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Main Aspect of the Use of Shallow Groundwater as a Heat Source in Households

Aleksandra Szulc-Wrońska[1], Barbara Tomaszewska[1]

[1]AGH - University of Science and Technology, Faculty of Geology, Geophysics and Environmental Protection, Department of Fossil Fuels, Mickiewicza 30 Av., 30-059 Krakow

E-mail: aszulc@agh.edu.pl

E-mail: bts@agh.edu.pl

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ABSTRACT

The paper presents the main aspects of use groundwater as a heat source in households discussed on the example of Poland. In many regions of the world, shallow geothermal energy is commonly used in individual district heating systems. The low-temperature geothermal systems have significant potential for reaching the climate goals, sustainable regional development and low carbon economy – especially in urban areas with air quality problems.

The paper indicates the basic technical and legal framework as well as environmental aspects related to the energetic use of shallow groundwater. In addition, the use of the *Mleczarnia 1* intake includes an assessment of the possibility of using groundwater in heat pump systems in the area of the Rabka-Zdrój health resort located in the southern part of Poland. The conducted analyzes have shown that already at the design stage, many factors should be taken into account. Their appropriate selection of meeting the local geological, hydrogeological or environmental conditions, will ensure the correct and effective functioning of the entire installation. Based on the results obtained for the selected intake, it can be determined that there is a significant potential for using groundwater in low-temperature geothermal systems. However, the assessment of physicochemical parameters showed that the permissible concentrations of hydrogen sulfide indicated by manufacturers of heat pumps were exceeded. Therefore, it is recommended to use an intermediate heat exchanger before the heat pump, which will ensure safe operation of the installation during its operation.

1. INTRODUCTION

Since 2014, there has been an increase in household energy consumption in the EU member states. In 2017, it was the second largest sector in terms of total final energy consumption in the EU. The housing sector in the EU member states uses energy mainly for heating purposes. In 2017, energy consumption for heating homes accounted for 64% of final energy consumption, and 14.8% of energy was used for water heating. In the case of Poland, where the study area is located, these rates are respectively, 66% and 16.1%. The main energy carrier used for heating purposes in the EU is gas (43%) and renewables and wastes (23.4%). In turn, in the residential sector in Poland is dominated by solid fuels (44.6%) and derived heat (20.8%) (Eurostat, 2020). Therefore, the use of geothermal low enthalpy energy supported by heat pumps is an opportunity to create a sustainable heating sector and increase the energy efficiency of heating, cooling and preparation of domestic hot water in Poland residential sector, in which solid fuels currently dominate.

Direct utilization of geothermal energy worldwide is still increasing. The largest direct-use of geothermal energy is noted for geothermal heat pumps, bathing & swimming and space heating since 2005. Moreover, installed capacity and annual energy use in individual space heating and district heating has increased in 2020, respectively 68.0% and 83.8% compared to 2015 (Lund and Toth, 2020). In 2018, according to the structure of obtaining energy from renewable energy sources in Poland: solid biofuels (68.8%), wind energy (12.5%) and liquid biofuels (10.3%) are dominated. The lowest values were recorded for heat pumps (0.7%) and geothermal energy (0.3%) (Berent-Kowalska et al., 2019). Despite the low index obtained for heat pumps, the market for this technology has been dynamically developing for several years. The largest share in sales was recorded for air source heat pumps – around 60%. They are used for heating (10630 devices) and preparation of domestic hot water – 9840 devices (as of 2018). Ground source heat pumps (5380 devices) have a relatively large share. The lowest share in total sales in 2018 is characteristic for water/water heat pumps and is 0.2% (Lachman, 2019).

Groundwater heat pumps are characterized by the highest efficiency. Water is a stable source of heat all year round and is an excellent heat transfer medium. However, water/water heat pumps are rarely used in Polish households. Therefore, the purpose of this research is to examine the main aspect of the use shallow groundwater as a heat source in households.

2. DESIGN OF GROUNDWATER HEAT PUMP SYSTEMS

Households can use natural resources of groundwater as the primary source of heat, domestic hot water preparation and cooling of the building. Heating systems based on geothermal heat pumps powered by groundwater are characterized by high performance and efficiency. An additional advantage of using groundwater is its almost constant and relatively high temperature of 8-12 °C at a depth of 10-15 m below the ground level (Mania and Kawa, 2016). However, groundwater used as a low-temperature heat source must meet a number of requirements imposed by national and local law and heat pump manufacturers. Open loop low temperature systems using groundwater can be divided into single-well and double-well ones (Figure 1). In the case of single-well systems, groundwater is taken from the aquifer, and once heat is released in the heat pump, it is discharged to surface watercourses. These types of systems are rarely used due to high requirements for the quality of water discharged into surface waters. In addition, there is a risk of the groundwater depletion and the lowering of the water table (Wu et al., 2015). Double-well systems feature a production well and an injection well. The groundwater is taken from the production well via submersible pump and after its energetic use by the heat pump, the cooled water is sent back to the aquifer via the injection well. The injection well should be situated at an appropriate distance (depending on the hydrogeological conditions of the aquifer) from the production well and located in accordance with the groundwater flow. The groundwater level in the production well affects the efficiency of the system. Therefore, it should be remembered that the deeper the groundwater level is, the more energy the submersible pump will need to supply to the heat pump (Lee et al., 2006).

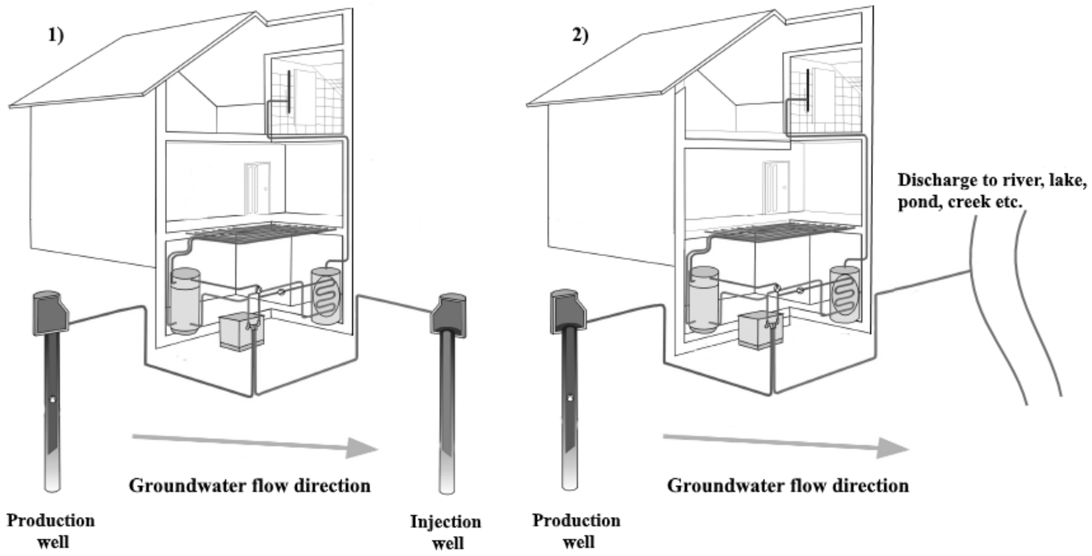

Figure 1: Open loop groundwater heat pump systems: 1) double well system; 2) single well system (based on *ogrzewamy.pl*).

The overview of main aspects related to the use of groundwater as a lower heat source was provided on the example of Poland. It was divided into three basic sections: 2.1 Technical requirements; 2.2 Legal framework; 2.3 Environmental aspects. Additionally, in order to extend the following analysis, an example of design of a low-temperature system supported by a water/water heat pump in a single-family house located in the southern part of the country is presented in the further part of the article.

2.1 Technical requirements

The basic condition for the possibility of using groundwater as a lower heat source for heat pumps are appropriate criteria regarding their quality and availability. The design of water heat pump installations must be adapted to the local geological and hydrogeological conditions. The main parameters that must be taken into account at the design stage include: groundwater temperature, aquifer yield and the quality of water taken. Groundwater temperature, due to technical requirements, should be in the range of 4 °C to 20 °C (VDI 4640 Part 2, 2019). Most heat pump manufacturers, however, recommend that the groundwater temperature should not be lower than 7-8 °C, due to the efficiency of the entire system (Dimplex, 2012, Hoval, 2018). In the case of existing wells, the temperature should be measured. In turn, for the planned wells, one should use the national hydrogeological database and refer to the nearest intake or locate a plot of land nearby that has a well with specific parameters that can be used for preliminary estimates. However, it is worth noting that the groundwater temperature is constant throughout the year at a depth of 10-15 m. In the case of shallow groundwater (i.e. < 10 m), seasonal water temperature variability should be taken into account. Another important issue is the availability of groundwater resources. The capacity of an existing or planned well must cover the heat and/or cooling demand of the building in question. What is more, the yield of the well must be confirmed with a pumping test. According to VDI 4640 Part 2 (2019), assuming a normal temperature spread (ΔT) in the heat pump of 3-5 K per 1 kW of evaporator capacity, the nominal flow is between 0.29-0.20 m^3/h.

The quality of groundwater depends on the natural factors prevailing in a given region and anthropogenic factors. Therefore, before starting the design of water/water heat pump systems, groundwater samples should be taken (from the existing well for which the investment is planned or, in the absence of it, from the well located closest to the investment in question) and a physicochemical analysis should be conducted in an accredited laboratory. The physicochemical analysis of groundwater should include the parameters recommended by heat pump manufacturers and legal requirements – depending on the type of installation, groundwater injection into the aquifer or its discharge to surface watercourses. The basic physicochemical parameters important for groundwater heat pump systems include: pH value, electric conductivity (EC), chloride (Cl^-), sulfate (SO_4^{-2}), carbon dioxide (aggressive free) ($CO_{2agg.}$), oxygen (O_2), ammonium (NH_4), iron (Fe), manganese (Mn), nitrate (NO_3^-), bicarbonate (HCO_3^-), hydrogen sulfide (H_2S) and aluminum (Al). The physicochemical parameters of groundwater have a significant impact on the proper functioning of the heat pump installation. Exceeding the concentration limits of chemicals can cause corrosion, scaling, encrustation and fouling problems that adversely affect individual components of the heat pump system (VDI 4640 Part 1, 2010, Wu et al., 2015).

2.2 Legal framework

The key European Union (EU) legislation on shallow geothermal energy is: Directive 2018/2001 on the promotion of the use of energy from renewable sources, Directive 2018/2002 on energy efficiency, Directive 2000/60/EC establishing a framework for Community action in the field of water policy, Directive 2006/118/EC on the protection of groundwater against pollution and deterioration (Directive EU 2018/2001, Directive EU 2018/2002, Directive 2000/60/EC, Directive 2006/118/EC). All EU Member States are required to incorporate the provisions of these Directives into their national law. In the case of heat pump installations based on groundwater, the most important legal grounds in Poland are: Water Law, Law on Providing Information on the Environment and Environmental Protection, Public Participation in Environmental Protection and on Environmental Impact Assessment, Environmental Protection Law, Geological and Mining Law, Construction Law, Spatial Planning and Development Law.

The Water Law Act regulates the issue of using groundwater to meet the needs of a household. According to its provisions, the intake of groundwater and the discharge of sewage into groundwater in an amount not exceeding an annual average of 5 m^3/day is a normal use of water and does not require any permits (according to the Polish law, groundwater used as a lower heat source in heat pumps injected into the aquifer is regarded as sewage). One does not bear any fees for the normal use of water. Exceeding the limit value for water abstraction or waste water discharge into groundwater requires Water Law permit. The Water Law permit for discharging sewage into waters is issued for a period not longer than 10 years, and in the case of special water use, for a period not longer than 30 years. The permit is also required for the construction of wells with a depth exceeding 30 m for the purpose of ordinary water use (Journal of Laws 2020, item 310, as amended).

Pursuant to the Law on the provision of environmental information and its protection, public participation in environmental protection and on environmental impact assessments, each project that may potentially affect the environment shall have a decision regarding environmental conditions (Journal of Laws 2020, item 283). Projects that can potentially have a significant impact on the environment include, inter alia, devices for which groundwater intake is not less than 10 m^3/h, devices that collect groundwater (not less than 1 m^3/h) from the same aquifer, if there are other devices collecting no less than 1 m^3/h and drilling for water supply, excluding underground water intakes with a depth of less than 100 m (Journal of Laws 2019, item 1839). In most cases, heating installations based on groundwater in single-family houses are not projects that may have a significant impact on the environment. The provisions of the Environmental Protection Law relate to one's liability for possible contamination of groundwater during works and drilling or at the stage of system use. Pursuant to the applicable provisions, whoever causes environmental pollution bears the costs of removing the effects of this pollution (Journal of Laws 2020, item 1219).

The Geological and Mining Law Act applies for drilling boreholes, and its requirements vary depending on the location of the well: within or outside the mining area. Importantly, the provisions of the Act do not apply to trenches and boreholes up to 30 m deep, as well as for the construction of groundwater intakes (up to 30 m) for the purposes groundwater abstraction in the amount not exceeding 5 m^3/day outside mining areas. In the case of boreholes up to 30 m located in the mining area and boreholes up to 100 m outside the mining area, a geotechnical site investigation plan should be prepared. For boreholes over 100 m, regardless of the location, it is necessary to prepare both a geotechnical site investigation plan and a mining works operation plan. The former includes description of the structure and hydrogeological conditions. It is necessary to observe the levels, perform the measurements of water flows, provide a pumping test, temperature and pressure measurements, as well as to take water samples for laboratory analysis (Journal of Laws 2020, item 1064).

The Construction Law Act states that the building permit is not required while installing heat pumps with an installed electrical capacity of no more than 50 kW and constructing groundwater intakes (Journal of Laws 2020, item 1333). According to the Spatial Planning and Development Law, the determination of the intended use of the land and the methods of land development and development conditions are determined by the local land development plan (Journal of Law 2020, item 293). At the investment planning stage, one should read the plan in detail and verify whether its provisions do not exclude the possibility of using groundwater as a lower heat source for heat pumps. The provisions that may potentially exclude the planned investment include, among others, restriction or prohibition of drilling and earthworks, geological works, location of investment in or near nature or landscape protection areas.

2.3 Environmental aspects

The main advantage of using groundwater heat pump systems is the positive impact on energy efficiency and the environment compared to heating systems based on coal, oil or gas. Professionally designed, constructed and properly operated installation based on water/water heat pumps results in minimal or negligible environmental impact. In fact, one should consider the potential risks arising from the use of groundwater in the shallow geothermal systems, both single- and double-well ones.

The use of single-well systems, in which the collected groundwater, after its thermal use, is not reintroduced into the aquifer, may lower the groundwater table, which in turn would result in the creation of a depression cone around the production well (VDI 4640 Part 1, 2010). As a result of a significant change in the level of the groundwater table, ground subsidence or rock movements may occur (Görz et al., 2017a, 2017b). Moreover, too much extraction of groundwater, exceeding the available natural resources of the aquifer, may lead to disturbance of the water balance, and in extreme cases to depletion of the aquifer. This type of system can represent a high risk factor for areas where multiple wells exist and operate.

Contrary to single-well systems, in double-well ones, the extracted groundwater is reintroduced into the aquifer. In such a situation, there is a risk of disturbances or thermal changes in the aquifer. Depending on the operating mode of the heat pump (heating, cooling), water with increased or reduced temperature enters the aquifer. Important factors influencing the possible formation and spread of thermal changes are hydraulic and thermal properties of the aquifer, its depth to the water table, thickness of the aquifer, distance between the production and injection wells, and the amount of energy introduced or taken from the system (Wu et al., 2015, Piga et al., 2017). Thermal changes can affect the porosity, the permeability of the aquifer, and chemical, physical and biological processes in groundwater. Increased water temperature (T > 25°C) affects redox processes, minerals solubility and precipitation, as well as the development of organisms. Currently used water/water heat pump systems operate in the range of 7-20 °C. While maintaining these conditions and proper operation of the entire system, there should be no problems related to the chemical properties of groundwater (Bonte et al., 2013, Possemiers et al., 2014, Malina and Bujak, 2017).

Both in single- and double-well systems, the risk of drilling boreholes should be taken into account. As a result of drilling works, groundwater contamination may occur, let alone the geotechnical problems related to the stability of the borehole. Life cycle assessment (LCA) can be an effective method in assessing the effectiveness of groundwater heat pump systems and their environmental impact. The most recent review of LCA of geothermal heating systems (Pratiwi and Trutnevyte, 2020) indicates the lack of LCA studies for groundwater based geothermal systems especially at shallow depths. Moreover, based on the available literature, it can be determined that about 50% of the negative environmental impact is caused by the heat pump operation process due to electricity consumption (Marinelli et al., 2019, Pratiwi and Trutnevyte, 2020). Additionally, Bayer et al. (2012) determined a minimum threshold for the seasonal performance factor (SPF), but only for ground source heat pumps below which greenhouse gas savings over the entire life cycle cannot be achieved. Taking into account the structure of heating the country, based mainly on coal, the authors of the article calculated the minimum SPF for Poland at the level of 3.8. In this context, too, there is a literature gap that needs to be filled for shallow geothermal systems based on groundwater. Summing up, in the context of LCA studies, the environmental impact can be assessed through the operation process of the installation as well as the electricity generation structure of the heat pump and its seasonal performance factor or coefficient of performance (COP).

3. EVALUATION OF THE POTENTIAL GROUNDWATER HEAT PUMP USE

3.1 Study area

The analysis of the possibilities of using water/water heat pumps was conducted for the health resort town of Rabka-Zdrój, located in the southern part of Poland (Figure 2). For years, the commune has been struggling with the problem of air pollution, which mainly results from the combustion of coal in households. The commune is located in the Rabczańska Valley, surrounded by the mountain ranges of the Island Beskid and the Gorce Mountains. The topography significantly reduces the occurrence of wind, which exacerbates the problem of air quality and often results in the phenomenon of low emission (understood as the emission of harmful substances introduced into the air by emitters located at a height of 40 m), especially in the autumn and winter period. The solutions based on alternative energy sources, which can replace the existing heating devices, i.e. coal boilers, provide an opportunity to improve air quality.

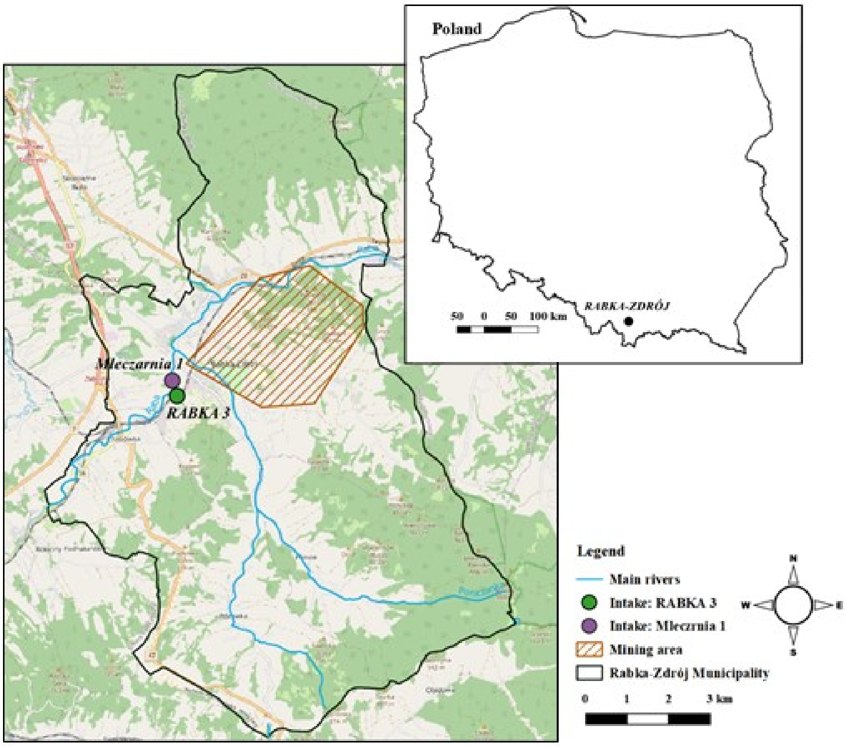

Figure 2: Location of the study area.

3.2 Methods

In order to assess the possibility of using a heat pump installation based on groundwater, the information obtained from the Central Hydrogeological Database on groundwater intakes in the selected research area was used (Polish Hydrogeological Survey, 2019). The *Mleczarnia 1* intake located in the north-western part of the commune near the Raba River was selected for a detailed analysis (Figure 2). Due to the available incomplete physicochemical analysis of the waters of the *Mleczarnia 1* intake, it was decided to use own data. It was obtained in October 2018 from a private intake (*RABKA 3*) located 300 m south of the selected intake and using the same aquifer. For the selected intake, the thermal power was estimated based on the formula (Buczyński, 2010):

$$Q_{geot} = Q_w \cdot \rho_w \cdot c_w \cdot (T_w - T_z) \quad (1)$$

where Q_{geot}, Q_w, ρ_w, c_w, T_w, T_z are heat power of intake [kW], efficiency of intake [m^3/s], water density (set as 1000 kg/m^3), specific heat of water (set as 4,19 kJ/(kg·°C)), water temperature at the head (°C), the temperature of cooled water (temperature at the outlet of the heat pump) (°C), respectively.

The analysis of the physicochemical parameters of groundwater from the *RABKA 3* intake was performed in the accredited Hydrogeochemical Laboratory of the Hydrogeology and Engineering Geology Department of the AGH University of Science and Technology in Krakow (PCA accreditation certificate No. AB 1050). The physicochemical parameters of groundwater were assessed in terms of the possibility of its direct use in the installation of a water/water heat pump. The assessment was based on requirements of heat pump manufacturers (Viessmann, 2017, Vaillant, 2020), the Regulations of the Minister of Health on the quality of water intended for human consumption (RMH) (Journal of Law 2017, item 2294) – single-well systems, the Regulations of the Minister of Marine Economy and Inland Navigation on the conditions to be met when discharging sewage into waters or into the ground and on substances particularly harmful to the aquatic environment (RMMEIN) (Journal of Law 2019, item 1311) – double-well systems.

3.3 Results

A Quaternary aquifer was found in the borehole, composed of sandstone and gravel river sediments. The thickness of the aquifer is 4.8 m, and the intake reaches the capacity of 8.1 m^3/h. The groundwater table stabilizes at a depth of 5.2 m. The water temperature was 14.4 °C. It should be emphasized that groundwater is taken from shallow layers and temperature fluctuations throughout the year should be expected. Based on data from another shallow intake located in the Rabka-Zdrój commune, it can be concluded that the temperature of the outflow waters will vary between 6.0 °C and 18.0 °C. The estimated intake thermal power is 47.1 kW, which would cover the demand for heat and domestic hot water for four households with an area of 150 m^2 inhabited by 4 people.

The results of the physicochemical analysis are error-burdened, calculated according to the ion balance at the acceptable level of 1.88%. Characteristics of physicochemical parameters with limit values are presented in Table 2. The underground water from the *RABKA 3* intake meets the requirements of RMH, which means that in the case of single-well installations, it can be used for household purposes, e.g. watering the garden or direct human consumption. The basic physicochemical parameters also do not exceed the limit values specified in RMMEIN, so there are no contraindications for re-introducing water into the aquifer with via a dry well. The analyzed groundwater, however, does not meet the requirements specified by heat pump manufacturers. A high value of electric conductivity (834 µS/cm) indicates an increased mineralization of the water, which for the manufacturer of the Viessmann heat pumps means that the limit value has been exceeded. Additionally, the permissible concentration of hydrogen sulfide (H_2S), which is one of the main causes of corrosion of metals, was exceeded for the manufacturers in question. The analysis below shows that nickel brazed exchangers are more resistant than copper brazed ones. Taking into account the guidelines of heat pump manufacturers, in the case of the considered intake, an intermediate heat exchanger should be used before the heat pump in order to ensure correct and effective operation of the entire system.

Table 1: Characteristics and limit values of physicochemical parameters of groundwater (based on: Viessmann, 2017, Vaillant, 2020, Journal of Law 2017, item 2294, Journal of Law 2019, item 1311).

Parameter	Result	Unit	VIESSMANN			VAILLANT		RMMEIN		RMH	
			Limit values	evaluation of the results – Plate heat exchanger		Limit values	evaluation of the results – Plate heat exchanger	Limit values	evaluation of the results	Limit values	evaluation of the results
				copper	stainless steal		Nickel[4]				
pH	7.10	[-]	< 7.5	◑[2]	◑	6.0-7.5	◑	6.5-9.0	●	6.5-9.5	●
EC	834.00	[µS/cm]	> 500	○	◑	> 500	●	un.[5]	–	≤ 2500	●
Cl^-	41.30	[mg/dm^3]	< 300	●[1]	●	< 300	●	≤ 1000	●	≤ 250	●
SO_4^{-2}	33.29	[mg/dm^3]	< 70	●	●	< 70	●	≤ 500	●	≤ 250	●
$CO_{2agg.}$	0.00	[mg/dm^3]	< 5	●	●	< 5	●	un.	–	un.	–
NH_4	0.06	[mg/dm^3]	< 2	●	●	< 2	●	≤ 10	●	≤ 0.5	●
Fe	0.06	[mg/dm^3]	< 0.2	●	●	< 0.2	●	≤ 10	●	≤ 0.2	●
Mn	0.007	[mg/dm^3]	< 0.1	●	●	< 0.1	●	un.	–	≤ 0.05	●
Al	0.005	[mg/dm^3]	< 0.2	●	●	< 0.2	●	≤ 3	●	≤ 0.2	●
HCO_3^-	452.30	[mg/dm^3]	> 300	◑	◑	> 300	●	un.	–	un.	–
O_2	5.24	[mg/dm^3]	> 0.2	◑	●	> 2	●	un.	–	un.	–
H_2S	0.12	[mg/dm^3]	> 0.05	○[3]	◑	> 0.05	○	un.	–	un.	–
NO_3^-	0.80	[mg/dm^3]	< 100	●	●	< 100	●	≤ 30	●	≤ 50	●

[1] [●] - the material has normally good resistance; [2][◑] - corrosion can occur if several factors are evaluated with ◑ ”; [3][○] - not recommended to use; [4] Nickel values are the definitive limit values as the groundwater station features a nickel brazed stainless steel plate heat exchanger; [5] un.- undefined.

In the field of spatial development of a commune, the binding document is the Study of conditions and directions of spatial development of the commune of Rabka-Zdrój (Resolution No. XXXV/255/01). The area where the intakes are located has been classified as an area with a predominance of general urban and settlement functions. Currently, consultations on the project of the Local Development Plan are in progress, in which the zone in question will be intended for service and single-family housing construction. There are no restrictions on the use of low-temperature geothermal energy in any of the mentioned documents/projects. In Rabka-Zdrój, due to the presence and exploitation of healing waters, a mining area has been designated, however, the *Mleczarnia 1* and *RABKA 3* intakes are outside its reach. Taking into account the location of the boreholes outside the mining area and the shallow presence of groundwater (wells up to 30 m), the provisions of the Geological and Mining Law will not apply here. Moreover, when using groundwater in a heat pump installation for a single-family house (heat pump power not exceeding 50 kW), obtaining a building permit is not required in accordance with the Construction Law. However, the abstraction of groundwater will certainly exceed the limit value for normal water use, i.e. 5 m^3/day, so it will be necessary to obtain Water Law permit.

4. CONCLUSION

The assessment of the main aspects of the use of groundwater as a lower heat source in installations supported by heat pumps, presented in the paper, showed that many factors related to technical requirements, legal conditions and the potential environmental impact of the entire system should be taken into account already at the design stage. For the initial assessment of the suitability of groundwater for energy purposes, both geological, hydrogeological and thermogeological conditions should be taken into account.

It should be emphasized, that groundwater is the thermally stable heat source used in heat pump house heating systems. The possibility of utilization the local groundwater resources depends on: water flow rates, physicochemical composition, water temperature and depth of aquifers. The high estimated thermal power (47.1 kW) and efficiency (8.1 m^3/h) of the studied area have a potential for using groundwater in low-temperature geothermal systems. The analysis showed that Quaternary groundwater have various physiochemical composition and should be constantly monitored. Moreover, the groundwater has been classified as aggressive and potentially corrosive. For that reason, it is recommended to use an intermediate heat exchanger. Furthermore, the use of groundwater as a heat source has an environmental effect compared to a coal-fired boiler.

Due to the need to meet many legal procedures, develop mandatory documentation, and obtain necessary permits, which additionally require a lot of time from the investor, in Poland the use of groundwater heat pump systems is much less popular than ground source heat pump systems. The scheme of conduct presented in this article for the analysis of the possibility of using groundwater in the installation of heat pumps can be successfully used in other areas of the country.

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