International Journal of Heat and Technology
Vol. 44, No. 2, April, 2026, pp. 461-469
Journal homepage: http://iieta.org/journals/ijht

The Impact of Input Parameters on the Thermal Power of Shallow Geothermal Systems: A Case Study of Kielce, Poland

Edyta Nartowska*, Izabela Trybek

Faculty of Environmental Engineering, Geomatics and Renewable Energy, Kielce University of Technology, Kielce 25-314, Poland

Corresponding Author Email: enartowska@tu.kielce.pl

https://doi.org/10.18280/ijht.440202

Received: 20 January 2026
Revised: 28 March 2026
Accepted: 7 April 2026
Available online: 30 April 2026

Keywords:
shallow geothermal systems, thermal power estimation, groundwater temperature, heat pump systems, parameter selection

ABSTRACT

The objective of this study is a new assessment of the impact of input parameter selection on thermal power estimation in shallow geothermal systems using groundwater heat pumps. The study focuses on site-specific conditions in Kielce, Poland. The methodology involves a comparative analysis of multiple calculation approaches. Particular emphasis was placed on the influence of groundwater temperature at the intake depth and on the temperature of the cooled water after heat extraction. A case study of groundwater intakes in Kielce was conducted using archival data from the Polish Geological Institute. From the available database, 63 intakes suitable for heat pump applications were selected. A total of 54 parameter-selection variants were analyzed, enabling the identification of the most probable calculation approach for this local context. The results reveal substantial variability in estimated thermal power depending on the chosen parameters. This highlights their critical role in assessing system performance. Using the most probable variant, the total thermal power potential of all analyzed intakes was estimated at 23,339.97 kW, with active intakes contributing 13,878.44 kW. Wells with thermal power exceeding 1,000 kW accounted for approximately 24% of active intakes. While the overall potential is insufficient for large-scale geothermal heating, the findings confirm that groundwater intakes can be effectively utilized in small- to medium-scale heat pump systems. These results provide new practical guidance for improving the reliability of thermal power estimation in shallow geothermal applications under local hydrogeological conditions.

1. INTRODUCTION

Shallow geothermal energy is an efficient and low-emission alternative to conventional heating and cooling systems [1, 2]. Growing energy demand and limited fossil fuel resources contribute to geopolitical conflicts and price instability. Therefore, there is an increasing need to develop stable and renewable energy sources [3, 4]. In practice, the temperature of groundwater used in shallow geothermal systems is typically limited to 21–23 ℃. Temperature increases usually do not exceed 5 ℃. Systems are generally implemented at depths of up to approximately 100 m to preserve aquifer sustainability and comply with regulatory thresholds in countries such as Italy, Switzerland, and Germany [5]. Shallow geothermal systems are expected to meet up to 28% of the European Union’s heating and cooling demand by 2050. They may also achieve energy savings of up to 50% and reduce CO_2 emissions by up to 85% [6]. Open-loop groundwater heat pump (GWHP) systems, which utilize groundwater directly, are particularly efficient and cost-effective in areas where water resources are readily available [7]. Kielce has significant groundwater resources, whereas its wind energy potential remains limited. Therefore, shallow geothermal energy should receive particular attention in this region. Effective utilization of shallow geothermal energy requires the application of heat pump installations. Their efficiency strongly depends on local hydrogeological conditions, and improper exploitation can lead to thermal disturbances and reduced system performance. Economic, informational, social, and legislative barriers may also limit the development of low-temperature geothermal systems [8, 9]. Compliance with geological, mining, water, environmental, and building regulations is a significant challenge. At the same time, installations that obtain heat directly from the ground face fewer procedures and are therefore more attractive to investors. Informational and educational barriers are also significant. Commonly available data are often promotional and lack detailed information on advantages, disadvantages, and technical requirements, especially for water-to-water heat pumps [10].

Determining the energy potential of a geothermal reservoir is generally a complex and uncertain process, primarily due to limited data availability [11]. Estimation of geothermal resources is often performed by calculating the stored heat capacity of the reservoir, based on temperature measurements and rock property data [12, 13]. The THERMAL method has been identified as a promising tool for managing shallow geothermal energy in urban environments. This method highlights the crucial role of temperature in system performance [6]. Using this method, thermal power in GWHP systems can be optimized through key input parameters such as groundwater temperature, cooled water temperature, flow rate, and operational thresholds. This optimization helps minimize thermal interference and improve system efficiency. To apply these concepts effectively at a local scale, site-specific hydrogeological analysis is required.

Current literature reveals significant variability in methods and values used, resulting in inconsistent and sometimes inaccurate power calculations [14]. The lack of standardized parameter selection complicates the reliable assessment of geothermal potential. Available maps of low-temperature geothermal resources cover only parts of Poland and are typically produced at regional scales, making local interpretation difficult [8]. The diverse geological and hydrogeological conditions of the Kielce district further limit the development of low-temperature geothermal investments using groundwater heat pumps [15]. Nevertheless, the future use of shallow geothermal energy for heating and cooling systems in the region is promising [1].

In the case of Kielce, a site-specific analysis adapted to local hydrogeological conditions is still lacking. Developing such an approach is essential to accurately determine the most probable parameter values, improve thermal power estimates, and enable more effective utilization of groundwater heat resources in local heat pump systems. Therefore, this study presents a novel, locally adapted methodology with the following objectives:

(i) to analyze and select the most probable set of calculation parameter values for determining the thermal power of shallow groundwater intakes;

(ii) to assess the potential of 63 groundwater intakes in the city of Kielce for heating purposes, including the estimation of their available thermal power.

The study is based on the following hypotheses:

(i) It is assumed that a most probable set of calculation parameters exists for accurate and efficient estimation of the thermal power of shallow groundwater intakes. This approach may also be applicable in regions with similar hydrogeological conditions;

(ii) The shallow groundwater intakes in Kielce have sufficient thermal potential to be effectively utilized for heating purposes;

(iii) The available thermal power of groundwater intakes in Kielce may provide significant support for the operation of the local district heating system.

2. MATERIALS AND METHODS

The assessment of the potential use of groundwater intakes in the city of Kielce, Poland (50.8703° N, 20.6275° E) for heating purposes was carried out. It was based on maps and well profiles from Sheet 815 of the Hydrogeological Map provided by the Polish Geological Institute [16], as well as literature data and calculations using empirical formulas. A total of 63 wells were analyzed. All of them meet the requirements for the application of water-to-water heat pumps, including good water quality [5] and an exploitable yield greater than 1.3 m^3/h (Table 1).

Groundwater temperature, together with water chemistry and well yield, is one of the key parameters in assessing the potential of groundwater intakes. In hydrogeological documentation, contractors were not required to report the groundwater temperature at the intake. Therefore, its theoretical value was estimated using two empirical Eqs. (1) and (2), which most accurately reflected the average actual water temperature in the analyzed intakes.

Direct measurement of groundwater temperature was difficult. This was due to seasonal temperature fluctuations extending to depths of approximately 18 m. Another limitation was the lack of clear guidelines regarding the depth at which such measurements should be taken. For these reasons, the use of empirical equations that account for multiple influencing factors was considered justified. Eq. (1) includes the average annual air temperature (t_{avg}), a constant dependent on elevation above sea level (A), groundwater occurrence depth (H), the depth of the zone of constant temperature (h), and the geothermal gradient expressed as the geothermal degree (g). The second Eq. (2) includes the average annual air temperature (t_{avg}) and the geothermal gradient (G).

The Pazdro–Kozerski equation [17] was used to calculate groundwater temperature:

$$T_w = t_{avg} + A + \frac{H - h}{g} \tag{1}$$

where,

T_w – water temperature at depth H [°C];

t_{avg} – average annual air temperature in a given region [°C];

A – constant dependent on elevation above sea level [°C], its value increases with altitude and ranges from 0.8 at 0 m a.s.l., through 1.0 at 500 m and 1.3 at 1000 m, to 2.3 at 2000 m and 3.0 at 2500 m above sea level [17];

H – depth at which the water occurs [m];

h – depth of the constant-temperature zone =18 [m];

g – geothermal degree = 44.05 [m].

The Habrat formula [17] was used to calculate groundwater temperature while accounting for the thermal properties of the rock medium:

$$T_w = t_{avg} + G \cdot H \tag{2}$$

where,

T_w – water temperature at depth H [°C];

t_{avg} – average annual air temperature in a given region [°C];

G – geothermal gradient [°C·m^{-1}], determined according to Eq. (3):

$$G = q \cdot \chi \tag{3}$$

where,

q – surface heat flux of the Earth =75 [W·m^{-2}] (in Poland) [18];

χ – thermal resistance of rocks [m·°C·W^{-1}], which is the reciprocal of the thermal conductivity of aquifer rocks (Appendix 1).

The thermal resistance of rocks (χ) was calculated as the reciprocal of the thermal conductivity of the aquifer layers (λ), i.e., $\chi = 1/\lambda$. For example, a limestone layer with λ = 2.8 W/m·K corresponds to $\chi \approx$ 0.36 m·K/W, whereas a dolomite layer with λ = 3.2 W/m·K corresponds to $\chi \approx$ 0.31 m·K/W. Sandstone with λ = 2.3 W/m·K corresponds to $\chi \approx$ 0.43 m·K/W, while sand or gravel with λ = 2.1 W/m·K corresponds to $\chi \approx$ 0.48 m·K/W.

Table 1. The groundwater wells analyzed in the city of Kielce

Well Number	Well Yield Q_w [m^3/h]	Filter Section from [m]	Filter Section to [m]	Water Table Depth [m]	Elevation [m a.s.l.]	Water Table Type
8150023	100.5	68	97	48	266.3	confined
8150037	123.9	32.5	89.5	26	251	confined
8150038	30	20.5	39.7	20.5	267	confined
8150043	1.9	24	36	17.4	320.2	unconfined
8150052	193.4	36.5	97.5	7.3	247.3	unconfined
8150098	29.2	37.5	60	17	264	confined
8150101	288.8	45.1	76	20	250.1	confined
8150118	131.7	59.3	97.4	13	258	confined
8150127	211.6	40	76	8	244.6	confined
8150134	211.6	46.1	94.8	24	255.8	confined
8150144	211.5	42.9	94.4	20	249.3	confined
8150145	211.6	48.9	54.9	19.5	244.8	confined
8150147	211.6	42	74.3	30	250.1	confined
8150219	5.5	57	99.2	5.1	267.3	unconfined
8150239	5.5	54	65.5	45	286.8	confined
8150253	4	10.5	17.2	9.8	295.4	confined
8150273	1.9	69.5	97	14.5	296.7	unconfined
8150288	14	35	41	32	283.8	confined
8150313	54	41.4	91	26	280.1	confined
8150385	5.2	18.5	20.5	17	285.59	confined
8150387	7.5	37	55	30	312.73	unconfined
8150389	2.8	45	57	20	286	unconfined
8150409	2.5	39	55	35	283.5	confined
8150410	2.5	10	15	2.25	268.2	unconfined
8150417	5	45	54	45	253.1	confined
8150418	2.4	61	64	53	271.54	confined
8150420	6	49	58	50	311.8	confined
8150460	1.7	14.6	20.6	11.5	308.2	confined
8150532	5	52	67	49	243.8	confined
8150001	1.7	7.6	7.7	5	279.3	confined
8150012	0.9	41.6	59	27	279.34	confined
8150013	18	26	60	25	278.97	confined
8150017	6	10	16	2	239.8	unconfined
8150018	32.7	58	64.3	58	279.8	confined
8150021	20	42.9	72.9	25	280.2	confined
8150024	144	32.5	40	1.3	239.2	confined
8150027	12	58	100	30	277	confined
8150032	8	38.2	90	31.7	270	confined
8150033	153	60	80	22	240.6	confined
8150034	144	29	44	20	238.9	confined
8150035	7.2	17.8	19	12.5	275	confined
8150051	80	31.7	40	26	284.5	confined
8150059	19	26.7	39	1.8	265	unconfined
8150063	27.5	53	80	51	292.6	confined
8150081	171.9	28	101	17.4	258.6	unconfined
8150094	200	57.8	104	9	267.9	confined
8150097	87	60	88	21	272.1	confined
8150102	16.4	45	99	40	268.6	confined
8150168	37.7	132	170	93	257.8	confined
8150188	3.8	14	24.9	22	290.1	confined
8150205	42	86.6	164	44	277.2	confined
8150208	12.6	51	117	32.8	275	confined
8150229	1.3	54	68	32.6	323.7	unconfined
8150230	14.1	40	48	30	312.7	confined
8150231	8	39.5	48	28.2	315.8	unconfined
8150285	4.4	16.6	22.6	13.5	276.2	unconfined
8150286	4.1	16.6	21.6	13.8	276.1	confined
8150295	27.7	78	102	76	290.76	confined
8150361	2.6	33	42	26.5	266.12	confined
8150370	25	41	59	50	279.2	unconfined
8150374	25	54	87	26	273.5	confined
8150406	2.2	55	67	19.2	301.1	unconfined
8150419	24.2	78	96	73	298.23	confined

The thermal power of groundwater wells was calculated according to Eq. (4) [19, 20]:

$$Q_{geot} = Q_w \cdot \frac{1}{3600} \cdot 1000 \frac{kg}{m^3} \cdot 4.19(T_w - T_c) \tag{4}$$

where,

Q_{geot} – thermal power of the well [kW];

Q_w – well yield [m³·h⁻¹] (adopted from well logs obtained from the Polish Geological Institute; operational yield for each well was considered);

T_w – groundwater temperature [°C];

T_c – temperature of cooled water [°C] (cooled water typically reaches a temperature in the range of 5–7 °C; therefore, three variants were considered in the calculations: 5 °C, 6 °C, and 7 °C.

In the calculations of the theoretical groundwater temperature (T_w) at a given depth, different variants of the average annual air temperature (t_{avg}) and groundwater occurrence depth (H) were assumed.

The average annual air temperature values (t_{avg}) were adopted as follows:

(i) the design average annual outdoor temperature for climate zone III of 7.6 °C;

(ii) the average annual air temperature in 2023 for the climatic region encompassing Kielce of 10.0 °C;

(iii) the average annual air temperature based on the 1991–2020 climate normals for Kielce of 8.2 °C.

The groundwater occurrence depth (H) was determined for each intake based on lithological borehole profiles and the following assumptions:

(i) the maximum depth of the well filter (H_1);

(ii) the stabilized groundwater table depth (H_2);

(iii) the average depth of well filter installation (H_3).

To illustrate differences in the power of the considered approaches when selecting various parameter variants for the calculations, different values of water temperature (T_w) were adopted. These values were calculated using Eqs. (1) and (2) under different assumptions regarding the depth of water occurrence, H. The experimental plan is summarized in Table 2.

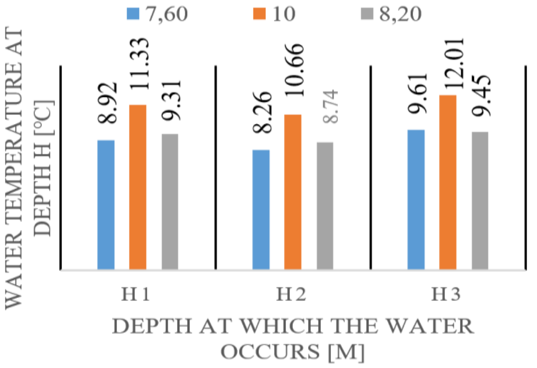
Table 2. Assumptions adopted for the calculation of the thermal power of the individual intake

No.	Considered Variants
A	$\boldsymbol{T_w}$ from Eq. (1), H = $\boldsymbol{H_1}$, $\boldsymbol{t_{avg}}$ = 7.6 °C, $\boldsymbol{T_c}$ = 5 °C
B	$\boldsymbol{T_w}$ from Eq. (1), H = $\boldsymbol{H_2}$, $\boldsymbol{t_{avg}}$ = 7.6 °C, $\boldsymbol{T_c}$ = 5 °C
C	$\boldsymbol{T_w}$ from Eq. (1), H = $\boldsymbol{H_3}$, $\boldsymbol{t_{avg}}$ = 7.6 °C, $\boldsymbol{T_c}$ = 5 °C
D	$\boldsymbol{T_w}$ from Eq. (2), H = $\boldsymbol{H_1}$, $\boldsymbol{t_{avg}}$ = 7.6 °C, $\boldsymbol{T_c}$ = 5 °C
E	$\boldsymbol{T_w}$ from Eq. (2), H = $\boldsymbol{H_2}$, $\boldsymbol{t_{avg}}$ = 7.6 °C, $\boldsymbol{T_c}$ = 5 °C
F	$\boldsymbol{T_w}$ from Eq. (2), H = $\boldsymbol{H_3}$, $\boldsymbol{t_{avg}}$ = 7.6 °C, $\boldsymbol{T_c}$ = 5 °C
G	$\boldsymbol{T_w}$ from Eq. (1), H = $\boldsymbol{H_1}$, $\boldsymbol{t_{avg}}$ = 10 °C, $\boldsymbol{T_c}$ = 5 °C
H	$\boldsymbol{T_w}$ from Eq. (1), H = $\boldsymbol{H_2}$, $\boldsymbol{t_{avg}}$ = 10 °C, $\boldsymbol{T_c}$ = 5 °C
I	$\boldsymbol{T_w}$ from Eq. (1), H = $\boldsymbol{H_3}$, $\boldsymbol{t_{avg}}$ = 10 °C, $\boldsymbol{T_c}$ = 5 °C
J	$\boldsymbol{T_w}$ from. Eq. (2), H = $\boldsymbol{H_1}$, $\boldsymbol{t_{avg}}$ = 10 °C, $\boldsymbol{T_c}$ = 5 °C
K	$\boldsymbol{T_w}$ from Eq. (2), H = $\boldsymbol{H_2}$, $\boldsymbol{t_{avg}}$ = 10 °C, $\boldsymbol{T_c}$ = 5 °C
L	$\boldsymbol{T_w}$ from Eq. (2), H = $\boldsymbol{H_3}$, $\boldsymbol{t_{avg}}$ = 10 °C, $\boldsymbol{T_c}$ = 5 °C
M	$\boldsymbol{T_w}$ from Eq. (1), H = $\boldsymbol{H_1}$, $\boldsymbol{t_{avg}}$ = 8.2 °C, $\boldsymbol{T_c}$ = 5 °C
N	$\boldsymbol{T_w}$ from Eq. (1), H = $\boldsymbol{H_2}$, $\boldsymbol{t_{avg}}$ = 8.2 °C, $\boldsymbol{T_c}$ = 5 °C
O	$\boldsymbol{T_w}$ from Eq. (1), H = $\boldsymbol{H_3}$, $\boldsymbol{t_{avg}}$ = 8.2 °C, $\boldsymbol{T_c}$ = 5 °C
P	$\boldsymbol{T_w}$ from Eq. (2), H = $\boldsymbol{H_1}$, $\boldsymbol{t_{avg}}$ = 8.2 °C, $\boldsymbol{T_c}$ = 5 °C
R	$\boldsymbol{T_w}$ from Eq. (2), H = $\boldsymbol{H_2}$, $\boldsymbol{t_{avg}}$ = 8.2 °C, $\boldsymbol{T_c}$ = 5 °C
S	$\boldsymbol{T_w}$ from Eq. (2), H = $\boldsymbol{H_3}$, $\boldsymbol{t_{avg}}$ = 8.2 °C, $\boldsymbol{T_c}$ = 5 °C
T	$\boldsymbol{T_w}$ from Eq. (1), H = $\boldsymbol{H_1}$, $\boldsymbol{t_{avg}}$ = 7.6 °C, $\boldsymbol{T_c}$ = 6 °C
U	$\boldsymbol{T_w}$ from Eq. (1), H = $\boldsymbol{H_2}$, $\boldsymbol{t_{avg}}$ = 7.6 °C, $\boldsymbol{T_c}$ = 6 °C
W	$\boldsymbol{T_w}$ from Eq. (1), H = $\boldsymbol{H_3}$, $\boldsymbol{t_{avg}}$ = 7.6 °C, $\boldsymbol{T_c}$ = 6 °C
X	$\boldsymbol{T_w}$ from Eq. (2), H = $\boldsymbol{H_1}$, $\boldsymbol{t_{avg}}$ = 7.6 °C, $\boldsymbol{T_c}$ = 6 °C
Y	$\boldsymbol{T_w}$ from Eq. (2), H = $\boldsymbol{H_2}$, $\boldsymbol{t_{avg}}$ = 7.6 °C, $\boldsymbol{T_c}$ = 6 °C
Z	$\boldsymbol{T_w}$ from Eq. (2), H = $\boldsymbol{H_3}$, $\boldsymbol{t_{avg}}$ = 7.6 °C, $\boldsymbol{T_c}$ = 6 °C
AA	$\boldsymbol{T_w}$ from Eq. (1), H = $\boldsymbol{H_1}$, $\boldsymbol{t_{avg}}$ = 10 °C, $\boldsymbol{T_c}$ = 6 °C
AB	$\boldsymbol{T_w}$ from Eq. (1), H = $\boldsymbol{H_2}$, $\boldsymbol{t_{avg}}$ = 10 °C, $\boldsymbol{T_c}$ = 6 °C
AC	$\boldsymbol{T_w}$ from Eq. (1), H = $\boldsymbol{H_3}$, $\boldsymbol{t_{avg}}$ = 10 °C, $\boldsymbol{T_c}$ = 6 °C
AD	T_w from Eq. (2), H = H_1, t_{avg} = 10 °C, T_c = 6 °C
AE	T_w from Eq. (2), H = H_2, t_{avg} = 10 °C, T_c = 6 °C
AF	T_w from Eq. (2), H = H_3, t_{avg} = 10 °C, T_c = 6 °C
AG	T_w from Eq. (1), H = H_1, t_{avg} = 8.2 °C, T_c = 6 °C
AH	T_w from Eq. (1), H = H_2, t_{avg} = 8.2 °C, T_c = 6 °C
AI	T_w from Eq. (1), H = H_3, t_{avg} = 8.2 °C, T_c = 6 °C
AJ	T_w from Eq. (2), H = H_1, t_{avg} = 8.2 °C, T_c = 6 °C
AK	T_w from Eq. (2), H = H_2, t_{avg} = 8.2 °C, T_c = 6 °C
AL	T_w from Eq. (2), H = H_3, t_{avg} = 8.2 °C, T_c = 6 °C
AM	T_w from Eq. (1), H = H_1, t_{avg} = 7.6 °C, T_c = 7 °C
AN	T_w from Eq. (1), H = H_2, t_{avg} = 7.6 °C, T_c = 7 °C
AO	T_w from Eq. (1), H = H_3, t_{avg} = 7.6 °C, T_c = 7 °C
AP	T_w from Eq. (2), H = H_1, t_{avg} = 7.6 °C, T_c = 7 °C
AR	T_w from Eq. (2), H = H_2, t_{avg} = 7.6 °C, T_c = 7 °C
AS	T_w from Eq. (2), H = H_3, t_{avg} = 7.6 °C, T_c = 7 °C
AT	T_w from Eq. (1), H = H_1, t_{avg} = 10 °C, T_c = 7 °C
AU	T_w from Eq. (1), H = H_2, t_{avg} = 10 °C, T_c = 7 °C
AW	T_w from Eq (1), H = H_3, t_{avg} = 10 °C, T_c = 7 °C
AX	T_w from Eq. (2), H = H_1, t_{avg} = 10 °C, T_c = 7 °C
AY	T_w from Eq. (2), H = H_2, t_{avg} = 10 °C, T_c = 7 °C
AZ	T_w from Eq. (2), H = H_3, t_{avg} = 10 °C, T_c = 7 °C
BA	T_w from Eq. (1), H = H_1, t_{avg} = 8.2 °C, T_c = 7 °C
BB	T_w from Eq. (1), H = H_2, t_{avg} = 8.2 °C, T_c = 7 °C
BC	T_w from Eq. (1), H = H_3, t_{avg} = 8.2 °C, T_c = 7 °C
BD	T_w from Eq. (2), H = H_1, t_{avg} = 8.2 °C, T_c = 7 °C
BE	T_w from Eq. (2), H = H_2, t_{avg} = 8.2 °C, T_c = 7 °C
BF	T_w from Eq. (2), H = H_3, t_{avg} = 8.2 °C, T_c = 7 °C

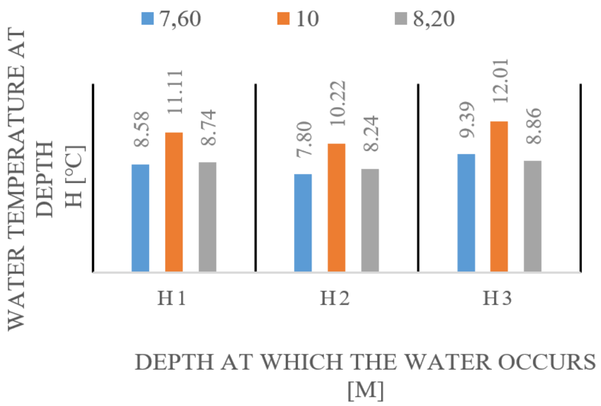
Note: $T_w = t_{avg} + A + \frac{H-h}{g}$ (Eq. (1)),
$T_w = t_{avg} + q \cdot \chi \cdot H$ (Eq. (2)),
$H = H_1$ – the maximum depth of the well filter,
$H = H_2$ – the depth of the stabilized water table,
$H = H_3$ – the average depth at which the well filter is installed,
t_{avg} – the values of the average annual air temperature,
$\boldsymbol{T_c}$ – temperature of cooled water.

3. RESULTS AND DISCUSSION

The results showed that the water temperature calculated using Eq. (1) differs from the value obtained with Eq. (2), even when the same average annual air temperature for the Kielce area and the same depth of groundwater occurrence were assumed (Figure 1). This highlighted the important role of both the geothermal degree and the geothermal gradient in determining this parameter.



(a) Water temperature (T_w) calculated from Eq. (1)



(b) Water temperature (T_w) calculated from Eq. (2)

Figure 1. Water temperature at depth H calculated from Eqs. (1) and (2) in well No. 8150052 – limestone aquifer, λ = 2.8 W/(m·K); t_{avg} (average annual air temperature in a given region [°C]) = 7.6 °C, 8.2 °C, and 10 °C

In the analyzed case, Eq. (2) yields lower estimates of water temperature. This equation is based on the geothermal gradient derived from terrestrial heat flux and the thermal resistance of aquifer rocks. In contrast, Eq. (1) produces higher temperature values. This results from the inclusion of a positive elevation correction factor (A) and the use of the geothermal degree. In the study area, this approach corresponds to a greater effective increase in temperature with depth than the gradient-based method.

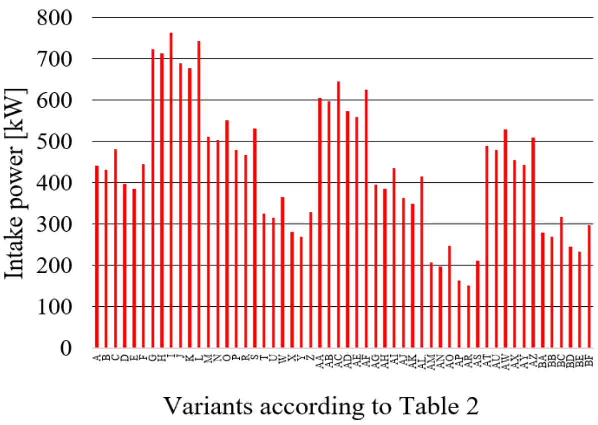


Figure 2. Overview of the thermal power for the example intake (8150023) according to the selected calculation variants

Table 3. Assessment of the possibility of the given values of calculation parameters for evaluating the thermal power of intakes according to formula (4) and the criteria for selecting the most probable variant

Variants	Scale	Comments
		$T_w = t_{avg} + A + \frac{H-h}{g}$ (Eq. (1)) $T_w = t_{avg} + q \cdot \chi \cdot H$ (Eq. (2))
		Selection of parameters H and t_{avg} for groundwater temperature estimation
T_w from Eq. (1) or (2), $H = H_1$	2	Optimal variant: Assuming a water temperature calculated using Eq. (1) and Eq. (2) at a depth corresponding to the upper boundary of the filter installation point ($H=H_1$) does not account for heat loss during transmission when the filter is installed at a significant depth.
T_w from Eq. (1) or (2), $H = H_2$	3	Assuming a water temperature (Eq. (1)) and (Eq. (2)) at the stabilized water table depth ($H = H_2$) likely yields a higher temperature than that estimated under this assumption. However, this temperature can be considered a minimum, disregarding heat loss. Adopting this more conservative approach appears to be the most economically justified option.
T_w from Eq. (1) or (2), $H = H_3$	2	Assuming the water temperature at the average depth where the well filter is installed ($H = H_3$) best represents the actual temperature of the extracted water. However, this assumption does not account for heat loss during transmission.
T_w from Eq. (1) or (2), t_{avg} = 7.6 °C	1	The design average annual outdoor temperature for Climate Zone III is 7.6 °C (PN–EN 12831), with no reference to the latest data.
T_w from Eq. (1) or (2), t_{avg} = 10 °C	3	The temperature trend for Kielce from 1979 to 2023 suggests that future temperatures may fluctuate around the value recorded in the final year (2023) of the forecast (Polish Institute of Meteorology and Water Management).
T_w from Eq. (1) or (2), t_{avg} = 8.2 °C	2	The average annual air temperature for Kielce, based on climate norms from 1991-2020, is 8.2 °C (Polish Institute of Meteorology and Water Management). The decadal average indicates a continuing warming trend.
		Choice of the equation for estimating T_w
T_w from Eq. (1), $H = H_2$, t_{avg} =10 °C	3	Eq. (1) includes correction A for calculating water temperature based on altitude; the depth of constant temperatures is h = 18 m; and does not account for the geothermal gradient [17, 21].
T_w from Eq. (2), $H = H_2$, t_{avg} =10 °C	2	Eq. (2) accounts for the geothermal gradient but does not include correction A or the depth of constant temperatures. Requires knowledge of the lithology and thermal conductivity of aquifer rocks.
		Calculation of the thermal power of a groundwater intake
		$Q_{geot} = Q_w \cdot \frac{1}{3600} \cdot 1000 \frac{kg}{m^3} \cdot 4.19(T_w - T_c)$ (4)
T_c = 5 °C	3	This equation is commonly accepted in the literature and used in water heat pumps, as it allows for achieving maximum efficiency with a minimum discharge water temperature [18].
T_c = 6 °C	2	Used in water heat pumps
T_c = 7 °C	2	Used in water heat pumps

Note: g = 44.05 m – geothermal gradient- How many meters deep does the temperature increase by 1 °C; h = 18 m, A – constant dependent on elevation above sea level [°C];
q = 75 mW/m^2- the density of the Earth's surface heat flux, $\chi = 1/\lambda$ (acc. to appendix 1).

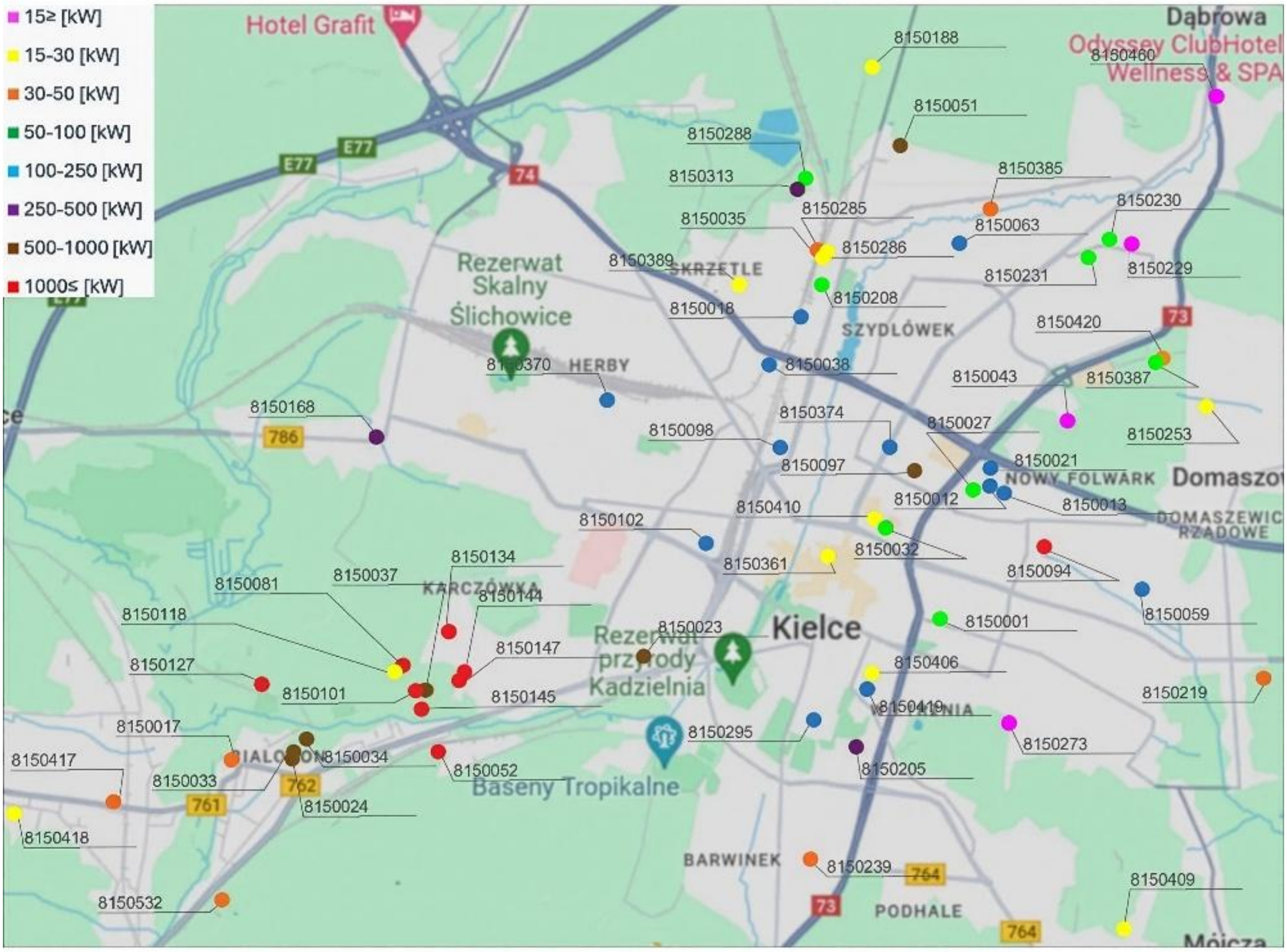


Figure 3. Map showing the estimated thermal power of Kielce's groundwater intakes by power range
Note: Well numbers as per the Polish hydrogeological map, sheet 815.

It was also observed that higher assumed average annual air temperatures generally led to higher groundwater temperature values. In addition, groundwater occurrence depth (*H*) had a significant influence on the final results. Careful selection is necessary to obtain reliable and representative temperature estimates. Figure 2 illustrates the thermal power of the example intake (8150023) for each calculation variant. The results showed significant differences depending on the assumed parameter values, highlighting the importance of selecting the most probable calculation scenario, as each parameter directly influenced the final thermal power estimates.

To support these calculations, the thermal power of groundwater intakes was determined using selected parameters that were not directly measured, including the cooled water temperature (T_c) and groundwater temperature (T_w). Since direct measurements were unavailable, a likelihood scale for these temperature values was adopted based on assumptions derived from the literature. Table 3 presents the probabilities assigned to the different variants. A three-point scale was applied, where 1 indicated the least probable variant, 2 indicated an uncertain variant, and 3 indicated the most probable variant.

The thermal potential of the groundwater intakes in Kielce was calculated using the most probable parameter values adopted in accordance with the methodology described above. These included the water temperature at the intake, calculated using Eq. (1) and taking into account the average temperature in Kielce in 2023, and the depth of the stabilized water table, as well as the cooled water temperature assumed to be 5 °C. The presented data correspond to calculation variant H according to Table 2, which was adopted as the most probable case. The obtained results are summarized in Figure 3.

The total thermal power of all considered wells amounted to 23,339.97 kW, of which 13,878.44 kW came from active wells and 9,461.53 kW from inactive wells, representing approximately 60% and 40% of the total, respectively. Considering only the 29 active wells, the results were as follows:

- The largest share (24%) consisted of wells with a power greater than 1000 kW (7 wells).
- Wells with a power below 15 kW accounted for about 10% (3 wells), which is the same as wells in the 500–1000 kW range.
- The 50–100 kW and 100–250 kW ranges included 2 wells each (approximately 7%).
- There were 5 wells (approximately 17%) in the 15–30 kW range, and 6 wells (approximately 21%) in the 30–50 kW range.
- One well (about 4%) fell into the 250–500 kW range.

The analysis showed that the wells in Kielce exhibited considerable variation in thermal power. The largest group of wells with potential for use as a low-temperature heat source was in the 100–250 kW range, comprising 13 wells. The smallest groups corresponded to the 250–500 kW range (3 wells) and below 15 kW (4 wells). In the 15–30 kW range, there were 10 wells, while the 30–50 kW, 50–100 kW, and 500–1000 kW ranges each included 8 wells. There were 9 wells with a thermal power above 1000 kW (Figure 3). The most favourable wells in terms of thermal potential were located in the Białogon Valley (Nos. 8150017, 8150127, 8150024, 8150033, 8150034, 8150101, 8150118, 8150134, 8150144, 8150147, 8150037, 8150145, 8150052, 8150081). However, most of these wells are operated by Wodociągi Kieleckie, which limits their potential use for heat pump installations.

In summary, Kielce does not have sufficient potential for large-scale investment in shallow geothermal energy as a primary heat source. Nevertheless, individual wells within the city could be utilized for small- to medium-scale heating systems with water-to-water heat pumps.

The observed agreement of the results with the literature highlighted the critical importance of the proper selection of input parameters used for estimating thermal power. Parameters such as the hydraulic variant, water temperature, and the degree of cooling directly affected the final calculation results. Due to the archival nature of the data, direct experimental validation was not possible. Existing geothermal maps developed by the Polish Geological Institute – National Research Institute (PIG-PIB) did not yet cover this location [22]. In addition, the available data on rock thermal conductivity provided through the portal were limited, although they were consistent with the values used in this study. The estimated groundwater temperatures were consistent with those reported in the literature. For Kielce, Devonian formations were reported to have temperatures in the range of 10–20 °C [23].

The analysis, therefore, introduced a significant degree of novelty, providing detailed estimates of thermal conductivity and geothermal potential for a previously poorly documented area. These results may serve as a valuable basis for further research and for planning geothermal investments. It is worth emphasizing that the applied computational methodology is not limited to local conditions and can also be applied in other geothermal regions, provided that hydrogeological differences are taken into account. Proper selection of input parameters allows results consistent with the actual geothermal potential of the analyzed area.

Additional confirmation of the reliability of the results was provided by the estimated thermal power for the most probable variant. Within the analyzed group of intakes, the highest power of 1,922.67 kW was recorded for well no. 8150101, located in the Białogon Valley. This value was consistent with the literature data. For the Białogon area, a realistically achievable thermal power of approximately 1,700 kW had been reported for a water temperature reduction of about 2 °C [23]. This agreement confirms both the high energy potential of the area and the reliability of the calculations.

It should be noted that for several intakes in the analyzed set (including wells 8150017, 8150127, 8150024, 8150033, 8150034, 8150101, 8150118, 8150134, 8150144, 8150147, 8150037, 8150145, 8150052, and 8150081), no data on realistically exploitable resources were available. These wells are not currently used for district heating purposes.

Many of the most promising wells are already used by the local water utility. At present, only about half of their resources are utilized, which limits the possibility of additional exploitation for district heating purposes. However, partially unused resources may still allow for additional abstraction or the development of new intakes in this area.

4. CONCLUSIONS

The study demonstrated that the selection of input parameters is critical for assessing water temperature and thermal power in shallow geothermal systems. In particular, groundwater temperature (T_w) and the temperature of water leaving the heat exchanger (T_c) were identified as the most influential factors determining the calculation results. The use of different methods for estimating Tw led to significant differences in predicted values. One approach incorporated elevation correction and geothermal degree, while the other was based on the geothermal gradient and the thermal conductivity of aquifer rocks. This highlights the importance of both the selected method and the assumed parameter values.

External factors, such as mean annual air temperature and the depth of groundwater occurrence, also had a substantial impact. Higher air temperatures resulted in increased predicted groundwater temperatures, which in turn translated into higher thermal power. Assuming a depth corresponding to the stabilized groundwater table provided more realistic and conservative estimates, thereby reducing the risk of overestimation.

The analysis of 63 groundwater intakes in Kielce revealed considerable variability in thermal power depending on the selected parameters. The total estimated power of all intakes amounted to 23,339.97 kW, of which 13,878.44 kW came from active intakes. Most intakes fell within the 100–250 kW range, while the highest power (1,922.67 kW) was observed at intake No. 8150101 in the Białogon Valley. The results indicate that the shallow geothermal potential in Kielce is limited as a primary heat source. However, the existing wells could still effectively support small- to medium-scale heat pump systems and contribute to local heating demand.

The findings also underscore that selecting the most probable calculation scenario is essential for obtaining reliable estimates. Future research should focus on several directions, including verification of the actual performance of the intakes, assessment of potential climate change impacts, and evaluation of the economic feasibility of their use.

Such an approach will enable a more realistic assessment of geothermal resource utilization and support the development of low-temperature heating systems within the city.

ACKNOWLEDGMENT

This work is supported by the Kielce University of Technology, Grant NO.: 05.0.12.00/1.02.001/SUBB.IKGT.26.002.

REFERENCES

[1] Figueira, J.S., García Gil, A., Vieira, A., Michopoulos, A.K., et al. (2024). Shallow geothermal energy systems for district heating and cooling networks: Review and technological progression through case studies. Renewable Energy, 236: 121436. http://doi.org/10.1016/j.renene.2024.121436

[2] Vukelic, Z., Sporin, J. (2024). Groundwater potential for the utilisation of shallow geothermal energy from a closed coal mine. Water, 16(11): 1572. http://doi.org/10.3390/w16111572

[3] Molajou, A., Pouladi, P., Afshar, A. (2021).

Incorporating social system into water-food-energy nexus. Water Resources Management, 35: 4561-4580. http://doi.org/10.1007/s11269-021-02967-4

[4] Vokurka, M., Kunz, A. (2022). Case study of using the geothermal potential of mine water for central district heating—The Rožná deposit, Czech Republic. Sustainability, 14(4): 2016. http://doi.org/10.3390/su14042016

[5] Angelotti, A., Sterpi, D. (2024). Shallow geothermal systems in dense urban areas: The issue of thermal interference and long-term sustainability. E3S Web of Conferences, 523: 05001. http://doi.org/10.1051/e3sconf/202452305001

[6] Martínez-León, J., Marazuela, M.Á., Baquedano, C., Jiménez, J., Cavero, S.G., Calvo, O.E., García-Gil, A. (2025). Sustainable shallow geothermal operations through THERMAL management in urban aquifers. Journal of Hydrology, 661(Part B): 133672. http://doi.org/10.1016/j.jhydrol.2025.133672

[7] Sezer, T., Sani, A.K., Singh, R.M., Cui, L. (2023). Numerical investigation and optimization of a district-scale groundwater heat pump system. Energies, 16(20): 7169. http://doi.org/10.3390/en16207169

[8] Gryszkiewicz, I., Lasek-Woroszkiewicz, D., Socha, M., Stożek, J. (2021). The support of geothermal energy by the polish geological institute – national research institute. Przegląd Geologiczny, 69(9): 611-623. https://www.pgi.gov.pl/dokumenty-pig-pib-all/publikacje-2/przeglad-geologiczny/2021-2/9-wrzesien-1/8633-wspieranie-rozwoju-geotermii-w-polsce-przez-panstwowy-instytut-geologiczny-panstwowy-instytut-badawczy/file.html.

[9] Latosińska, J., Miłek, D. (2023). The state of knowledge and attitudes of the inhabitants of the polish świętokrzyskie province about renewable energy sources. Energies, 16(21): 7445. http://doi.org/10.3390/en16217445

[10] Nartowska, E., Budzianowski, D., Styś-Maniara, M. (2022). Assessment of the thermal power of groundwater intakes in the kielce district. Civil and Environmental Engineering Reports, 32(4): 25-49. http://doi.org/10.2478/ceer-2022-0043

[11] Dekkers, K., Gravatt, M., Maclaren, O.J., Nicholson, R., Nugraha, R., O'Sullivan, M., O'Sullivan, J. (2022). Resource assessment: Estimating the potential of a geothermal reservoir. In 47th Stanford Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, pp. 1-10.

[12] Romanov, D., Leiss, B. (2022). Geothermal energy at different depths for district heating and cooling of existing and future building stock. Renewable and Sustainable Energy Reviews, 167: 112727. http://doi.org/10.1016/j.rser.2022.112727

[13] Tiwari, S.K., Ragnarsson, Á., Axelsson, G. (2025). Characterization of geothermal resources and estimation of power potential of Badrinath geothermal field, northwest Himalaya, India. Scientific Reports, 15: 35291. http://doi.org/10.1038/s41598-025-19120-5

[14] Franco, A., Donatini, F. (2017). Methods for the estimation of the energy stored in geothermal reservoirs. Journal of Physics: Conference Series, 796: 012025. http://doi.org/10.1088/1742-6596/796/1/012025

[15] Łukasiewicz, E., Shamoushaki, M. (2022). Heating potential of undeveloped geothermal water intakes in Poland in the context of sustainable development and air protection. Water Resources and Industry, 27: 100175. http://doi.org/10.1016/j.wri.2022.100175

[16] Prażak, J. (1997) MHPGUPW0815 Explanations. https://bazadata.pgi.gov.pl/data/hydro/mhp/gupw/txt/mhpgupw0815objasnienia.pdf, accessed on 1 October 2025.

[17] Staśko, S., Buczyński, S., Błachowicz, M. (2021). Temperatura wód podziemnych i jej znaczenie w badaniach hydrogeologicznych, Przegląd Geologiczny, 69(4): 224-233. http://doi.org/10.7306/2021.12

[18] GeoTrainet Training Manual for Designers of Shallow Geothermal Systems. (2011). Geo-Education for a sustainable geothermal heating and cooling market, Project: IEE/07/581/S12.499061, GEOTRAINET, EFG. Brussels. http://geotrainet.eu, accessed on 19 May 2024.

[19] Buczyński, S. (2010). Szacunkowa moc cieplna wód podziemnych z kenozoicznych poziomów wodonośnych na bloku przedsudeckim. Biuletyn Państwowego Instytutu Geologicznego, 440(440): 15-24.

[20] Mazurkiewicz, J., Kmiecik, E., Tomaszewska, B. (2017). Analiza możliwości wykorzystania wód podziemnych z utworów czwartorzędowych w systemach geotermii niskotemperaturowej w Małopolsce. Część II. Przykład ujęcia Zawoja 3. Przegląd Geologiczny, 65(11/1): 995-999. https://bibliotekanauki.pl/articles/2075754.

[21] Pazdro, Z. (1964). Hydrogeologia Ogólna. Warszawa: Wydawnictwa Geologiczne. https://katalogi.uj.edu.pl/discovery/fulldisplay/alma991007340429705067/48OMNIS_UJA:uja.

[22] CBDG Geology portal. (2026). https://geolog.pgi.gov.pl/, accessed on 23 March 2026.

[23] Barbacki, A., Bujakowski, W., Kasztelewicz, A. (2009). Sytuacja geologiczna Kielc w aspekcie potencjalnego występowania wód termalnych. Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią Polskiej Akademii Nauk, 76: 65-80. https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-AGHM-0023-0062.

NOMENCLATURE

t_{avg}	average annual air temperature in a given region, °C
T_w	water temperature, °C
T_c	temperature of cooled water, °C
A	constant dependent on elevation above sea level, °C
H	depth at which the water occurs, m
h	depth of the constant-temperature zone, m
g	geothermal degree, m
G	geothermal gradient, °C·m^{-1}
Q_{geot}	thermal power of the well, kW
Q_w	well yield, m^3·h^{-1}

Greek symbol

q	surface heat flux of the Earth, W·m^{-2}
χ	thermal resistance of rocks, m·°C·W^{-1}

APPENDIX

(1) The lithology of the aquifer layers in the wells is as

follows:

- Limestone (λ = 2.8 W/m·K): 8150023, 8150037, 8150052, 8150101, 8150118, 8150127, 8150134, 8150144, 8150145, 8150147, 8150219, 8150273, 8150417, 8150418, 8150385, 8150024, 8150027, 8150032, 8150033, 8150034, 8150051, 8150168, 8150188, 8150102, 8150295, 8150361, 8150406, 8150419.
- Dolomite (λ = 3.2 W/m·K): 8150012, 8150013, 8150018, 8150021, 8150239, 8150288, 8150387, 8150389, 8150460, 8150532, 8150059, 8150063, 8150094, 8150097, 8150208, 8150229, 8150230, 8150231, 8150374.
- Sandstone (λ = 2.3 W/m·K): 8150420.
- Mudstone (λ = 2.2 W/m·K): 8150043, 8150001.
- Sand, gravel (λ = 2.1 W/m·K): 8150253, 8150017.
- Pebbles, gravel (λ = 1.7–1.8 W/m·K): 8150285, 8150286.