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THE FRESH WATERS OF THE KRAKOW REGION AS THE LOWER SOURCE FOR HEAT PUMPS**

1. INTRODUCTION

Krakow is a city that due to its location (in the basin), buildings blocking air ducts and meteorological conditions (a large number of windless days) has problems with air pollution.

Particularly big problems occur during the heating season, as some residents heat their houses with solid fuel stoves. The use of these furnaces causes the dust and gas pollution. Car traffic is another factor greatly influencing air quality. It is a source of exceedances of nitrogen dioxide, but also contributes to the formation of dust pollution.

Currently, measures are being taken to improve the quality of air, for example, through the exchange of old non-ecological coal furnaces, household checks and compliance with the ban on waste burning as well as activities in the sphere of traffic organization. The ban on solid fuels, which will come into force on the 1st of September 2019, will also be an important step in the fight for clean air.

Solid fuels may be replaced by natural gas or energy from renewable sources, including low temperature geothermal energy. Low-temperature geothermal energy can be exploited from a shallow rock mass or groundwater using heat pumps.

The article proposes the use of thermal energy accumulated in groundwater in Krakow area in heat pump installations. For this purpose, the water temperatures and thermal powers that can be obtained from existing groundwater intakes have been estimated.

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Based on the results of analyzes performed at the chemical monitoring points, the physical and chemical properties that influence the possibility of using these waters as a source in heat pumps were analyzed.

2. GEOLOGY AND HYDROGEOLOGICAL CONDITIONS OF THE KRAKOW REGION

Geology

The Krakow agglomeration is located within three regional geological units: the Silesian-Krakow Monocline, the Miechów Trough and the Carpathian Foredeep [35].

The oldest rocks in the area of the Silesian-Krakow Monocline are Permian sandstones and conglomerates. Above them lie the sandy-clay deposits of the Lower Triassic, dolomite-lime-marly deposits of the Middle Triassic and the Upper Triassic clays. The Middle Jurassic is represented by sands, sandstones and conglomerates. The Upper Jurassic is represented by marly-limestone sediments. Middle Oxfordian is represented by platy limestones, the Oxfordian – massive limestones [23, 24]. The Pleistocene sediments are composed by clays and glacial sands, silts and clastic silts, river and glacier sands as well as river sands and gravels [19].

In the Miechów Trough in the basement there are Paleozoic rocks of the Miechów–Rzeszów region. The trough is filled with Upper Cretaceous deposits – marls, sands and sandstones, and rocks with sandstone inserts. In the southern part of the trough, the Cretaceous rocks fall under the Miocene deposits. The thickness of the Upper Cretaceous rocks in the Krakow region is 25 m, while in NE the part of the Miechów Trough reaches 600 m.

In the area of the Carpathian Foredeep, the oldest rocks appearing on the surface are Upper Jurassic limestones with many silica concretions [1]. Above these rocks lies the complex of clastic silt-sand Miocene sediments that fill the Carpathian Foredeep [29, 31]. Miocene deposits in Krakow area are located at depths of 10 m to 30 m [35], their thickness depends on the basement morphology. In the elevations, the thickness is reduced, while in the hollows the thickness is from about 40 m to about 70 m [37].

Quaternary deposits fill the Vistula's pradoline. They form a series of terraces and alluvial fans of Prądnik and Rudawa [7]. These are mainly alluvial sand-gravel deposits and fluvioglacial: sands, gravels, clays, organic muds and loams of water-glacial genesis, alluvial and aeolian. Loesses (Vistulian Glaciation) is covered by slopes and horsts as well as sand deposits of the terrace of the middle Vistula valley [7]. The thickness of the Quaternary deposits ranges from 10 m to 20 m, and in river valleys even up to around 30 m [37].

There are two structural stages in the Krakow area. The Variscan stage includes Devonian and Carboniferous rocks, which were tectonized during the Variscan orogenic cycle [42]. Permian and Mesozoic rocks were tectonized during the Alpine cycle, they caused a monoclinic deflection towards ENE of a sheet built from the deposits of both stages and cutting it with faults. Presumably, the early Miocene movements led to the formation of horsts and depressions [9]. Most of the horsts are made of the Upper Jurassic rocks exposed on the surface, less often the Upper Cretaceous rocks. The depressions fill the Miocene deposits [13, 36].

Hydrogeological conditions

In the Krakow agglomeration there are four aquifers (Tab. 1): Quaternary, Tertiary, Cretaceous and Jurassic [4, 18].

Table 1

Characteristics of aquifers in the Krakow region [4, 7]

Aquifer	Lithology	Permeability coefficient [m/d]	Transmissivity [m^2/d]	Potential discharge of a well [m^3/h]	Renewable resources module [$m^3/d \cdot km^2$]	Disposable resources module [$m^3/d \cdot km^2$]
Upper Jurassic	Massive and platy limestones	$2 \cdot 10^{-4}$–121	1–200	< 10–50	372	223
Upper Cretaceous	Marls, opoka, limestone, sandy and marly limestones, conglomerates	$3.5 \cdot 10^{-2}$–115	1–400	10–70	337	202
Neogene	Sands, sandstones	0.5–6.9	< 100	4.4–218	372	149
Quaternary	Sands, sands with gravels, gravels	8.6–17.2	0.5–24	10–70	372	223

The Jurassic multiaquifer formation is associated with cracked and partially karsted Upper Jurassic limestones. Mesozoic rocks are cut by faults, so the Upper Jurassic limestones do not form a uniform aquifer. It is possible to distinguish a series of separate hydrostructures in which the groundwater table occurs at different depths. Water flow between individual structures is possible. Waters circulation in the Upper Jurassic aquifer depend on morphology, tectonics and coverage of low-permeable rocks [34]. The underground waters in the Jurassic aquifer flows from the upland (watershed zones) towards the river valleys. The location of the water table is strongly dependent on the amount of precipitation. This aquifer is drained by numerous springs [8]. In the area of the Jurassic limestones outcrops are recharged by precipitation infiltration. The infiltration coefficient is high due to the occurrence of karst phenomena and fissures in the surface zone. The waters of the Upper Jurassic aquifer in the outcrop areas (no isolation) are exposed to pollution, which may adversely affect their quality. It is particularly visible in the region of Krakow-Podgórze and Krowodrza [7, 25]. In cases of isolation of Jurassic waters by Miocene clays, there are some artesian or sub-artesian waters, often with increased mineralization [18]. The system of circulation in depressions under the Miocene cover is complicated. Local groundwater in the western and north-western part of the Krakow agglomeration are usually found in several water wells, so-called Krakow spa.

The Cretaceous aquifer is associated with Senonian cracked marls and opoka as well as Cenomanian and Turonian organodetrital and sandy limestones and conglomerates. The thickness of the Cretaceous aquifer ranges from a few meters in the western part of Krakow to 40–50 m in the north-eastern part of the city [18, 35]. Cretaceous deposits form a multi-layer underground water reservoir of the slit type. The recharge of the Upper Cretaceous aquifer takes place mainly through infiltration of precipitation directly on outcrops or through Quaternary deposits. Presumably, a portion of the water flows, as a matter of course, from the Upper Jurassic limestones to higher-lying Upper Cretaceous deposits. The water-bearing chalky is drained with numerous springs and surface water-courses [8]. The area of occurrence of the Cretaceous aquifer is part of the major groundwater basin (GZWP) No. 409 – Niecka Miechowska SE [14].

In the area Neogene aquifer only sands within the Bogucice layers (Bogucice sands) occurring in the eastern part of Krakow are useful aquifer. This area is a fragment of GZWP No. 451 – Bogucice Subzbiornik [14]. The water-bearing level is formed by sandy, sand and sandstone deposits with a thickness of 5 to 60 m, locally over 100 m. Recharge the Bogucice sands takes place mainly through infiltration of precipitation on outcrops. A subordinate role in recharge this aquifer is the seepage of waters from the Quaternary floor and the lateral recharge of waters from the Jurassic aquifer [27]. In addition to outcrops, the waters are protected against pollution by an insulating clay complex and have favorable physico-chemical properties [20]. The GZWP No. 451 – the Bogucice Sub-reservoir [14, 27, 39], was distinguished within the Neogene aquifer associated with the Bogucice Sands.

Within the Quaternary aquifer the most important is the Pleistocene aquifer associated with the Vistula's pradoline [7, 17]. Groundwaters occur in gravel and sandy deposits, most often underlain by impermeable Miocene clays, locally by Jurassic or Cretaceous deposits. Quaternary groundwater formations in the Vistula Buried Valley and within the Prądnik fan reach a thickness of up to several meters, while the smallest thickness have deposits of the contemporary Vistula alluvial channel. The Quaternary aquifer is recharge by direct infiltration of rainwater and lateral or ascending inflow from the Jurassic and Cretaceous aquifer. In a natural way, the Quaternary aquifer is drained by rivers and streams, and artificially by exploitation and drainage wells [4].

The groundwaters of Jurassic deposits are characterized by a very diverse chemical composition, which is influenced by geological conditions (tectonics and lithology of Miocene deposits). In the area of Krakow, the mineralization of Jurassic waters ranges from 410 to 4290 mg/L. The general hardness varies from 4.6 to 11.6 mval Ca/L, iron content from 0.3 to 2.4 mg/L, and manganese from 0.1 to 23.0 mg/L. These are mainly HCO_3-Ca-Mg and HCO_3-Ca type water [7, 20]. The quality of Jurassic waters varies from good to bad [7]. Usually, however, these are medium-quality waters. In the case of their limited exchange, they are characterized by increased mineralization. This group includes water exploited by the Krakow spa [18]. Cretaceous waters have a mineralization of 430–900 mg/L and a total hardness of 6.6–19.6 mval Ca/L. They contain small amounts of iron, occasionally up to 2.1–3.2 mg/L. Most often they are of the HCO_3-Ca-Mg type [7].

The groundwaters of the Neogene aquifer (Bogucice sands) are characterized by low mineralization from 160 to 880 mg/L and average general hardness. They are of the HCO_3-Ca-Mg type. In the Paleogene sands and in the Miocene limestones, covered with Miocene clays. These are SO_4-Cl-Na-Mg-Ca waters with H_2S content and mineralization of approx. 2.5 g/L [3, 17, 18, 40, 41]. On the southern part of the city, groundwater is found in the Miocene gypsum series and is of the SO_4-HCO_3-Ca-Mg type with a significant content of H2S and mineralization of approx. 2.5 g/L [15].

Mineralization of underground waters of a Quaternary aquifer is very spatially and seasonally differentiated. The dry residue varies from approx. 0.2 to over 2 g/L [16]. The predominant are multi-ionic waters, usually four- and five-ion: HCO_3-SO_4-Ca-Na, SO_4-HCO_3-Ca-Na and HCO_3-SO_4-Ca-Mg. These waters have different contents of iron and manganese, chlorides, sulphates, hardness and ammonium nitrogen [7, 16].

3. POSSIBILITIES OF HEAT RECOVERY FROM FRESH WATERS IN THE KRAKOW REGION

Heat accumulated in shallow parts of the rock mass can be used by means of low-temperature geothermal systems based on heat pumps. Geothermal heat pumps as the lower source can use energy accumulated in soil or in groundwater.

Groundwaters in the Krakow area can be used as a source of heat for geothermal heat pumps. The main factors determining the possibility of geothermal energy recovery are: natural environmental conditions, technologies of its use and economic conditions. The thermal power of the shot used as the bottom source in the heat pump is the basic parameter that determines the possibility of using it for heating purposes. Its size depends on the coefficient of performance of the heat pump and geological factors – the temperature of underground water and the discharge of water intakes.

Analysis included waters in 1462 groundwater intakes located in Krakow. About half of the intakes are active or periodically active (718), the remaining intakes are liquidated or inactive (413) or emergency (266). Most of the intakes are intended for exploitation (1037), the remaining are research approaches (76), piezometers (235), drainage (76) and environmental protection (2). These shots were made in the years 1964–2011. The shots have a diversified total depth from 1 to 396 m. The smallest depth up to 10 m has 144 views, the depth in the range of 10–50 m has 1200 shots, depth above 50 m has 77 shots. The stabilized water table lies at a depth of –44.2 m above sea level. to 18.5 m above sea level, the average depth of the mirror is –6.55 m above sea level.

To determine the thermal power of individual intakes, it is necessary to know their operational parameters, including the temperature of groundwater at a given depth. A pattern was used to estimate the water temperature [30]:

$$T = t_{av} + A + \frac{H - h}{g}$$

where:

T – water temperature at depth H [°C],

t_{av} – average annual air temperature [°C],

A – constant depends on the altitude above sea level [°C],

H – the depth of water [m],

h – depth of constant temperature zone [m],

g – geothermal degree [m].

The average annual air temperature in 1981–2010 for the city of Krakow was 8.5°C [43]. The constant dependent on altitude is from 0.8 for a height of 0 m. up to 3.0 for 2500 m. was adopted individually depending on the ordinate on which the shot lies [30]. The depth of occurrence of water for individual intakes was adopted on the basis of data from the National Geological Archives of PGI-NRI in Warsaw. The depth of the constant temperature zone is based on literature data and it is 10 m [11], while the geothermal stage is about 45 m [22].

Groundwater temperatures in Krakow range from 7.87 to 9.36°C (Fig. 1). The average water temperature is at the level of 8.5°C, while the median temperature is 8.45°C (Tab. 2). Most water temperatures have values above the average (8,5°C), which is evidenced by the skewness at 1.13 and the occurring right-side asymmetry. Most of the estimated temperatures are close to the average (kurtosis 4.14).

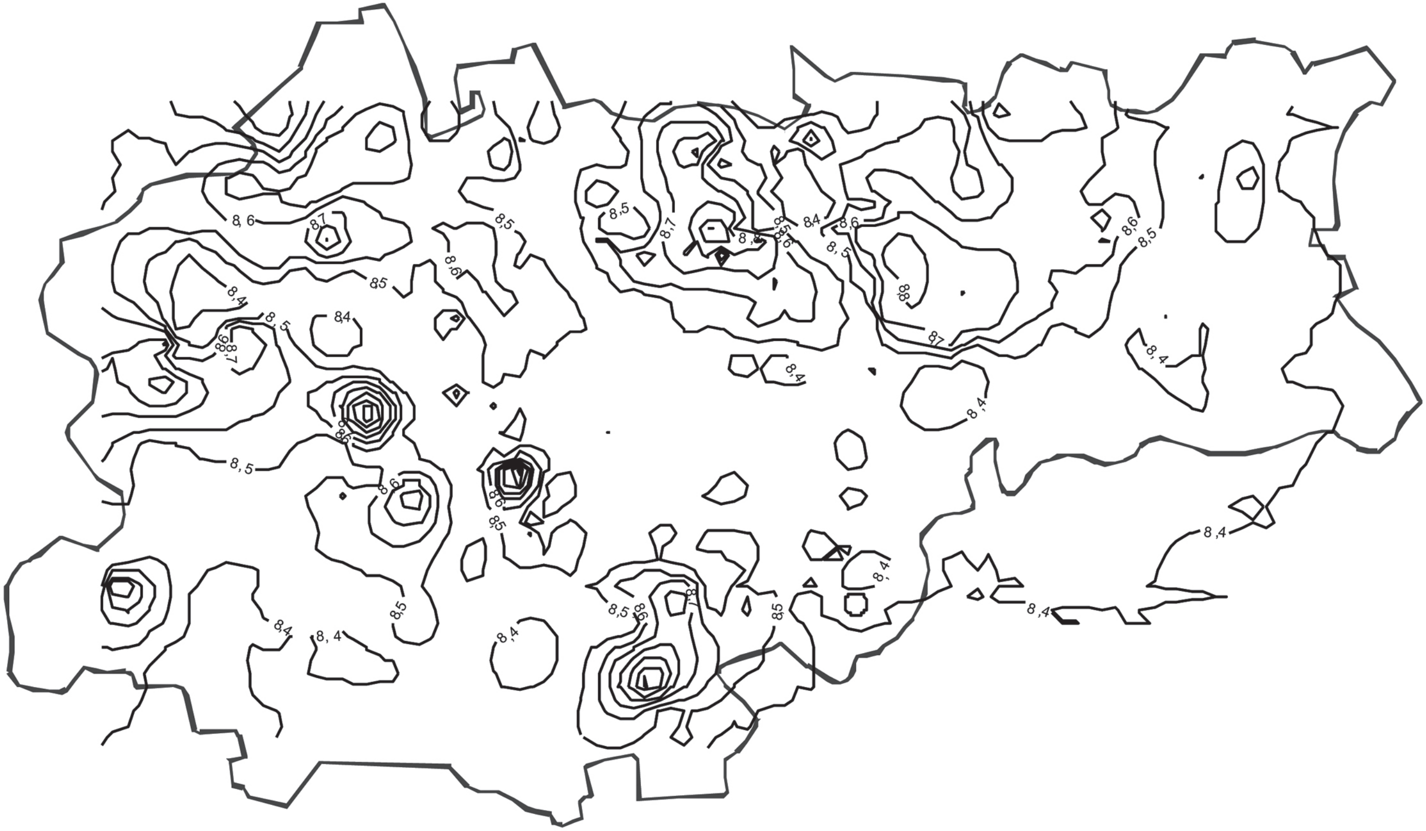

Fig. 1. Distribution of groundwater temperatures in the Krakow region

Table 2

Descriptive statistics of the temperature of groundwater
and intake thermal power in the Krakow region

Statistical parameter	Water temperature [^{o}C]	Intake thermal power [kW]
Mean	8.497251	88.30455
Median	8.455242	64.84857
Standard deviation	0.139468	93.43763
Kurtosis	4.141557	33.32061
Skewness	1.133654	4.064431
Range	1.491333	1 117.641
Minimum	7.866667	0.39382
Maximum	9.358	1 118.035
Number	1 572	1 033

Thermal power possible to obtain from individual intakes was calculated on the basis of the following formula [2]:

$$Q_{geot} = Q_W \cdot \frac{1}{3600} \cdot 1000\ \text{kg/m}^3 \cdot 4.19 \cdot (T_W - T_s)$$

where:

Q_{geot} – well thermal power [kW],
Q_W – water discharge [m^3/h],
T_w – water temperature at the head [°C],
T_s – temperature of cooled water [°C].

The thermal power of the intakes ranges from 0.394 to 1108.035 kW, the average power is on the order of 88.305 kW (Tab. 2). The majority of estimated thermal outputs possible to obtain from underground water intakes in Krakow have values above average, which is evidenced by skewness at 4.06 and the occurring right-side asymmetry. Most of the estimated thermal outputs have a value close to the average (kurtosis 33.32).

In low-temperature geothermal systems based on groundwater as heat sources, water chemistry can affect system operation. The main problems are related to scaling or corrosion [21, 33]. Scaling or precipitation of water sediments (silicates, carbonates, sulphates and metal oxides) can cause the installation to colmatise. Precipitation may occur at hardness above 100 mg/L ($CaCO_3$), and becomes a serious problem above

200 mg/L. Scaling increases with increasing calcium, hardness, alkalinity, pH and temperature [32].

Corrosivity of water is determined inter alia by the content of chlorides, sulphates and nitrates, carbonate hardness (alkalinity), total water hardness, pH, mineralization, proper electrolytic conductivity, pressure, dissolved gas content (O_2, H_2S, CO_2), anaerobic bacteria content and others [26, 28, 33].

According to pump manufacturers' recommendations, physical and chemical parameters of waters should be within specified limits, which depend on the type of material (copper or stainless steel) from which heat exchangers are made [6, 38]. One of the factors that significantly affect the corrosivity is the reaction of water, H^+ ions intensify this process. The risk of corrosion is lowest when the pH is maintained between 7.5 and 9.0 [10, 38]. In the case of steel, exposure to corrosion exists at $pH < 7.5$. For both steel and copper exchangers, the general hardness should be in the range 4.0 to 8.5 deg. H. Electrolytic conductivity indirectly indicates the total content of ions (water mineralization). The greater the conductivity, the greater the risk of corrosion. In the case of copper installations, the water must not have the greater electrolytic conductivity than 500 μS/cm or less than 10 μS/cm. The content of bicarbonate ions does not affect the corrosion exposure of stainless steel exchangers. In the case of copper exchangers, if HCO_3 concentration in water is low (< 70 mg/L), copper corrosion products are dissolved and released. In the case of copper exchangers, it is also recommended not to increase the HCO_3 concentration above 300 mg/L.

High concentration of sulphates increases the risk of pitting corrosion in copper pipe. For use in heat pumps water with SO_4^{2-} content above 300 mg/L is not suitable. When using copper, SO_4^{2-} content in water used in heat pump installations should be less than 70 mg/L. When using copper exchangers, the SO_4^{2-}/HCO_3^- ratio, which should not be greater than 1.0, is also taken into account. The concentration of ammonia (NH_3) above 2 mg/L in water indicates the possibility of corrosion in copper exchangers. The presence of chlorides in water increases the risk of local corrosion in stainless steel. The limit value depends on the temperature, for temperatures below 60°C a value below 300 mg/L is recommended. The content of aluminum and iron above 0.2 mg/L, manganese above 0.1 mg/L and nitrates above 100 mg/L may cause corrosion in copper exchangers [38].

The recommendations of the Viessman pump producer [38] regarding 11 chemical parameters were analyzed and compared with published data on the quality of water from the Quaternary and Jurassic aquifers in the Krakow region (Tab. 3). The collated data show that copper has a lower corrosion resistance than stainless steel. The wide ranges of points that apply to all the presented parameters indicate that corrosion and scaling is possible during the operation of the systems. However, it does not mean that in the studied area not all waters will be characterized by chemistry, excluding the use of heat pumps. Nevertheless, the analyzed data indicate that before starting the system it is necessary to analyze the composition of water quality from the used intakes and consider the use of exchangers.

Table 3

Physicochemical parameters of groundwaters in Krakow region characterizing corrosion resistance [38]

Parameter	Good resistance under normal conditions		Groundwaters in Krakow area	
	Stainless steel	Copper	Quaternary aquifer [12]	Jurassic aquifer [5]
HCO_3^- [mg/L]	0	70–300	101–987	–
SO_4^{2-} [mg/L]	< 300	< 70	112–713	171–332
SO_4^{2-}/HCO_3^- [weight]	0	> 1.0	0.33–2.66	–
NH_3 [mg/L]	0	< 2	–	0.0–2.8
Cl^- [mg/L]	< 300	< 300	24–2800	53–98
Fe [mg/L]	0	< 0.2	0.005–23.540	0.6–4.0
Mn [mg/L]	0	< 0,1	< 0.001–2.21	<0.05–0.03
NO_3^-	0	< 100	< 0.5–61.60	0.04–4.53
Total hardness [°dH]	4.0–8.5	4.0–8.5	0.005–25.41	8.96–26.82
pH	> 6.0	7.5–9.0	6.64–8.53	7.2–8.2
Conductivity [µS/cm]	0	10–500	952–9120	979–1329

* ranges of values of selected parameters characterizing corrosion resistance based on data from published papers on groundwater chemistry in Krakow

4. SUMMARY

Analysis of water parameters available in the intakes in Krakow showed that there is the possibility of using thermal energy contained in groundwater. Water temperatures in the range of 7.87–9.36°C allow to obtain thermal outputs from 0.395 to 1108.035 kW.

Analyzing published data on groundwater chemistry in the Krakow region and comparing them with the recommendations of heat pump manufacturers indicates that the use of water as a lower heat source may in some cases cause technical problems and it may be necessary to use preliminary exchangers.

The use of groundwater as the lower heat source in heat pump installations requires a detailed recognition of water chemistry.

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