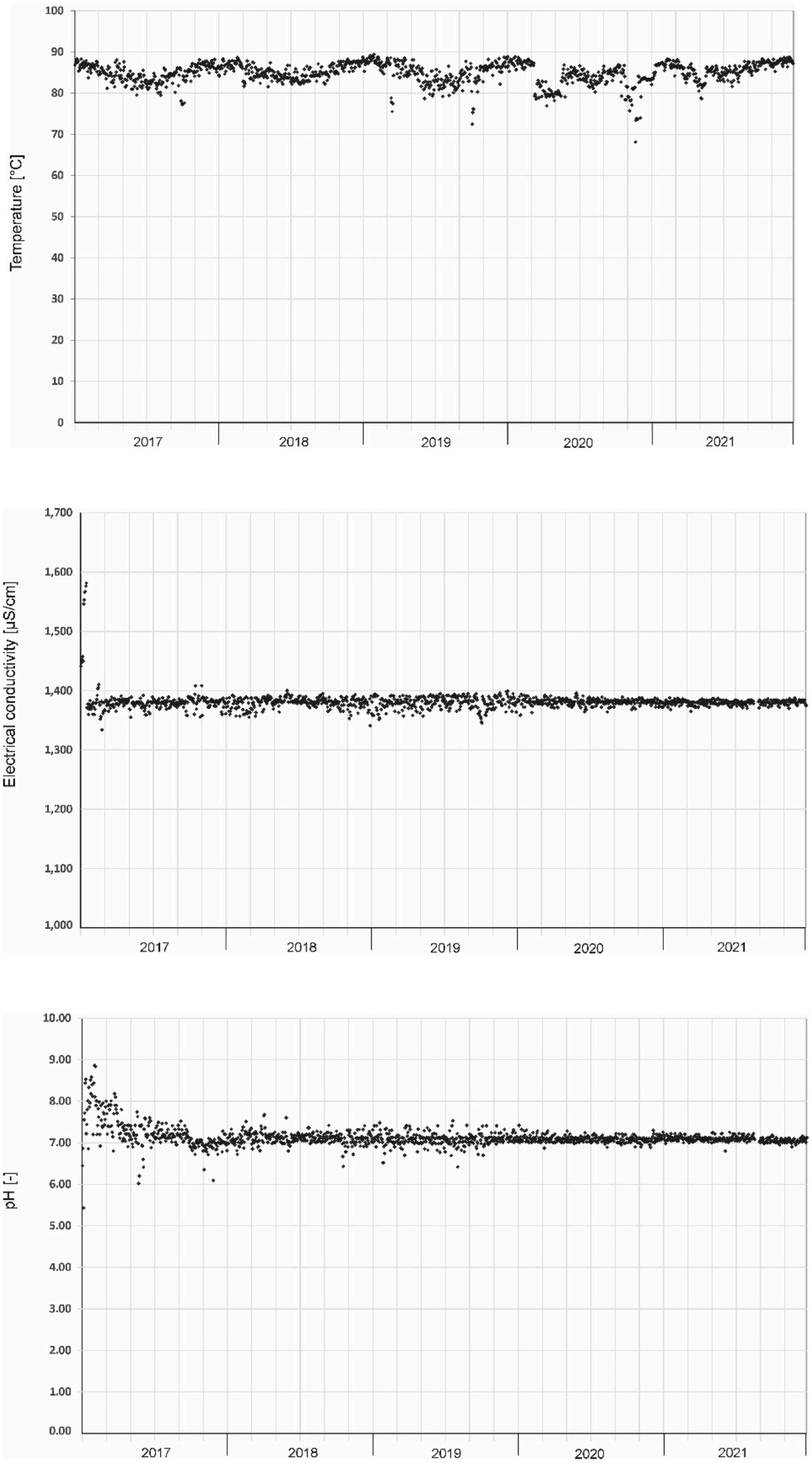


Fig. 4. Variability of temperature, EC and pH of water in the Chochołów PIG-1 borehole for the multi-year period 2017–2021.

analysis. In the case of the Chochołów PIG-1 borehole presented in this paper, the most important parameter determining the use of the extracted waters is temperature. For the maintenance of pumping and water supply equipment, EC and pH are also important as factors that can influence, among other things, the precipitation of chemical compounds and potential damage to equipment. These parameters are also monitored as part of the water permit for the discharge of used geothermal waters into the Czarny Dunajec stream.

Fig. 4 shows the temporal variation of temperature, EC and pH of the geothermal waters extracted from the Chochołów PIG-1 borehole based on stationary observations at a frequency of once a day for the multi-year period 2017–2021. Boxand whisker plots for the analysed parameters are also shown.

The analysis of Fig. 4 confirms that the waters extracted from the Chochołów PIG-1 borehole can be considered as geothermal waters in terms of the legal conditions applicable in Poland [10], as the temperature values significantly exceed the contractual threshold of 20 °C. The average temperature observed at the outflow is almost 85 °C and the lowest temperature recorded is 68.1 °C (Table 1). In terms of EC, the geothermal waters exploited by the Chochołów PIG-1 borehole is a water with relatively low mineralisation (1.380 mg/L on average), as for deep aquifer geothermal waters [37]. Typically, such waters are brines, and only injection into the rock mass is permitted [38,39]. The pH of the extracted water is generally typical of groundwaters, and the analysis in Fig. 4 shows that during the initial period of operation of the intake (2017), there were fluctuations in pH that are difficult to explain, probably due to errors in the determination phase or stabilisation of conditions during the initial period of well operation. It should be noted that the pH value stabilised around June 2017 and no major deviations occurred until the end of the multi-year period analysed.

The statistical characteristics of the parameters in question, together with the value of the coefficient of variation calculated by formula (1), are given in Table 1.

The coefficient of variation for the temperature of the extracted water and for pH calculated according to Eq. (1) was 3 %, and for EC it was 1 %. Thus, the variability is low for all the parameters included in the analysis (Table 1). The most important conclusion of such an analysis is the confirmation of low variability of temperature, EC and pH of the extracted geothermal water, which in case of possible confirmation of stability within the range of natural variability (after the full course of action according to Fig. 3) will allow to ensure stable operation of the recreation complex and undisturbed exploitation conditions. There is no risk of the exploited waters losing their status of geothermal waters temperature significantly above 20 °C [10]. The knowledge of the average temperature also allows planning and selection of the use of the warm waters, which according to the Lindal diagram [7] can include, among others, geothermal energy production, wood or fruit drying, recreation or fish farming.

4.2. *Temporal variation of major ions in geothermal waters*

In view of the fact that the water extracted from the Chochołów PIG-1 borehole is to be used for balneotherapy, the physical and chemical properties of the extracted water are also important. The Schoeller diagram is one of the methods frequently used in hydrogeological practice to graphically present a large number of physical and chemical analyses. Fig. 5 shows the variability of the contents of major ions in the geothermal waters extracted from the Chochołów PIG-1 borehole on the basis of analyses performed with a frequency of once a month in the multi-year period 2017–2021. Each line represents one analysis.

There is clearly a high degree of agreement between the analyses, which is confirmed by the overlapping lines. The graphical preliminary assessment indicates stability of the physical and chemical composition of the geothermal waters extracted from the Chochołów PIG-1 borehole with the exception of chloride concentrations, which graphically show some variation, especially when considering the logarithmic scale. The graphical analysis of the Schoeller diagram was extended by providing statistical characteristics and calculating the coefficient of variation according to formula (1) (Table 2).

The coefficient of variation (Table 2), calculated according to formula (1), for all the ions included in the analysis takes values below 25 %, thus indicating a low variability according to the conventional scale. The highest value of the coefficient of variation was obtained for the chloride ion determinations, confirming the preliminary graphical conclusions of the Schoeller chart analysis (Fig. 5). The first conclusion of such an analysis is the confirmation of the low variability of the main ions in the geothermal waters in question, which with the knowledge of the range of natural variability makes it possible to ensure undisturbed exploitation conditions through infrastructure maintenance. A more important conclusion for the potential use of the waters for balneotherapeutic purposes is the expected stable physical and chemical composition of the waters, which translates into a stable health effect. With regard to the discharge of used geothermal waters into the surface waters environment, the low variability of the physical and chemical composition creates optimal conditions for the selection of its treatment methods and reduces the risk of failure of the treatment system. Thus, it increases the safety of the effluent-laden aquatic environment represented by the used geothermal waters.

4.3. *Analysis of correlations*

In order to verify possible relationships between the analysed parameters, an analysis of the occurring correlations was carried out

Table 1

Statistical characteristics of the main parameters in the GW from the Chochołów PIG-1 borehole in the period 2017–2021.

Parameter	Min	Max	Mean	Mediana	Standard deviation	Coefficient of variation [%]
Temperature [°C]	68.1	89.4	84.8	85.2	2.6	3
EC [μS/cm]	1334	1581	1380.7	1381	15.4	1
pH [−]	5.4	8.9	7.1	7.1	0.2	3

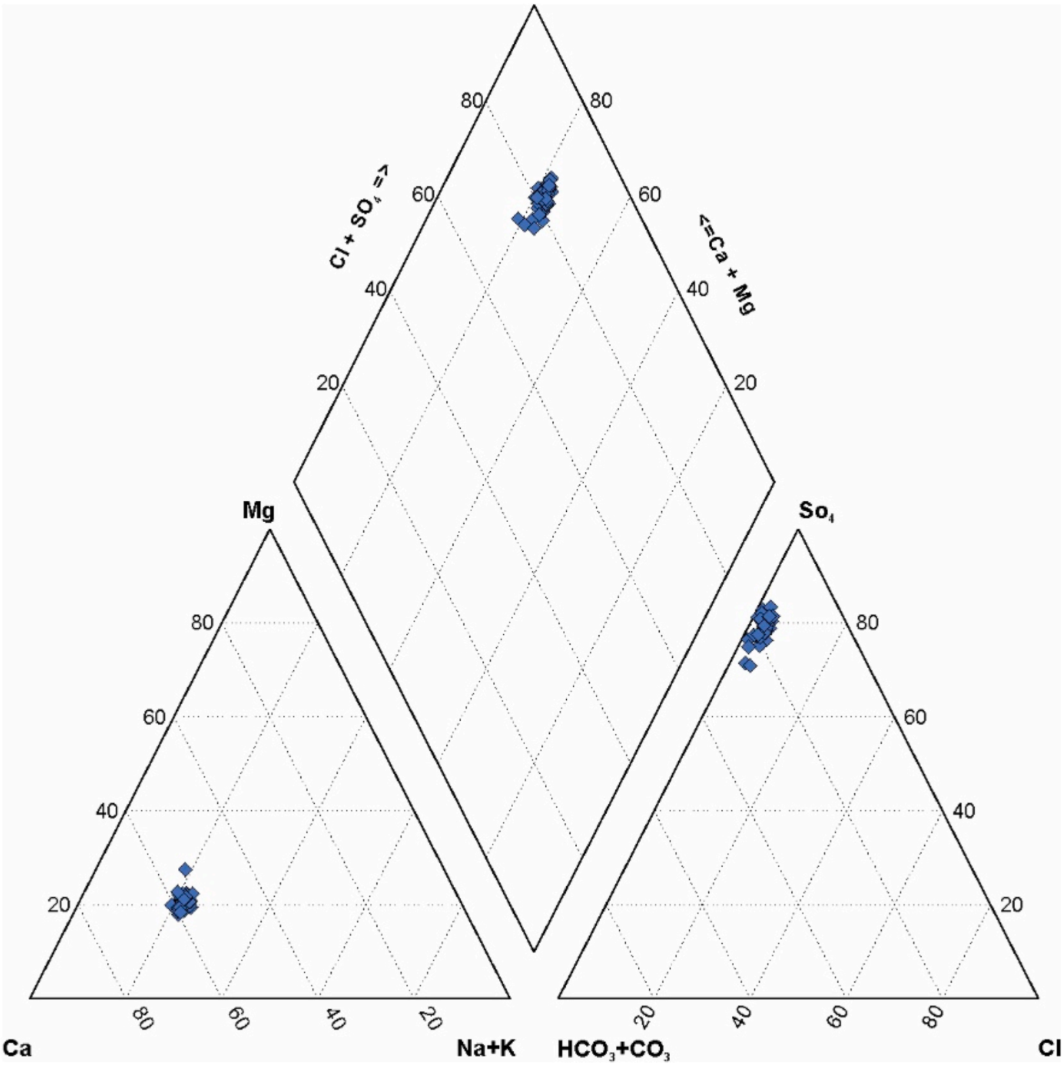


Fig. 5. Piper diagram of the physical and chemical characteristics of the waters in the Chochołów PIG-1 borehole in the multi-year period 2017–2021.

Table 2
Statistical characteristics of concentrations of major ions in GW from Chochołów PIG-1 borehole in the period 2017–2021.

Ion [mg/L]	Min	Max	Mean	Mediana	Standard deviation	Coefficient of variation [%]
Na	52.5	82.7	69.2	69.3	5.1	7
K	10.6	20.7	16.6	16.7	1.9	11
Ca	145.3	203.3	181.2	182.3	11.0	6
Mg	31.7	56.2	40.2	41.1	4.1	10
Cl	5.6	27.5	18.2	19.3	4.6	24
SO_4	403.5	735.1	595.4	583.9	54.5	9
HCO_3	126.3	244.4	168.6	165.5	18.8	11

in the Statistica programme. The exploratory procedure in Statistica, i.e. the Shapiro-Wilk test [34], was used to verify the normality of the distribution of the analysed data. The results are shown in Table 3.

Significance values lower than 0.05 indicate that for Mg, Cl, SO_4, HCO_3, EC and pH the distributions are significantly different from the normal distribution. The remaining parameters are characterised by a normal distribution. A Box-Cox transformation was chosen to restore the normal distribution of the data. A Pearson linear correlation matrix analysis was performed to determine the degree of linear dependence between the random variables (Table 4). Correlation analysis was performed in Statistica for all pairs of parameters in the database. The correlation coefficients were interpreted using the scale proposed by Stanisz [35].

Table 3
The Shapiro-Wilk tests for the analysed parameters.

Parameter/ion	Shapiro-Wilk statistica “W”	Statistical significance “p”
Na	0.963	0.065
K	0.978	0.341
Ca	0.978	0.348
Mg	0.934	0.003[a]
Cl	0.890	0.000[a]
SO_4	0.954	0.024[a]
HCO_3	0.786	0.000[a]
Temperature	0.974	0.224
EC	0.648	0.000[a]
pH	0.951	0.018[a]

[a] Non-normal distribution.

Table 4
Correlation matrix for parameters in GW from Chochołów PIG-1 well.

	Na	K	Ca	Mg	Cl	SO_4	HCO_3	Temperature	EC	pH
Na	–	0.17	0.67[a]	0.47	−0.14	0.55[a]	0.16	−0.11	0.06	−0.38
K	0.17	–	0.53[a]	0.06	−0.25	0.40	−0.28	−0.04	−0.28	−0.03
Ca	0.67[a]	0.53[a]	–	0.63[a]	−0.12	0.74[a]	0.09	−0.23	−0.29	−0.18
Mg	0.47	0.06	0.63[a]	–	−0.12	0.56[a]	0.48	−0.21	0.02	−0.21
Cl	−0.14	−0.25	−0.12	−0.12	–	−0.26	−0.29	−0.02	−0.01	−0.12
SO_4	0.55[a]	0.40	0.74[a]	0.56[a]	−0.26	–	−0.06	−0.26	−0.34	−0.01
HCO_3	0.16	−0.28	0.09	0.48	−0.29	−0.06	–	0.07	0.33	−0.08
Temperature	−0.11	−0.04	−0.23	−0.21	−0.02	−0.26	0.07	–	0.20	0.12
EC	0.06	−0.28	−0.29	0.02	−0.01	−0.34	0.33	0.20	–	−0.08
pH	−0.38	−0.03	−0.18	−0.21	−0.12	−0.01	−0.08	0.12	−0.08	–

[a] Significance.

Significant correlations with a strong relationship were observed for selected major ion pairs Ca–Na, Ca–K, Ca–Mg, Ca–SO_4, Mg–SO_4, SO_4–Na (Fig. 6). For the other parameters no significant correlations with more than a moderate relationship were found.

The confirmed relationships between selected ions (Fig. 5) are characterised by a positive correlation coefficient, which means that an increase in the value of the independent variable causes an increase in the value of the dependent variable. It can therefore be concluded that an increase in the Ca content is correlated with an increase in the concentrations of Na, K, Mg and SO_4, and an increase in the concentrations of Mg and Na ions is strongly correlated with an increase in the content of SO_4. This is a natural relationship that is often confirmed in hydrogeological practice [40–43]. The mathematical formulae describing the correlations presented in Fig. 6 allow not only to confirm the observed phenomenon, but also to express it with a specific numerical value, e.g. an increase in the Na content in geothermal waters by 10 mg/L results in an increase in the Mg ion content by 13 mg/L and an increase in the sulphate content of SO_4 by 52 mg/L.

4.4. Stability analysis of geothermal waters

The stability of the analysed parameters over time was determined by assuming an acceptable range of variation associated with natural variability according to formula (2). For this purpose, an interval of ± twice the standard deviation from the arithmetic mean was plotted for each of the parameters included in the analysis (Fig. 7).

Analysis of the data shows that the values of all the parameters included in the study are largely within the range indicated. Outside the lines there are individual determinations which represent a few percent exceedance from a minimum of 1.1 % for EC to a maximum of 8.3 % for chlorides in relation to the long-term database. Therefore, it should be considered that the studied parameters and contents of the main ions in the geothermal waters extracted from the Chochołów PIG-1 borehole are stable. Individual exceedances do not lead to loss of stability and, most importantly, such accidental changes do not lead to significant difficulties in the use of the water or possible discharge of used water into the environment. Previous observations in the recipient of used geothermal water, i.e. the Czarny Dunajec stream, confirm the absence of negative effects of water discharge on the water quality of the recipient [20]. It should be mentioned that the geothermal swimming pool complexes operating in the Podhale Basin do not usually have absorption wells, and the discharge of used geothermal waters into surface waters is carried out in accordance with the requirements of water law permits [44]. This way of dealing with used geothermal waters, which constitute wastewater, is only possible due to their low EC values and the stability of their physico-chemical composition. The stability estimation procedure presented in this paper should be mandatory for the introduction of used geothermal waters into the surface waters environment.

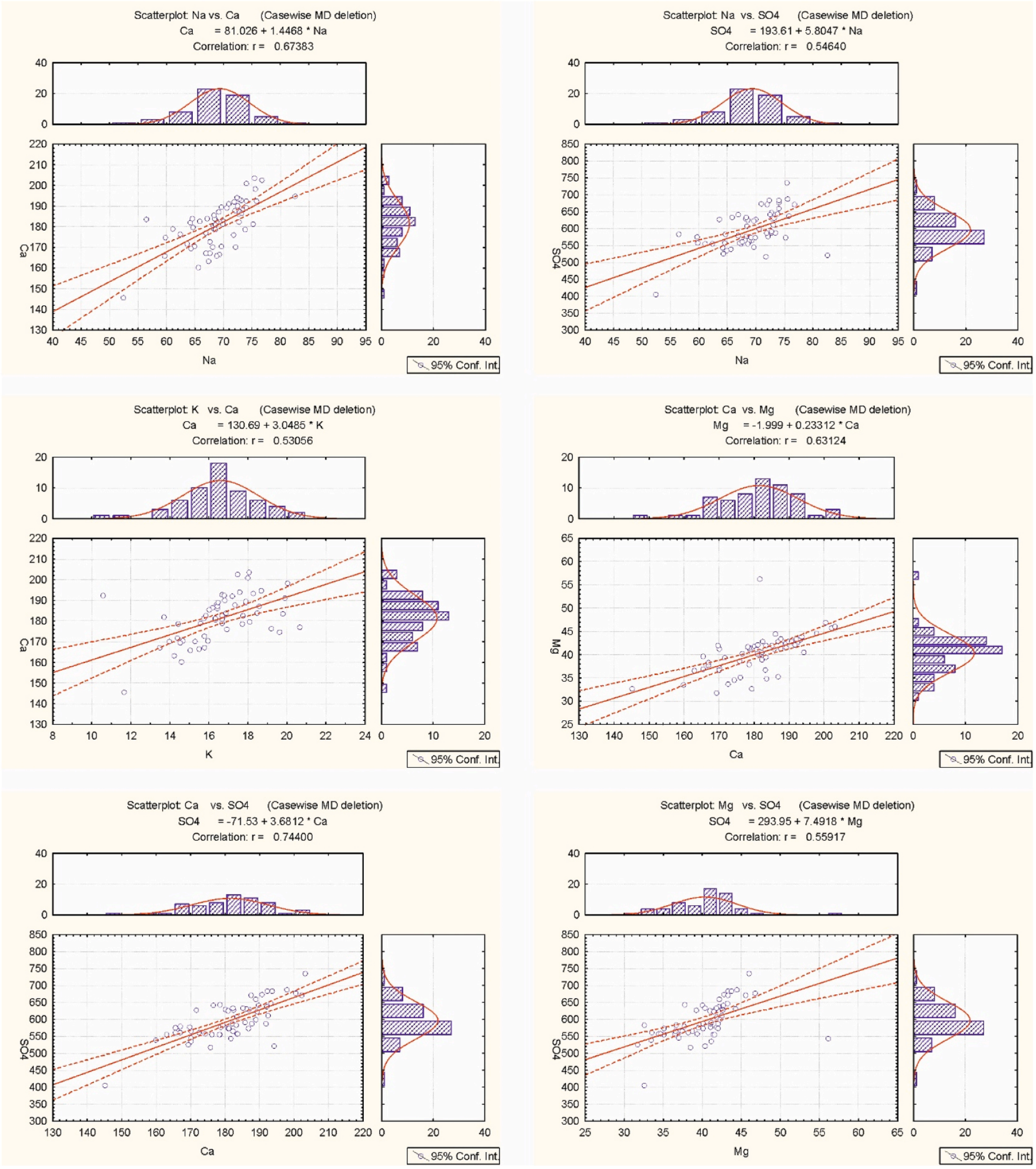


Fig. 6. Plots for observed strong correlations (color online).

5. Conclusions

For the optimal use of geothermal waters, taking into account its great geothermal potential, it is extremely important to know not only the average temperatures of the extracted waters, but above all the stability of this parameter, understood as a low variability within the limits of natural variability, covering the expectations of the investor. Other parameters of geothermal waters, such as major ions or pH, may also be of interest for balneological use or for the reliable and long-lasting operation of plant components. To this end, this paper proposes a universal procedure for assessing stability. The parameters for assessing stability should be selected individually, depending on the specific geothermal waters use installation. Regardless of the number and type of parameters, the proposed procedure is universal, correct and should be applied universally to all such installations worldwide. An analysis of the stability of selected parameters was carried out on the example of the Chochołowskie Termy complex in southern Poland, Europe. The complex uses geothermal waters mainly for heat production, recreation and balneotherapy, and the used geothermal waters are discharged into the aquatic environment of the Czarny Dunajec stream. The stability of the parameters is also very important in terms of the environmental impact of the used geothermal waters as wastewaters. The temperature of the water extracted from the Chochołów PIG-1 borehole for the Chochołowskie Terme is characterised by low variability, with values significantly higher than the limit of 20 °C, which determines

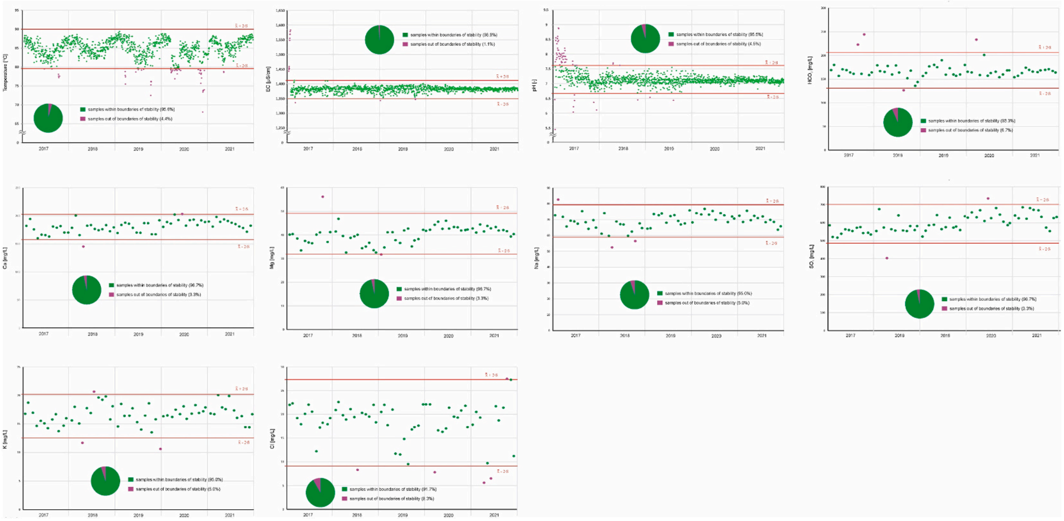


Fig. 7. Stability assessment (color online).

its recognition as geothermal waters in Poland. The assessment shows that the hydrogeochemical composition of the geothermal waters from the Chochołów PIG-1 borehole is stable and does not show any significant changes. The low variability of the basic hydrogeological and hydrochemical parameters determines undisturbed conditions of water use and stable operation of the Chochołowskie Termy complex. The presented procedure is an innovative approach to assessing the possibility of using geothermal waters in newly designed facilities, but it should also be carried out in existing facilities. It will reduce the risk of the investment, ensure undisturbed and stable operation and possible future projections of the investment. The authors hope that it will be implemented for widespread use and improve the operation of installations using geothermal waters.

CRediT author statement

Agnieszka Operacz: Writing-original draft; Writing-review & editing; Visualization, Conceptualization; Methodology; Investigation, Formal analysis, Supervision Agnieszka Zachora-Buławska: Writing-original draft; Writing-review & editing; Conceptualization; Methodology; Investigation, Formal analysis Zuzanna Gonek: Writing-original draft, Validation Barbara Tomaszewska: Investigation, Writing-review & editing Bogusław Bielec: Resources, Investigation Tomasz Operacz: Resources, Formal analysis; Investigation Jochen Bundschuh: Investigation, Writing-review & editing.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

References

[1] M.T. Islam, M.N. Nabi, M.A. Arefin, K. Mostakim, F. Rashid, N.M.S. Hassan, S.M.A. Rahman, S. McIntosh, B.J. Mullins, S.M. Muy, Trends and prospects of geothermal energy as an alternative source of power: a comprehensive review, Heliyon 8 (2022), https://doi.org/10.1016/j.heliyon.2022.e11836, 1-17.

[2] C.A. Vargas, L. Caracciolo, P.J. Ball, Geothermal energy as a means to decarbonize the energy mix of megacities, Commun Earth Environ 3 (2022) 1–11, https://doi.org/10.1038/s43247-022-00386-w.

[3] S. Mehmood, J. Lizana, D. Friedrich, Low-energy resilient cooling through geothermal heat dissipation and latent heat storage, J. Energy Storage 72B (2023), 108377, https://doi.org/10.1016/j.est.2023.108377.

[4] M. Vondra, Marek, J. Buzík, D. Horňák, M. Procházková, V. Miklas, M. Touš, Z. Jegla, V. Máša, Technology for hot spring cooling and geothermal heat utilization: a case study for balneology facility, Energies 16 (7) (2023) 2941, https://doi.org/10.3390/en16072941.

[5] E. Barbier, Geothermal energy technology and current status: an overview, Renew. Sustain. Energy Rev. 6 (2002) 3–65, https://doi.org/10.1016/S1364-0321(02)00002-3.

[6] H.K. Gupta, S. Roy, Geothermal Energy: an Alternative Resource for the 21st Century, Elsevier, 2006.
[7] B. Lindal, Industrial and Rother applications of geothermal energy, except power production and district heating, in: H.C.H. Amstead (Ed.), Geothermal Energy, Earth Sciences, UNESCO, 1973, p. 12.
[8] B. Igliński, R. Buczkowski, W. Kujawski, M. Cichosz, G. Piechota, Geoenergy in Poland, Renew. Sustain. Energy Rev. 16 (2012) 2545–2557, https://doi.org/10.1016/j.rser.2012.01.062.
[9] G. Vespasiano, G. Cianflone, M. Taussi, R. De Rosa, R. Dominici, C. Apollaro, CShallow geothermal potential of the Sant'Eufemia plain (south Italy) for heating and cooling systems: an effective renewable solution in a climate-changing society, Geosciences 13 (2023) 110, https://doi.org/10.3390/geosciences13040110.
[10] PGG, Ustawa Z Dnia 9 Czerwca 2011 R. Prawo Geologiczne I Górnicze (Dz.U. 2011 Nr 163 Poz. 981 Ze Zmianami), 2011. https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=wdu20111630981. (Accessed 1 August 2023).
[11] T. Sharmin, N.R. Khan, M.S. Akram, M.M. Ehsan, A state-of-the-art review on for geothermal energy extraction, utilization, and improvement strategies: conventional, hybridized, and enhanced geothermal systems, Int. J. Thermofluids 100323 (2023), https://doi.org/10.1016/j.ijft.2023.100323.
[12] A. Dashti, M. Gholami Korzani, Study of geothermal energy potential as a green source of energy with a look at energy consumption in Iran, Geoth. Energy 9 (2021) 28, https://doi.org/10.1186/s40517-021-00210-2.
[13] Z. Guzović, B. Majcen, S. Cvetković, Possibilities of electricity generation in the Republic of Croatia from medium-temperature geothermal sources, Appl. Energy 98 (2012) 404–414, https://doi.org/10.1016/j.apenergy.2012.03.064.
[14] A. Sowiżdżal, Geothermal energy resources in Poland–Overview of the current state of knowledge, Renew. Sustain. Energy Rev. 82 (2018) 4020–4027, https://doi.org/10.1016/j.rser.2017.10.070.
[15] M. Hajto, A. Przelaskowska, G. Machowski, K. Drabik, G. Ząbek, Indirect methods for validating shallow geothermal potential using advanced laboratory measurements from a regional to local scale—a Case study from Poland, Energies 13 (2020) 5515, https://doi.org/10.3390/en13205515.
[16] M. Yalcin, F. Sari, A. Yildiz, Exploration of potential geothermal fields using MAXENT and AHP: a case study of the Büyük Menderes Graben, Geothermics 114 (2023), 102792, https://doi.org/10.1016/j.geothermics.2023.102792.
[17] A. Operacz, J. Chowaniec, Perspectives of geothermal water use in the Podhale Basin according to geothermal step distribution, Geology Geophys. Environ. 44 (2018) 379–389, https://doi.org/10.7494/geol.2018.44.4.379.
[18] J. Benavides, P. Sharma, A. Al Saedi, S. Kabir, Techno-economic analysis of green energy resources for power generation & direct use by preserving near-wellbore geothermal gradient, Energy Sustain.e Dev. 74 (2023) 127–139, https://doi.org/10.1016/j.esd.2023.03.009.
[19] M. Soltani, F.M. Kashkooli, M. Souri, B. Rafiei, M. Jabarifar, K. Gharali, J.S. Nathwani, Environmental, economic, and social impacts of geothermal energy systems, Renew. Sustain. Energy Rev. 140 (2021), 110750, https://doi.org/10.1016/j.rser.2021.110750.
[20] K. Wątor, R. Zdechlik, Application of water quality indices to the assessment of the effect of geothermal water discharge on river water quality – case study from the Podhale region (Southern Poland), Ecol. Indicat. 121 (2021), 107098, https://doi.org/10.1016/j.ecolind.2020.107098.
[21] A. Sowiżdżał, A. Chmielowska, B. Tomaszewska, A. Operacz, J. Chowaniec, Could geothermal water and energy use improve living conditions? Environmental effects from Poland, Arch. Environ. Protect. 45 (2019) 109–118, https://doi.org/10.24425/aep.2019.127985.
[22] A. Operacz, B. Bielec, B. Tomaszewska, M. Kaczmarczyk, Physicochemical composition variability and hydraulic conditions in a geothermal borehole—the latest study in Podhale Basin, Poland, Energies 13 (2020) 3882, https://doi.org/10.3390/en13153882.
[23] E. Łukasiewicz, M. Shamoushaki, Heating potential of undeveloped geothermal water intakes in Poland in the context of sustainable development and air protection, Water Resour. Ind. 27 (2022), 100175, https://doi.org/10.1016/j.wri.2022.100175.
[24] W. Bujakowski, B. Bielec, M. Miecznik, L. Pająk, Reconstruction of geothermal boreholes in Poland, Geoth. Energy 8 (2020) 10, https://doi.org/10.1186/s40517-020-00164-x.
[25] W. Górecki, A. Sowiżdżał, M. Hajto, J. Jasnos, The latest results of geothermal projects in Poland, in: Proceedings European Geothermal Congress, 2013, pp. 1–9. Pisa, Italy, 3–7 June 2013.
[26] W. Bujakowski, B. Tomaszewska, M. Miecznik, The Podhale geothermal reservoir simulation for long-term sustainable production, Renew. Energy 99 (2016) 420–430, https://doi.org/10.1016/j.renene.2016.07.028.
[27] J. Chowaniec, P. Długosz, B. Drozdowski, S. Nagy, S. Witczak, K. Witek, Hydrogeological Documentation of the Thermal Waters of the Podhale Basin, Arch. CAG, Warszawa, 1997 (in Polish, non published).
[28] J. Chowaniec, Studies of Hydrogeology of the Western Part of Polish Carpathians, vol. 734, Bulletin of the Polish Geological Institute, 2009, pp. 1–98 (in Polish, English summary).
[29] B. Kępińska, J. Ciągło, Possibilities of use of the Podhale geothermal waters for balneotherapeutical and recreational purposes, Geologia 34 (2008) 541–559 (in Polish).
[30] J. Chowaniec, D. Poprawa, K. Witek, Occurrence of thermal waters in the Polish part of the Carpathians, Przeglad Geol. 49 (2001) 734–742.
[31] J. Chowaniec, B. Olszewska, D. Poprawa, J. Skulich, M. Smagowicz, Hydrogeological Documentation of Groundwater Resources - Thermal Waters. Chochołów PIG-1 Borehole, CAG Warszawa, 1992 (in Polish, non-published).
[32] A. Operacz, A. Zachora-Buławska, I. Strzelecka, M. Buda, B. Bielec, K. Migdał, T. Operacz, The standard geothermal plant as an innovative combined renewable energy resources system: the case from south Poland, Energies 15 (2022) 6398, https://doi.org/10.3390/en15176398.
[33] B. Bielec, A. Operacz, Newest recognition of exploitation parameters based on Chochołów PIG-1 borehole in the aspect of temperature effect, Ecol. Eng. 19 (2018) 145–152, https://doi.org/10.12912/23920629/99550.
[34] S.S. Shapiro, M.B. Wilk, An analysis of variance test for normality, Biometrika 52 (1965) 591–611.
[35] A. Stanisz, Accessible Course in Statistics Based on the Program STATISTICA PL on Examples from Medicine, vols. I-II, StatSoft Kraków, 2000 (in Polish).
[36] J. Szczepańska-Plewa, E. Kmiecik, M. Drzymała, Assessment of stability of curative waters chemical composition from Zdrój Główny in Krzeszowice, Bulletin of the Polish Geological Institute 436 (2009) 497–506.
[37] A. Ádám, Geothermal effects in the formation of electrically conducting zones and temperature distribution in the earth, Phys. Earth Planet. In. 17 (1978) 21–28, https://doi.org/10.1016/0031-9201(78)90046-8. ISSN 0031-9201.
[38] J.W. Lund, Development and utilization of geothermal resources, in: Proceedings of ISES World Congress 2007 (Vol. I–V) Solar Energy and Human Settlement, Springer Berlin Heidelberg, Berlin, Heidelberg, 2008.
[39] S. Arnórsson, Injection of Waste Geothermal Fluids: Chemical Aspects, Proceedings of the World Geothermal Congress, 2000.
[40] T. Riedel, Temperature-associated changes in groundwater quality, J.Hydrol. 572 (2019) 206–212, https://doi.org/10.1016/j.jhydrol.2019.02.059.
[41] N. Subba Rao, B. Sunitha, L. Sun, B. Deepthi Spandana, M. Chaudhary, Mechanisms controlling groundwater chemistry and assessment of potential health risk: a case study from South India, Geochem. (Tokyo. 1967) 80 (4) (2020), 125568, https://doi.org/10.1016/j.chemer.2019.125568.
[42] K. Kurek, A. Operacz, P. Bugajski, D. Młyński, A. Wałęga, J. Pawełek, Prediction of the stability of chemical composition of therapeutic groundwater, Water 12 (2019) 103, https://doi.org/10.3390/w12010103.
[43] A. Operacz, Variability of Basic Geothermal Water Parameters in Chochołów PIG-1 Borehole in the Western Part of the Podhale Basin, Infrastructure and Ecology of Rural Areas, 2018, pp. 961–972, https://doi.org/10.14597/INFRAECO.2018.4.1.066.
[44] A. Zachora-Buławska, Formal-legal-environmental aspects of using thermal waters on the example of the Chochołów PIG-1 borehole, Instal 446 (2022) 17–21, https://doi.org/10.36119/15.2022.12.3CRediTauthorstatement.