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Estimation of Potential Low-temperature Geothermal Energy Extraction from the Closed-loop Systems Based on Analysis, Interpretation and Reclassification of Geological Borehole Data in Poland

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ABSTRACT

Recent growth of renewables share in the total mix of energy production in Poland aims at complying with the binding EU regulations on energy and adaptation to climate change. The ground source heat pumps (GSHP) extracting low-temperature geothermal energy through the closed-loop system are the efficient, safe and stable source of renewable energy for space heating and cooling. Application of GSHP contributes to reduction of low emissions which in effect positively influences state of the natural environment and human health.

Effectiveness of the GSHP is, to a large degree, determined by local geological and hydrogeological settings. Therefore, detailed studies of the subsurface and identification of natural conditions is crucial for an appropriate design and exploitation of the GSHP installations. For example, the thermal conductivity of soils and rocks, one of the key geothermal parameters which needs to be calculated for optimal GSHP design, depends on mineral composition of surrounding rocks, their texture as well as presence of groundwater.

For the sake of the research geological and hydrogeological data originating from the thematic databases, atlases and serial maps have been gathered in a unified database showing a uniform structure enabling spatial analysis with use of the GIS techniques. According to an algorithm adopted for calculations under the terms of research presented in this paper, reclassification of lithological parameters into the geothermal parameters have been performed and values of thermal conductivity λ [W/m·K] of analysed rock and soil types have been calculated. Based on the results of calculations 2 spatial layers of average geothermal conductivity coefficient λ have been computed, each for the depth interval up to 40 and 100 metres.

1. INTRODUCTION

According to statistical report published by the Statistics Poland (Berent-Kowalska et al. 2017) a share of energy from renewable sources in final energy consumption in 2016 was at the level of 8,0% for UE28, while for Poland it amounted up to 8,3%. In the same year a share of geothermal energy in total energy production from renewable energy sources (RES) was respectively 3,2 and 0,2% for UE and Poland. The implementation of the international and EU legal regulations and strategies, including a new EU directive on renewable energy sources (RED II 2018), with respect to reduction of low emissions are gaining an increasing attention and importance in shallow and deep geothermal investments (Kępińska 2015). At present, the Polish national programme *Czyste Powietrze* 2018-2020 (Clean Air) is a significant tool for sustainable development of RES market in Poland, including geothermal energy. The main aim of this programme is to improve the energy effectiveness of the buildings, reduction of gas and dust emission generated by existing or new residential buildings. In Poland the GSHP technology development is associated with and conditioned by:

- unification, simplification and adjustment of Polish legal regulations;
- accomplishment of methodology for licensing and development of the GSHP installations;
- servicing and monitoring of installation to reduce the ecological risk caused by intensified drilling and possibility of leakage from underground installations.

The GSHP technology, extracting shallow geothermal energy with help of so-called closed-loop systems, is a safe and stable source for renewable spatial heating and cooling (Casasso et al. 2017) with a minimum ecological impact. It contributes to reduction of CO_2 and dust emissions in Europe and beyond (Sarbu, Sebarchievici 2014). Development of SGE market varies very much among the European countries which is caused not only by the natural conditions and suitability for deployment of this type of technology but also by the national and regional legal regulations, strategies and policies (Somogyi, Sebestyén, Nagy 2017). The dynamic trends of GSHP technology development in recent years in Poland will facilitate achievement of main aims of EU 2020 energy targets: 3 x 20% climate and energy package - increase of energy effectiveness and renewable energy implementation up to 20%, as well as aims of the Paris Agreement concerning the reduction of CO2 emission.

In Poland currently there is a very limited amount of shallow geothermal potential maps. The areas covered by detailed maps derived from advanced 3D geological modelling and GIS geoprocessing cover areas of Kraków, Wałbrzych and Zgorzelec (as an effect of UE funded projects GeoPLASMA–CE and TransGeoTherm, respectively). As the coverage of detailed maps is low, in order to assess shallow geothermal potential at a national scale it is necessary to use all available sources of geological information and data. These sources include mostly geological databases hosted by the Polish Geological Institute. With data about lithological profiles, stratigraphy and local hydrogeological and geo-environmental conditions (interpreted from the regional geological maps), it is possible to determine the potential of shallow geothermal systems. However, for this purpose it is necessary to reclassify the geological information mentioned above into geothermal parameters, such as thermal conductivity of different rock and soil types.

For the purpose of this article it was assumed that geothermal conditions will be evaluated on a point basis, i.e. only available geological profiles from the databases and series of geological maps will be analysed. Reclassification of lithological and stratigraphic profiles for geothermal parameters – thermal conductivity (λ) for the available archival borehole data allowed statistical analysis of the results and evaluation of shallow geothermal conditions for the area of whole Poland. The developed methodology is limited to closed-loop systems in the form of borehole heat exchangers (BHE). It was assumed that the analyses cover BHE depth intervals of 40 and 100 metres.

2. DATA SOURCES AND PROCESSING

For proper assessment of shallow geothermal capacity it is necessary to use all accessible sources of geological information. These include the geological maps and borehole data published by the Polish Geological Institute (PGI). The data was obtained from following sources:

- **MHP**: Hydrogeological Map of Poland;
- **CBDH**: Central Hydrogeological Database;
- **CBDG**: Central Geological Database;
- **BDGI**: Geological-Engineering Database.

These data sources and other archives are essential for depicting geological structure and hydrogeological conditions as well as for preparing the perspective profiles of projected boreholes. The relevant attention ought to be paid to CBDH where profiles of wells and groundwater intakes are stored. This data base is basic source of information for projects of geological works (Cabalska et al. 2005). It is necessary to say that well prepared and verified geological profile let evaluate more precisely the GSHP system efficiency.

- **CBDH** – hydrogeological database collecting separate boreholes (wells, observation wells and test boreholes) and also water intake data. This dataset contains lithological borehole profiles, results of water chemical composition analyses and data concerning discharge and hydrodynamics of aquifers and location of low-permeable layers. Because of the depth of the identification (CBDH boreholes are usually up to 100-200 metres deep), this base is the primary source of geological information for the design of borehole heat exchangers and for the purpose of assessing the potential of shallow geothermal energy.

One of the most important thing in complex data geoprocessing for the purpose of assessing the potential of geothermal energy is collection and verification of borehole data. Next step is preparation of schemes (patterns) for attribute tables and algorithms used in calculation of thermal parameters for selected depth intervals. In connection to such approach – spatial geological, environmental, topographic data and tables ought to be appropriately prepared and put into the database structures in GIS environment (OpenSource or commercial). The basis for all calculations is an integrated geological borehole dataset containing complete information on the position, lithological profile, depth of groundwater table in the borehole and a table of average geothermal parameters (thermal conductivity λ) calculated for the individual lithological units. Only verified and integrated data can be calculated with algorithms and can be a basis for final results: tables, map composition, geological cross-sections and profiles.

The methodological approach used to perform estimation of potential low-temperature geothermal energy extraction from the closed-loop systems in Poland on the basis of borehole data is presented on Fig. 1.

Step 1. Collection of archive spatial data (query layer)

The available spatial data for spatial query must be collected. The layers chosen for analysis in this article include engineering-geological regions of Poland (according to Kaczyński 2017 and Majer et al. 2018) and current administrative division of Poland.

Step 2. Collection of archive data (PGI-NRI Central Hydrogeological Database)

All accessible archive boreholes fulfilling the depth criterion (minimum 100 metres for whole country and 40 metres for the biggest cities) were taken from the CBDG, CBDH and BDGI databases. Information on location, altitude and lithological profiles of boreholes were stored in a geodatabase file for later processing using SQL scripts. The dictionaries of unique lithologies from the boreholes in database were prepared and used as a basis for geothermal reclassification.

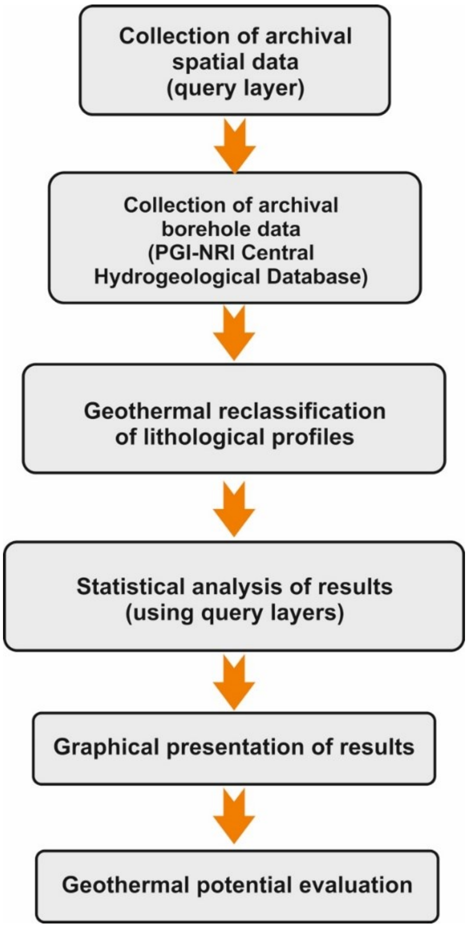

Figure1: Scheme of methodology used for shallow geothermal potential evaluation

Step 3. Geothermal reclassification of lithological profiles

The borehole data collected in the geodatabase file was converted into the defined depth intervals (40 and 100 metres) using the SQL algorithm for calculation of thermal conductivity (λ). Then, the SQL algorithm based on the conversion table assigned values of λ each lithological layer. The weighted average of heat conductivity λ was then recalculated for the defined depth intervals. So in result processed borehole data can be visualized as point maps of geothermal potential. The basis of this step was the table of conversion of lithological parameters to geothermal parameters derived on the basis of PORT PC Guidelines (2013).

Step 4. Statistical analysis of results (using query layers).

Statistical analysis of results was performed with the use of the Statistica software. The basic statistics, including mean value, median, standard deviation were calculated and the histograms were prepared for further evaluation. Final results were presented in the synthetic Tabs 1 and 2.

Step 5. Graphical presentation of the results

The borehole data processed in step 4 was transferred to the geodatabase file used by the GIS program (e.g. ArcGIS or QGIS). Maps showing point average values of thermal conductivity (λ_{avg}) at set depth intervals of 40 and 100 metres were prepared (see Figs 2, 3 and 4).

Step 6. Evaluation of geothermal conditions

Based on the geothermal reclassification of geological data, archival boreholes data it was possible to prepare a statistical evaluation of the shallow geothermal potential for analysed regions and city districts in form of analytic box plots (see Figs 5, 6 and 7).

3. ANALYZED DATASET

One of the main goals of this research was to create a geothermal database covering whole area of Poland. Spatial geological, environmental and topographic data were placed in the ESRI geodatabase file, while the table data used for geothermal calculations were included in the PostgreSQL database structure. The basis for all calculations were integrated geological borehole data containing complete information on the position, lithological profiles, depth of groundwater table in the boreholes and a table of average thermal conductivities (λ) calculated for individual lithological layers. All maps and geoprocessing were made in ArcGIS and QGIS environments.

In total, the analysed dataset consisted of 16 696 boreholes. The criterion used for borehole selection was minimum depth of 100 metres. Locally - for Warsaw and Wrocław areas, the boreholes with minimum depth of 40 metres were included into the database. The aim of such criterion was to include into analysis the profiles, with fully documented geological layers. This approach resulted in an amount of boreholes suitable for geothermal recalculation, however in the areas with occurrence of shallow groundwater table (shallow aquifer) data is rather scarce. Authors are aware of this issue, but from the point of view of generalized and large scale nation-wide analysis such simplification should be considered as justified.

The data for spatial query was collected for analysis, including the engineering-geological regions of Poland spatial layer, see Fig. 2, and current administrative division of Poland. For purpose of evaluation of shallow geothermal potential two approaches were assumed. First one was to perform analysis of shallow geothermal potential in the regional context, what was reached by application of engineering geological regions spatial layer. The results of reclassified borehole database query are presented by Figs 3 and 4 and Tabs 1 and 2.

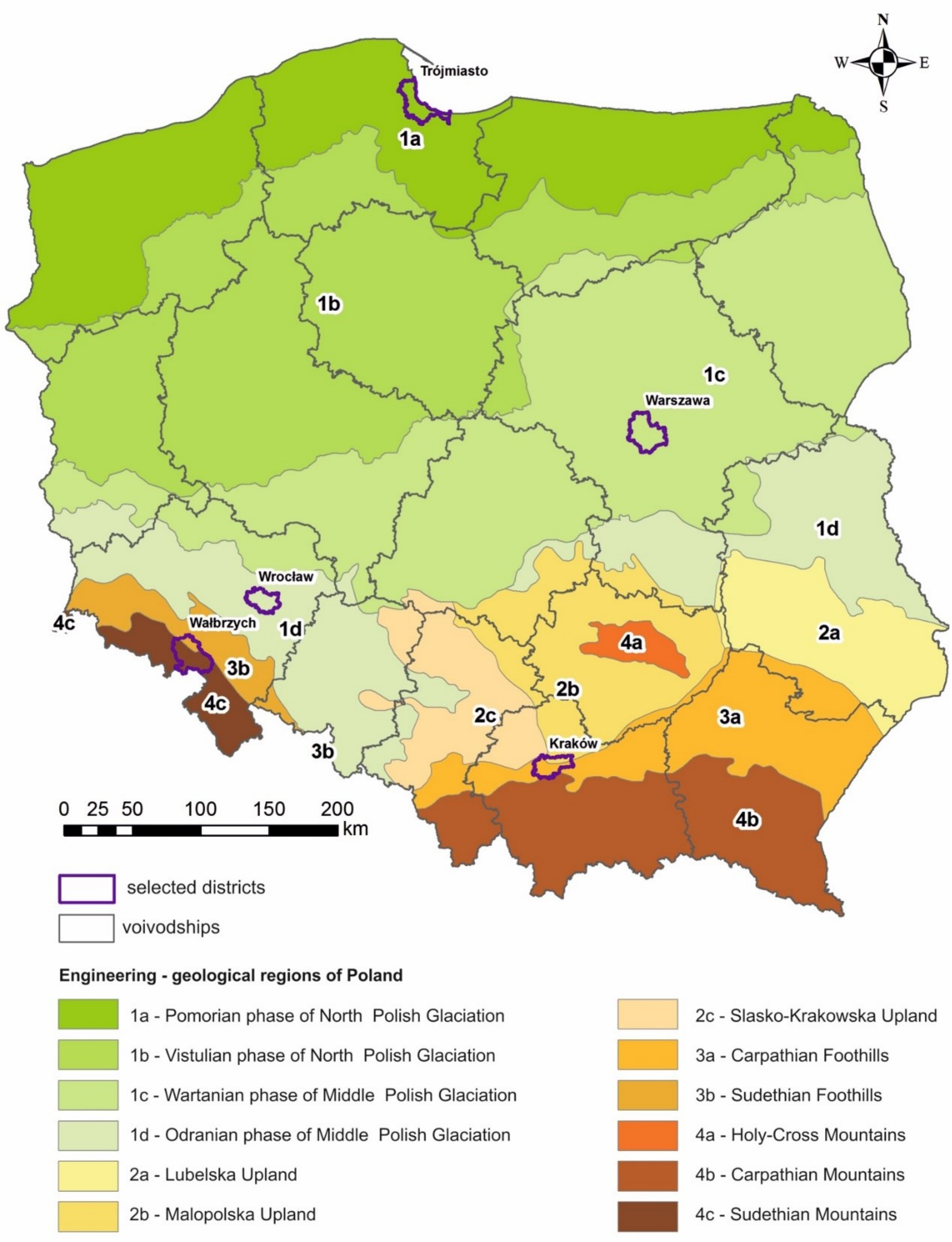

Figure 2: Geological-Engineering Regions in Poland by Kaczyński, 2017. Spatial layers used for query of CBDH borehole database.

4. RESULTS AND INTERPRETATION

The basis for geothermal calculations was the conversion table based on the guidelines of the Polish Organisation for Development of Heat Pump Technology (PORT PC), for the design, accomplishment and licensing of the geothermal heat pump installations (Part 1. Ground sources for heat pumps). In the course of reclassification process water saturation of rocks and soils was taken into account. Thermal parameters, such as an average thermal conductivity value for each given borehole were attributed for both dry and saturated conditions.

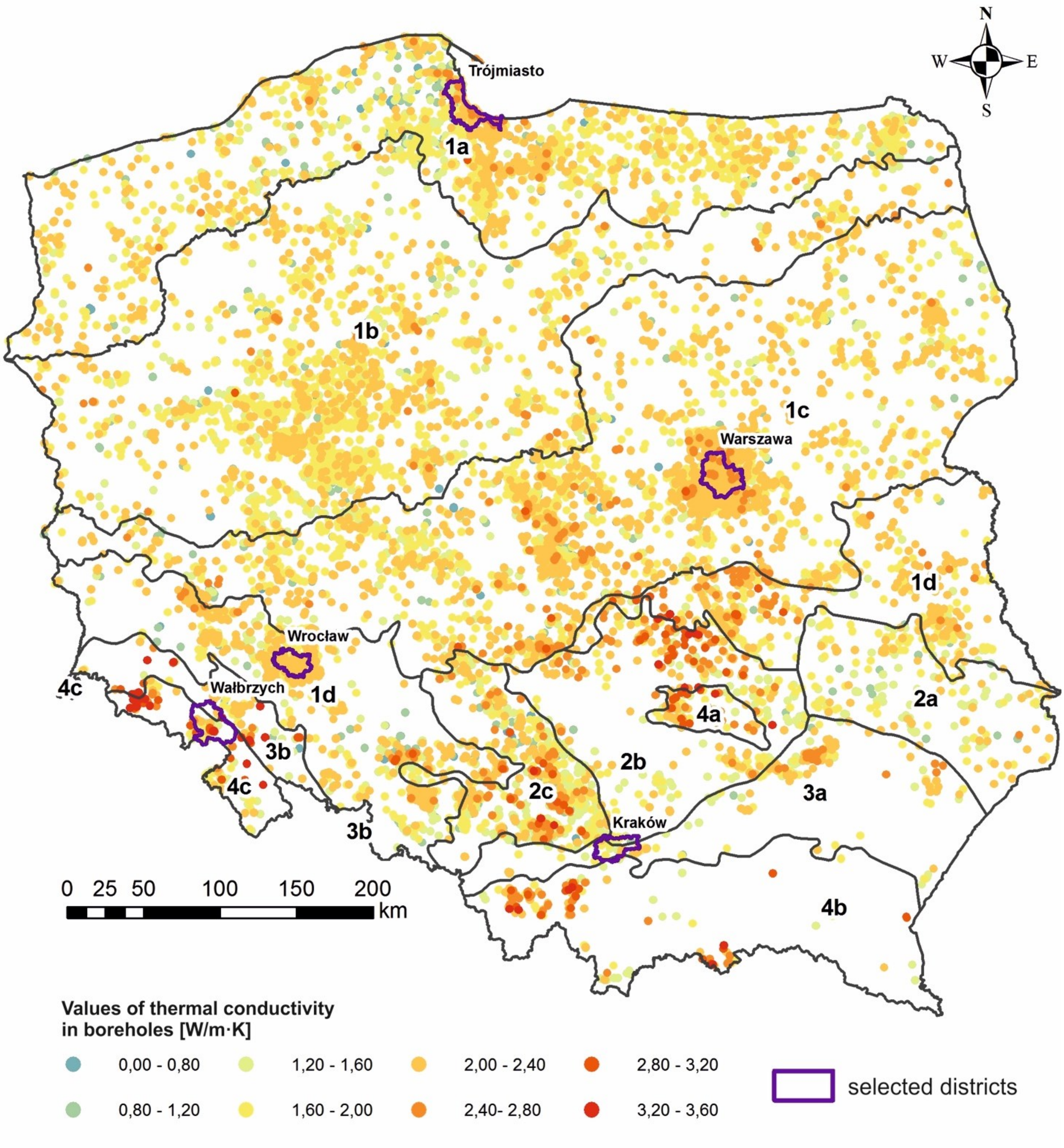

Fig.ure3: Map presenting estimation of shallow geothermal potential of Poland. Average values of thermal conductivity to a depth interval of 40 metres.

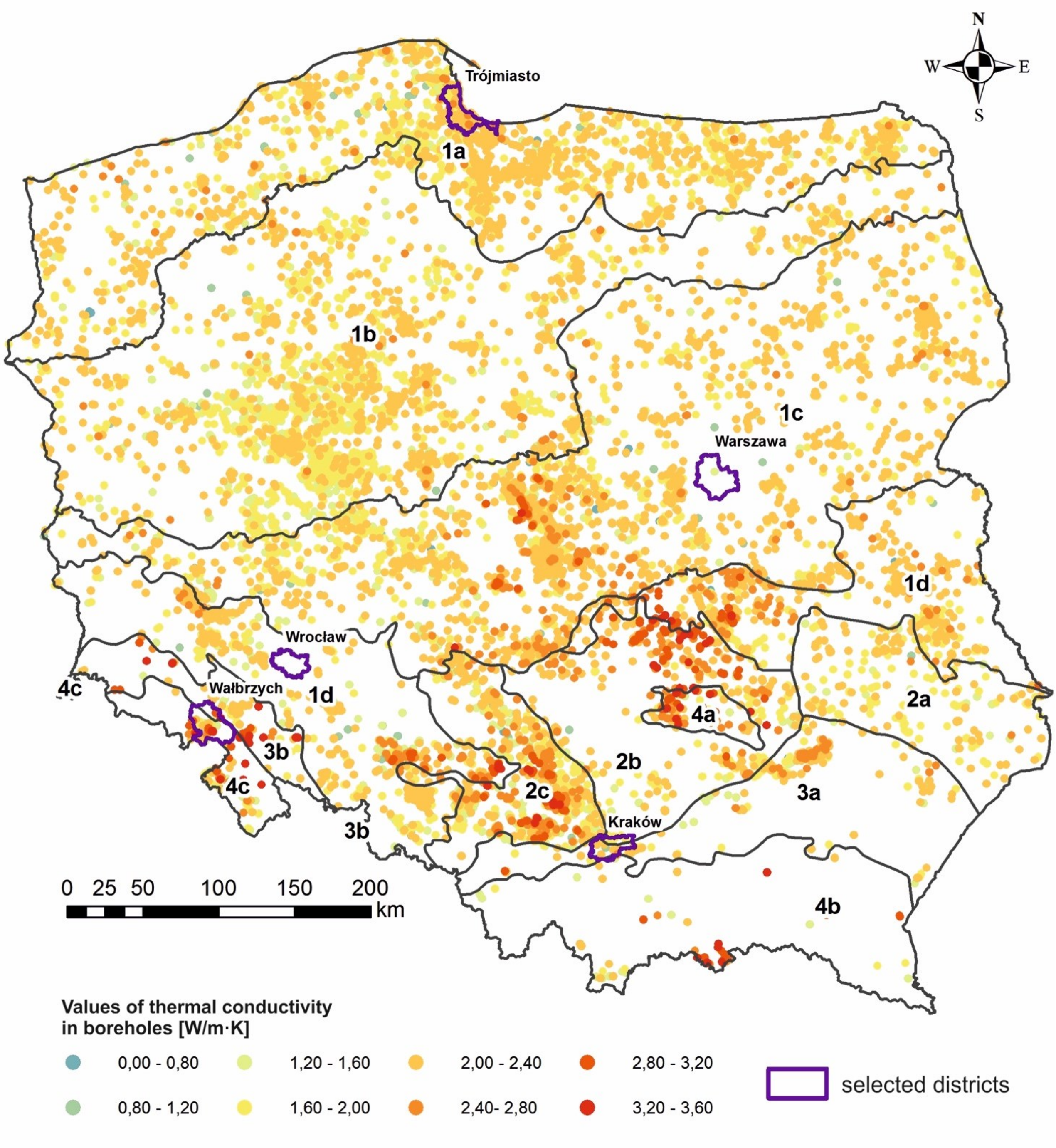

Figure4: Map presenting estimation of shallow geothermal potential of Poland. Average values of thermal conductivity to a depth interval of 100 metres.

In Tabs 1 and 2 statistical evaluation of geothermal data – the information about borehole amount (total) and analysed areas are presented. Also the amount of boreholes at a given depth intervals - 40 and 100 metres, are listed in the Tabs 1 and 2. The statistical evaluation was carried out for thermal conductivity λ values. Statistical analysis was performed on the dataset of archival boreholes, the mean values and the confidence interval of 95% which is also presented in the Tabs 1 and 2 (+/- 2 standard deviations (σ) from mean, assuming the normal distribution curve).

Table 1: Results of statistical evaluation of shallow geothermal potential spatial layers. Query layer – engineering-geological regions of Poland

REGION	Borehole data			Average thermal conductivity λ_{avg} (W/m*K) - archival boreholes $(\lambda_{avg}-2\sigma)\div(\lambda_{avg}+2\sigma)$ λ_{avg}	
	Area (km^2)	Number of 40 metres boreholes	Number of 100 metres boreholes	For 40 metres depth interval	For 100 metres depth interval
Pomorian phase of North Polish Glaciation (1a)	45851	2916	2920	0,93÷2,57 1,75	1,31÷2,55 1,93
Vistulian phase of North Polish Glaciation (1b)	71435	3625	3627	1,16÷2,39 1,78	1,29÷2,41 1,85
Wartanian phase of Middle Polish Glaciation (1c)	77749	5639	3609	1,17÷2,59 1,88	1,32÷2,66 1,99
Odranian phase of Middle Polish Glaciation (1d)	35760	1936	1438	1,16÷2,64 1,90	1,35÷2,84 2,09
Lubelska Upland (2a)	11642	250	250	1,09÷2,37 1,73	1,41÷2,52 1,96
Malopolska Upland (2b)	15830	455	455	0,96÷2,97 1,96	1,34÷3,13 2,23
Slasko-Krakowska Upland (2c)	9265	969	969	0,76÷2,73 1,74	1,06÷3,01 2,03
Carpathian Foothills (3a)	15494	289	289	1,05÷2,64 1,84	1,30÷2,66 1,98
Sudethian Foothills (3b)	4723	145	135	0,74÷3,37 2,05	1,09÷3,38 2,23
Holy-Cross Mountains (4a)	1768	96	96	1,03÷3,12 2,08	1,44÷3,40 2,42
Carpathian Mountains (4b)	19344	162	68	1,14÷3,27 2,20	0,97÷3,58 2,27
Sudethian Mountains (4c)	3640	170	136	0,75÷3,48 2,11	0,97÷3,48 2,23

Table 2: Results of statistical evaluation of shallow geothermal potential spatial layers. Query layer – five selected city districts in Poland

DISTRICT	Borehole data		Average thermal conductivity λ_{avg} (W/m*K) - archival boreholes $(\lambda_{avg}-2\sigma)\div(\lambda_{avg}+2\sigma)$ λ_{avg}
	Area (km^2)	Number of 40 metres boreholes	For 40 metres depth interval
Kraków (city with county rights)	326	32	0,93÷2,35 1,64
Wałbrzych (city with county rights) and Wałbrzych County	514	47	0,64÷3,54 2,09
Warszawa (city with county rights)	517	796	1,38÷2,52 1,95
Wrocław (city with county rights)	293	238	1,23÷2,44 1,84
Trójmiasto (Gdańsk, Gdynia, Sopot)	414	302	0,72÷2,72 1,72

The calculated values of average thermal conductivity and its variability for analysed 16 696 archive boreholes show correlation with the engineering geological regions of Poland (see box plots on Figs 5 and 6). Also the analyses performed for the city agglomeration areas (see Fig. 7) confirm that correlation, even with significantly smaller amount of available archival data. This is also confirmed by earlier studies – e.g. Baralis et al. (2018). The geological databases that can be used for semi-automated GIS geoprocessing are a very useful tool for preliminary assessment of shallow geothermal potential and can significantly disseminate the geological information necessary to develop strategies and implementation of renewable energy sources plans at the national level.

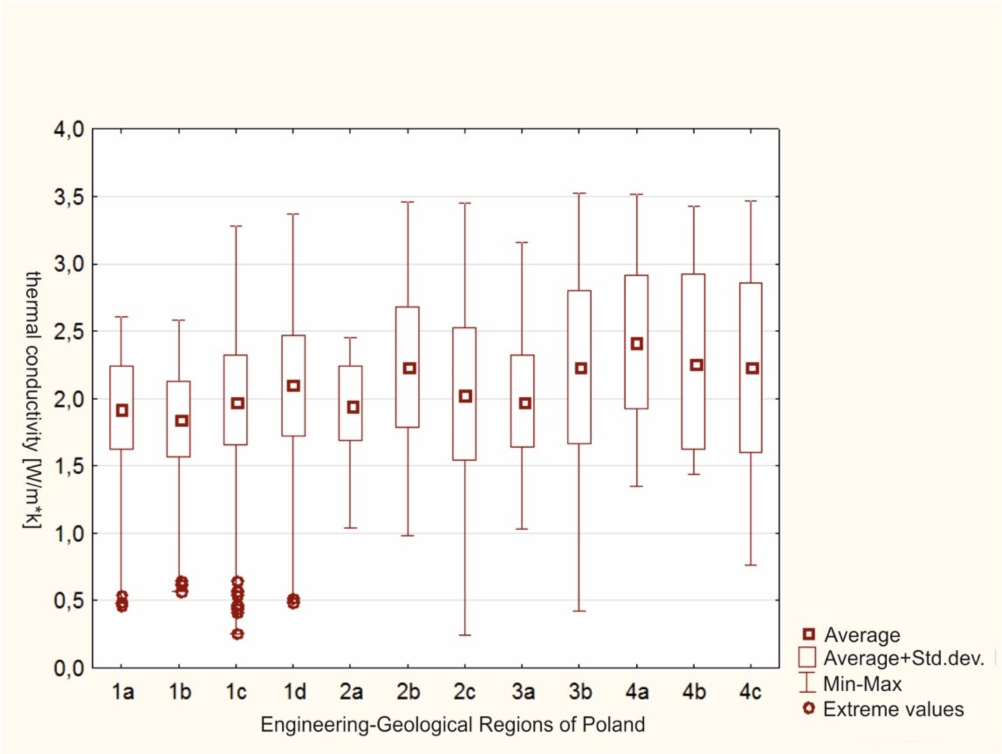

Figure 5: Box plot of average values of thermal conductivity for the depth interval of 40 meters. Region codes are following:1a - Pomorian phase of North Polish Glaciation, 1b - Vistulian phase of North Polish Glaciation, 1c - Wartanian phase of Middle Polish Glaciation, 1d - Odranian phase of Middle Polish Glaciation, 2a - Lubelska Upland, 2b - Malopolska Upland, 2c - Slasko-Krakowska Upland, 3a - Carpathian Foothills, 3b - Sudethian Foothills, 4a - Holy-Cross Mountains, 4b - Carpathian Mountains, 4c - Sudethian Mountains

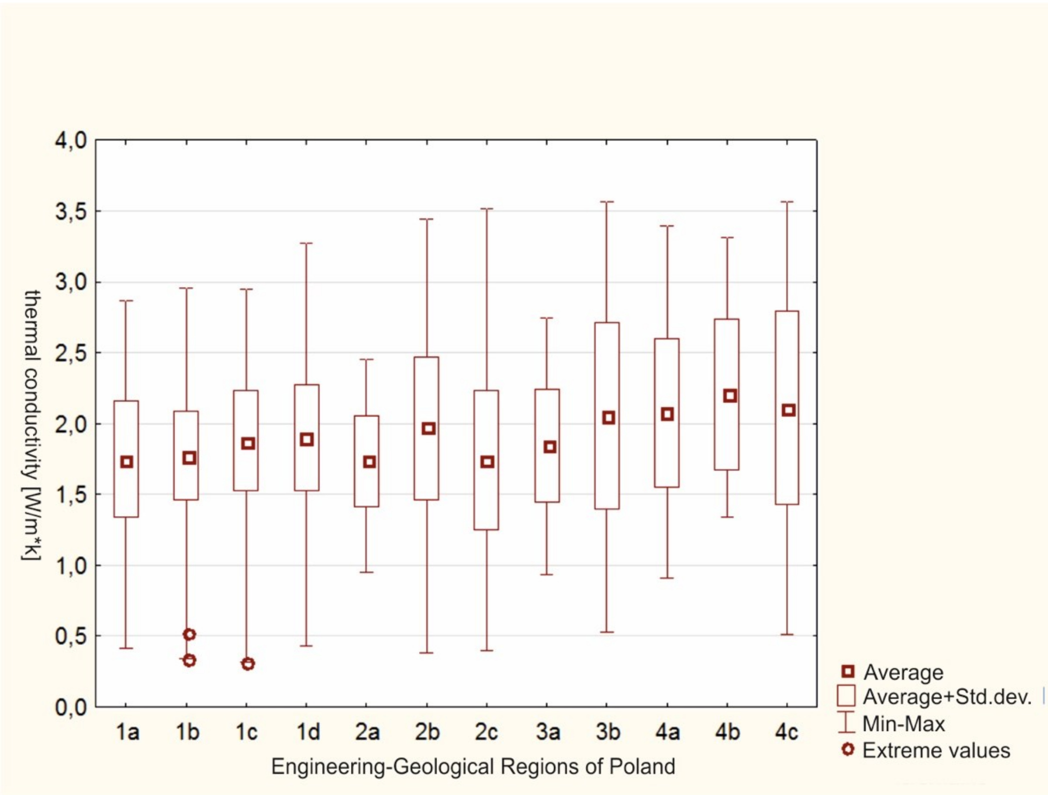

Figure 6: Box plot of average values of thermal conductivity for the depth interval of 100 metres. Region codes as described on the Fig. 4

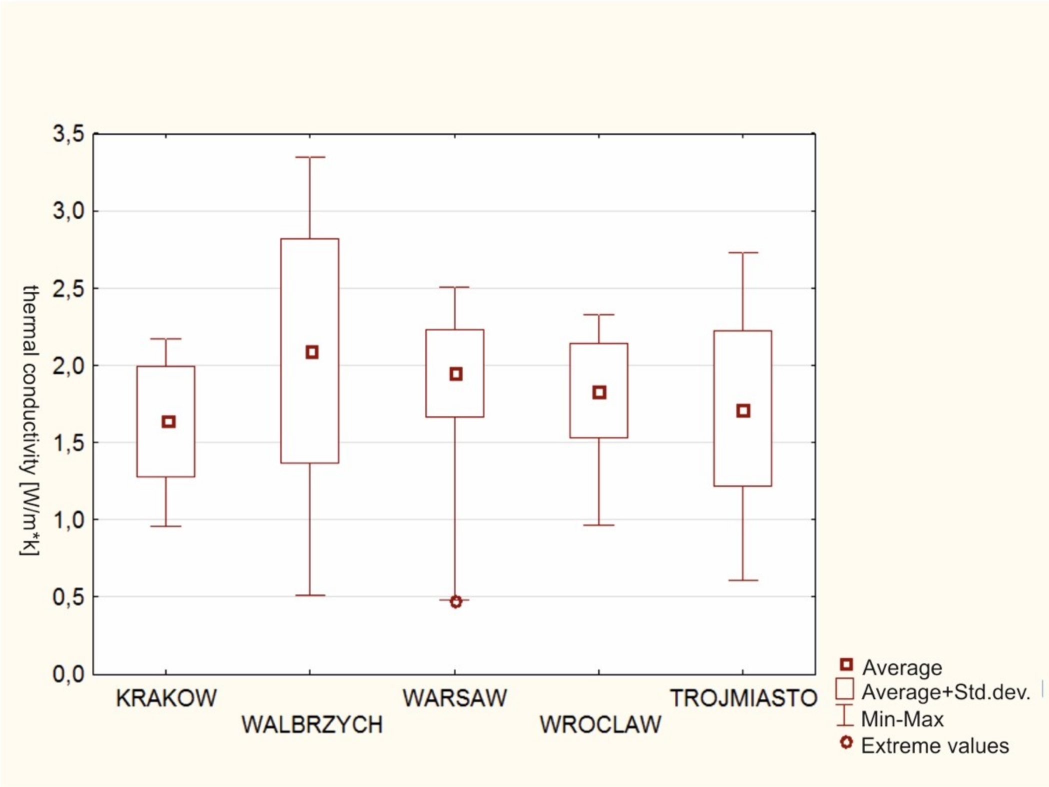

Figure 7: Box plot of average values of thermal conductivity for the depth interval of 40 metres for five selected city agglomerations in Poland

5. CONCLUSIONS

Geothermal potential maps are an important factor that can lead to widespread use of shallow geothermal energy, however the process of their creation is a time consuming process (see GeoPLASMA-CE maps – https://portal.geoplasma-ce.eu). In order to facilitate initial stages of shallow geothermal energy development planning the simple dot maps presented in this paper can be a useful tool. The map information presented, in a readable and comprehensible way, informs about the achievable thermal conductivity in the vicinity of existing archival boreholes. The wide range of recipients of such geological information includes, among others the local authorities and government administration responsible for regional development and spatial planning as well as investors and end users. It should be emphasized that the maps of geothermal potential can only support the initial planning process, however they cannot, in any case, replace the individual process of accomplishment a correct design and performance of calculations of rocks and soils thermal parameters.

Any geological surveying carried out at the initial stages of project implementation should be based on the verified and integrated borehole data. Precise location of the borehole, reliable and accurate description of the lithological profile and depth of the water table with the date of its measurement is important in determining the value of thermal parameters of geological layers underlying the investment. Correct interpretation of the borehole data and application of appropriate thermal conductivity calculation procedures and unit heat output coefficient also facilitates the conduct of any analysis related to the costs of installation and operation of the heat pump and the economics of using these systems during their lifetime of use.

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