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Potential for Implementation of Aquifer Thermal Energy Storage (ATES) Technology in Poland

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ABSTRACT

The aim of the article is to present a preliminary assessment of the possibility of using ATES (Aquifer Thermal Energy Storage) technology for seasonal storage of heat and cold in shallow aquifers in Poland. The ATES technology is designed to provide low-temperature heat and cold to big-area consumers. A study by researchers from the Delft University of Technology in the Netherlands indicates very favourable hydrogeological and climate conditions in most of Poland for its successful development. To confirm this, the authors used public hydrogeological data, including information obtained from 1324 boreholes of the groundwater observation and research network and 172 information sheets of groundwater bodies (GWBs). Using well-described in the world literature requirements for ATES systems, the selection of boreholes was carried out in the GIS environment, which allowed to capture aquifers that meet the required criteria. The preliminary assessment indicates the possibility of successful implementation of ATES technology in Poland, in particular in the northern and western parts of the country, including cities with over 350,000 citizens: Warsaw, Wrocław, Gdańsk and Bydgoszcz.

1. INTRODUCTION

Aquifer Thermal Energy Storage (ATES) is a technology that enables to store and recover thermal energy in shallow aquifers. It is one of the types of underground thermal energy storage, collectively referred to as UTES (Underground Thermal Energy Storage), which in addition to ATES includes also heat storage using borehole heat exchangers (BTES - Borehole Thermal Energy Storage), underground tanks (TTES - Tank Thermal Energy Storage), gravel-water pits (PTES - Pit Thermal Energy Storage) and rock caverns (CTES - Cavern Thermal Energy Storage). ATES is designed to supply heat and cold to distributed consumers, located outside municipal heating networks. This technology began to enter the commercial phase in the 1990s and since then there has been a rapid increase in the number of new installations, especially in the Netherlands and the Scandinavian countries (Fleuchaus et al. 2018).

The resented paper is focused on heat and cold storage in shallow aquifers. The basic principles and conditions for the operation of ATES systems are discussed in the article. The main goal of the research presented here is to indicate the possibilities of using ATES technology in Poland, taking into account favorable climatic and hydrogeological conditions that are advantageous both regionally and locally. Using publicly available hydrogeological data, including aquifer data contained in 1324 wells of the groundwater observation and research network and 172 groundwater bodies (GWBs) data sheets (Herbich et al., 2005), the authors made a preliminary selection of potential areas meeting the criteria set for ATES systems.

2. THE THEORETICAL BASIS OF OPERATION OF ATES SYSTEMS

The system of low-temperature heat and cold storage in the aquifer consists of at least two wells, with one cold storage well and one heat storage well. In the summer season, water with a temperature of approx. 5-10°C, extracted from the cold storage well, is directed to the heat exchanger in which it receives heat from an air-conditioned building. After passing through the exchanger, the water is preheated to a temperature of approx. 15-18°C and is injected to the formation via the hot storage well. In the winter season the circulation is reversed. Groundwater with elevated temperature is pumped from the hot well and directed to the evaporator of a heat pump that enables to heat the return water from the building to a temperature of approx. 40-50°C, while water supplied from the aquifer is cooled to a temperature of approx. 5-10°C, and then injected into the cold storage well (Nordel et al. 2015, Bloemendal et al. 2018). The diagram of the operation of the ATES system under cyclic flow regime is shown in Fig. 1.

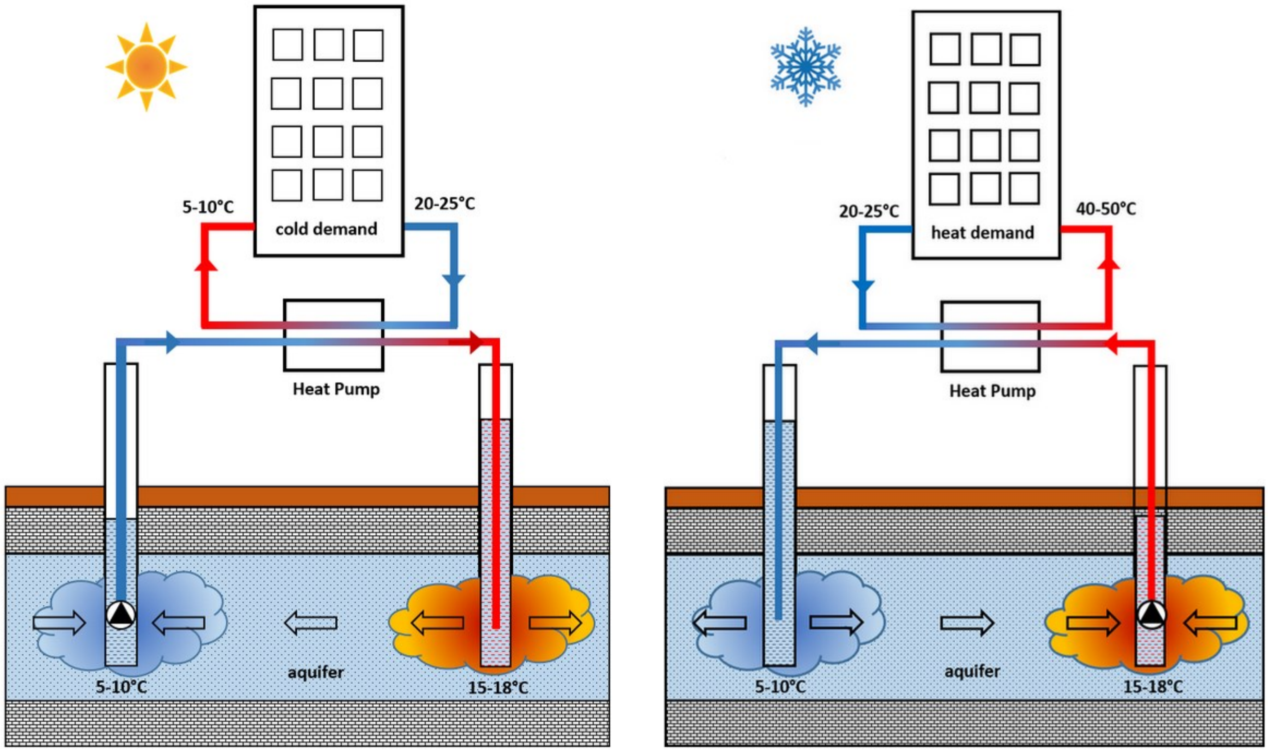

Figure 1: Diagram illustrating the operation of the ATES under cyclic flow regime (based on Bloemendal et al. 2018)

The ATES system works most often under cyclic flow regime: summer season - winter season. Each well serves both as a production and injection well. If the temperature of water in a cold storage well in the summer season is 6°C or lower, it can be used directly for cooling, i.e. bypassing the heat pump. The Seasonal Performance Factor (SPF[1]) of the heat pump, taking into account the above temperatures of the lower heat source, can reach 5.5-6 (using ground heat exchangers without heat storage SPF is 3.8-4.3), while in the cooling mode SEER (*Seasonal Energy Efficiency Ratio*[2]) may exceed 60 Btu/Wh, which is from 4 to 6 times more efficient than the conventional systems (Underground Energy LLC 2019). It allows for better efficiency than in the case of classic open-loop heat pump systems, higher energy savings, and greater value of the avoided emissions.

In general, ATES systems operating under cyclic flow regime require the occurrence of an aquifer capable of collecting and releasing water (water-bearing sands and gravels with a thickness >10 m, usually 20-50 m), with a high hydraulic conductivity (above $3{\cdot}10^5$ m/s), and at the same time a small hydraulic gradient and low natural filtration velocity (<25 m/year, which allows minimizing the advective heat loss), limited from the bottom and top by impermeable layers (e.g. clay) to protect against mixing warm and cold water, e.g. rainwater (Lee 2013, Nordell et al. 2015, and Malina and Bujak 2017). Geochemical gradients should also be avoided because mixing of water of different chemical composition can cause colmatation of well filters, contribute to lower efficiency and performance of wells, and increased operating costs of the system.

The ATES systems operating under continuous flow regime are much less common (Nielsen 2003). Under continuous flow regime, each well has a strictly defined role - it is either a production or injection well. Such ATES systems are an alternative solution for aquifers with high filtration velocity (>50 m/year). In this mode, ATES systems operate at a lower temperature difference between the natural temperature of the aquifer and the zones around production and injection wells, what results in lower energy efficiency.

Typically, thermal energy from ATES system is supplied to buildings that requires cooling in the summer season and low-temperature heating during winter (i.e. underfloor heating or air heating). Thus, energy consumers may be: residential buildings, office buildings, hospitals, computer centers that require continuous cooling, museums, warehouses, greenhouses, railway stations, and airport terminals. They do not have to be connected to the heating network, because ATES systems can be located near or directly under the object.

3. POSSIBILITIES OF USING ATES TECHNOLOGY IN POLAND

The question of the use of aquifer thermal energy storage (ATES) in Poland has begun to attract researchers' attention in the recent years. In addition to review articles on various technologies of underground heat storage (Miecznik 2016, Malina and Bujak 2017), preliminary studies, focused on assessing the ability of selected hydrogeological structures in Poland to meet the requirements of ATES systems, were undertaken. The studies focused on the young glacial areas of the Kashubian Lake District (Lemoine 2016),

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1 The SPF is a measure of the operating performance of an electric heat pump heating system over a year. It is the ratio of the heat delivered to the total electrical energy supplied to the heat pump over the year: SPF = Total heat output over a year [kWh]/ Total input electricity over a year [kWh].

2 The SEER rating is a measure of the seasonal efficiency of air conditioners. It is the cooling output during a typical cooling season divided by the total electric energy input during the same period.

Żarnowiec Plateau (Lemoine 2018), Central Poland - Quaternary and Upper Cretaceous aquifers of the Piotrków area (Bujakowski et al. 2016), and the city of Sochaczew (Skrzypczak et al. 2017), where Quaternary aquifers, and potentially also Oligocene ones were indicated as prospective water-bearing formations, are especially worth noting.

The combined analysis of hydrogeological and climatic conditions performed by researchers from the Delft University of Technology (Bloemendahl et al., 2015), taking into account the demand for both heat and cold in our climate zone, suggests that most of Poland has some of the best conditions in the world for the development of ATES systems. The aggregate assessment, including both factors, for Poland ranged from 7.1 to 9.0 on a scale of 1-10. The analysis covered the whole world, which makes its spatial resolution low. Despite the growing interest in low-temperature geothermal energy (geothermal heat pumps) in Poland, ATES technology has not received sufficient attention so far. Until now, there are no ATES systems in Poland, which is probably partly due to the technology used to develop high-temperature heating networks in Poland. With the development of low-energy building, the ATES technology would undoubtedly have a chance to emerge in Poland. The lack of studies on the evaluation of the applicability of ATES systems fundamentally limits the possibilities of development of this technology in Poland.

The impulse for the development of seasonal heat storage in shallow aquifers in Poland requires a comprehensive and widely available study that would combine rich hydrogeological information with technical knowledge about the principles of designing, construction, and trouble-free operation of ATES systems. Such a study requires a team of scientists from the fields of hydrogeology, cartography (GIS), energy, and HVAC designers. In order to meet this challenge, the authors attempted to pre-select the potential areas for ATES systems in Poland, which could be developed after a more detailed hydrogeological analysis. For this purpose, the publicly available hydrogeological data from the Polish Hydrogeological Survey were used:

- hydrogeological characteristics of 172 groundwater bodies (GWBs) (PGI-NRI 2019),
- aquifer data contained in 1324 wells of the groundwater observation and research network included in the report of the Chief Inspectorate of Environmental Protection (pol. GIOŚ) on the condition of groundwater bodies in river basins (PGI-NRI 2017).

2.1 Baseline Data

The baseline data was a review of the aquifer parameters based on 1324 wells of the groundwater observation and research network. This network is maintained by the Polish Geological Institute - National Research Institute, while its purpose is to document the dynamics and chemistry of groundwater in Poland.

Based on the appendix 1 to the report of the Chief Inspectorate of Environmental Protection on the condition of groundwater bodies in river basins (PGI-NRI 2017), the following data were obtained:

- type of porosity of reservoir rocks,
- stratigraphy and lithology of reservoir rocks,
- type of the water table in the aquifer,
- depth to the top of the aquifer,
- the depth range of the well screens,
- the depth range of the accessed aquifer,
- depth of the static water level.

Unfortunately, some key parameters necessary to fully assess the suitability of the aquifer for ATES systems are missing, i.e. the capacity of wells, the hydraulic conductivity of aquifers, and the chemical composition of waters. These data can be obtained at the next stage of verification of wells, using data of the Central Hydrogeological Data Bank (CHDB 2019). Information on the hydraulic conductivity of the aquifer and the chemical type of groundwater can be obtained from groundwater bodies data sheets corresponding to the analyzed wells, which at this stage allows to strengthen or reject the thesis about the suitability of a given aquifer for ATES systems. However, such a detailed hydrogeological analysis was not the purpose of this work.

At this stage of the analysis, the authors made maps presenting important reservoir parameters from the point of view of the underground heat storage. Analyzing the map in Fig. 2, it can be seen that over 80% and 91% of all wells are located in aquifers whose top is located at a depth not exceeding 50 m and 100 m below ground level, respectively. Over 74% of wells can be found in porous reservoirs, and in a broader perspective - nearly 90% in porous or porous-fractured media (Fig. 3). About 59% of the analyzed wells is located in aquifers with a confined water table, while almost 41% - with a free water table (Fig. 4).

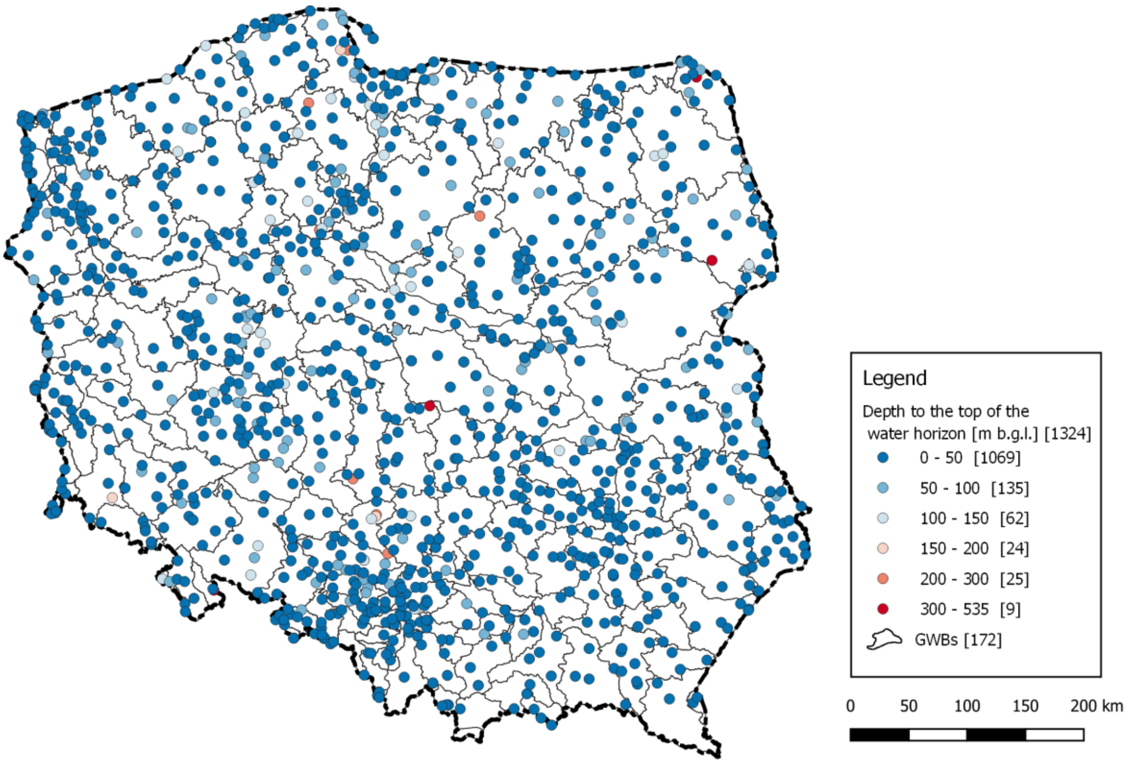

Figure 2: The distribution of wells of the groundwater observation and research network along with the information on the depth to the top of the aquifer

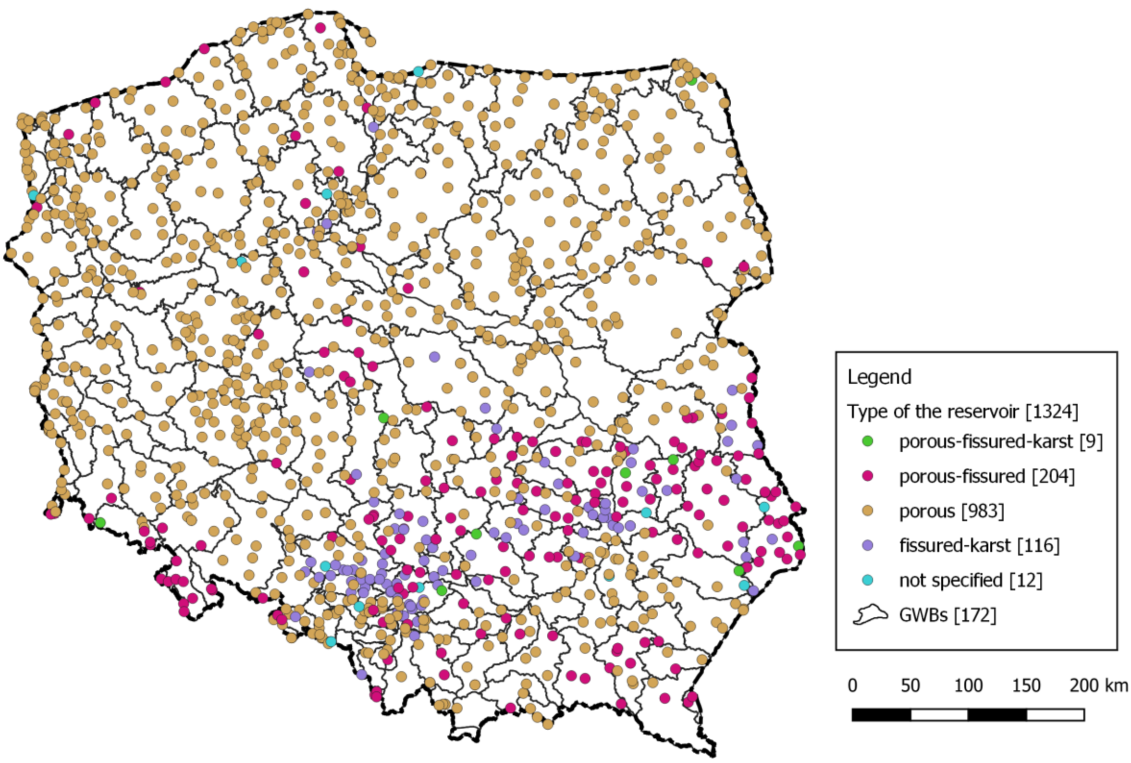

Figure 3: The distribution of wells of the groundwater observation and research network along with the data on the type of reservoir porosity

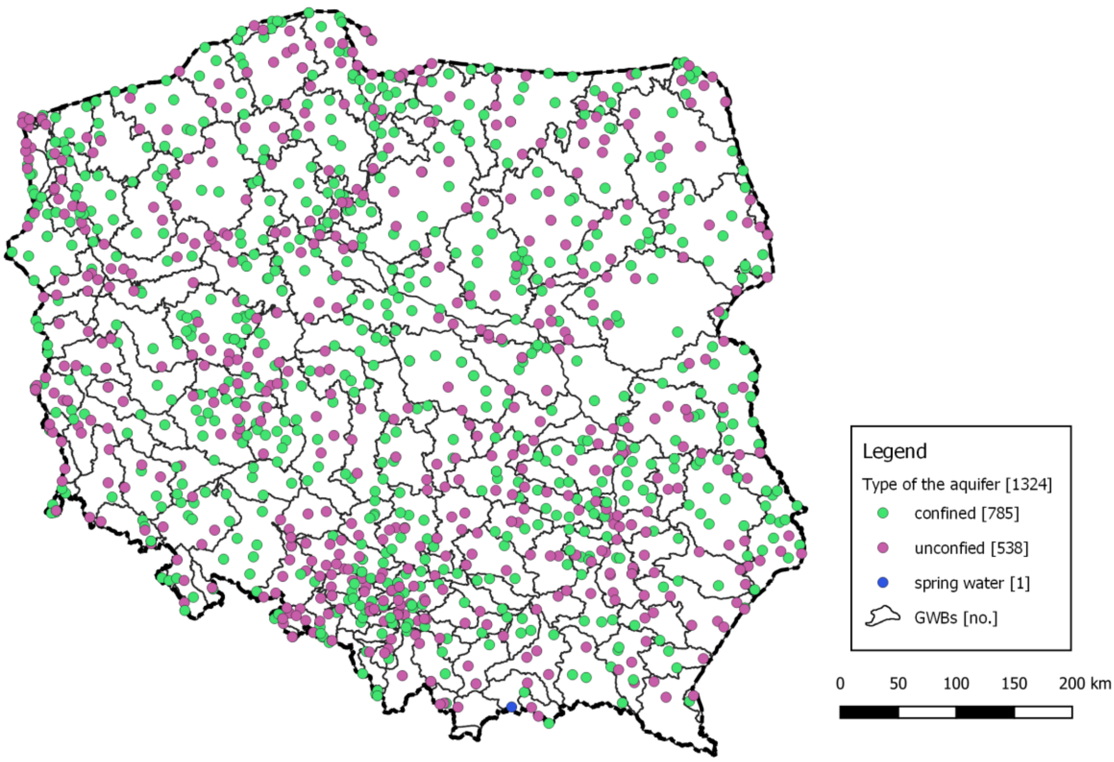

Figure 4: The distribution of wells of the groundwater observation and research network along with the data on the type of the water table of the aquifer

2.2 The First Stage of Selection

In the first stage of selection the following criteria were applied (Lee 2013, Nordell et al. 2015, Malina and Bujak 2017):

- the depth of the top of the aquifer should be min. 10 m, but shall not exceed 200 m below the ground level,
- reservoir shall be porous or porous-fractured,
- confined water table of the aquifer,
- the thickness of the aquifer ≥ 10 m.

The selection resulted in 213 wells meeting the above criteria (16% from the initial pool), with the majority of wells located in western and north-western Poland (Fig. 5-7). Nearly 77% of selected wells are located in aquifers whose top is located at a depth of up to 100 m below ground level. (Fig. 5). At the same time, over 45% of wells (97 out of 213) are located in the Quaternary aquifers, followed by the Miocene aquifers (30 out of 213, Fig. 6). In about 84% of cases, the static water table of the aquifer stabilizes at a depth not exceeding 20 m below the ground level, which suggests low pumping costs in the case of investment (Fig. 7).

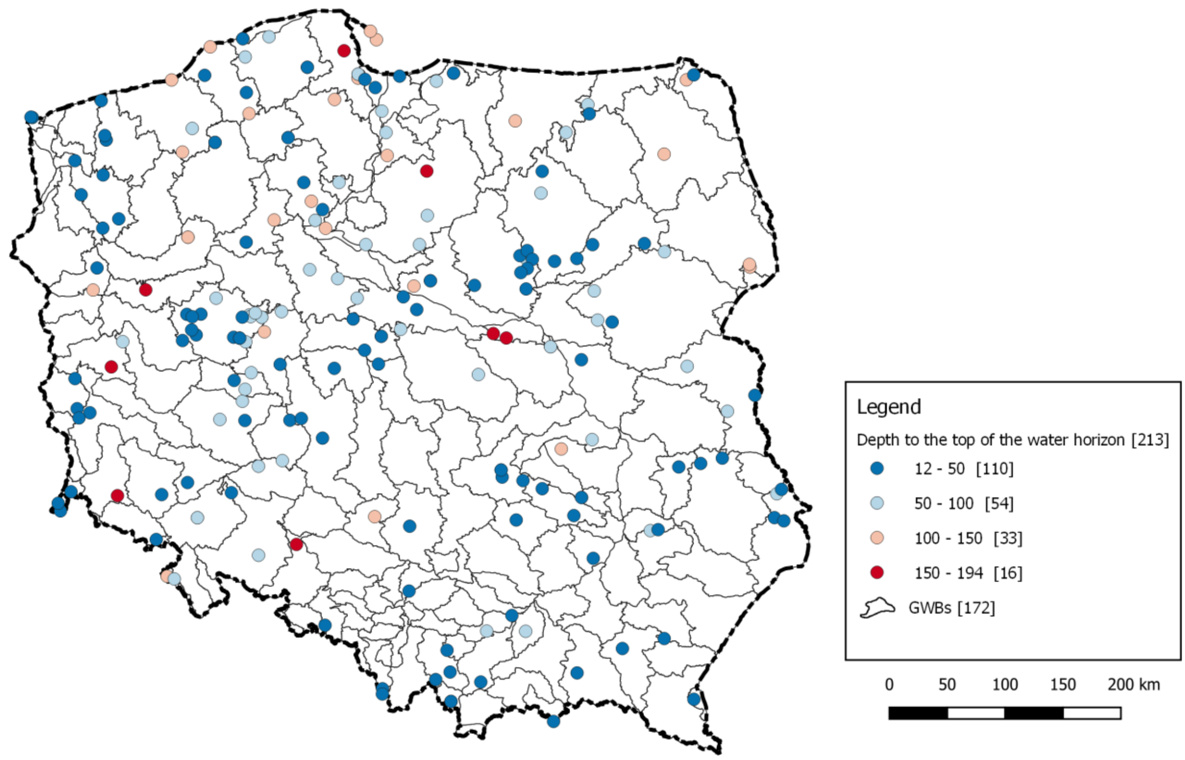

Figure 5: The distribution of wells of the groundwater observation and research network along with the information on the depth to the top of the aquifer after the first selection stage

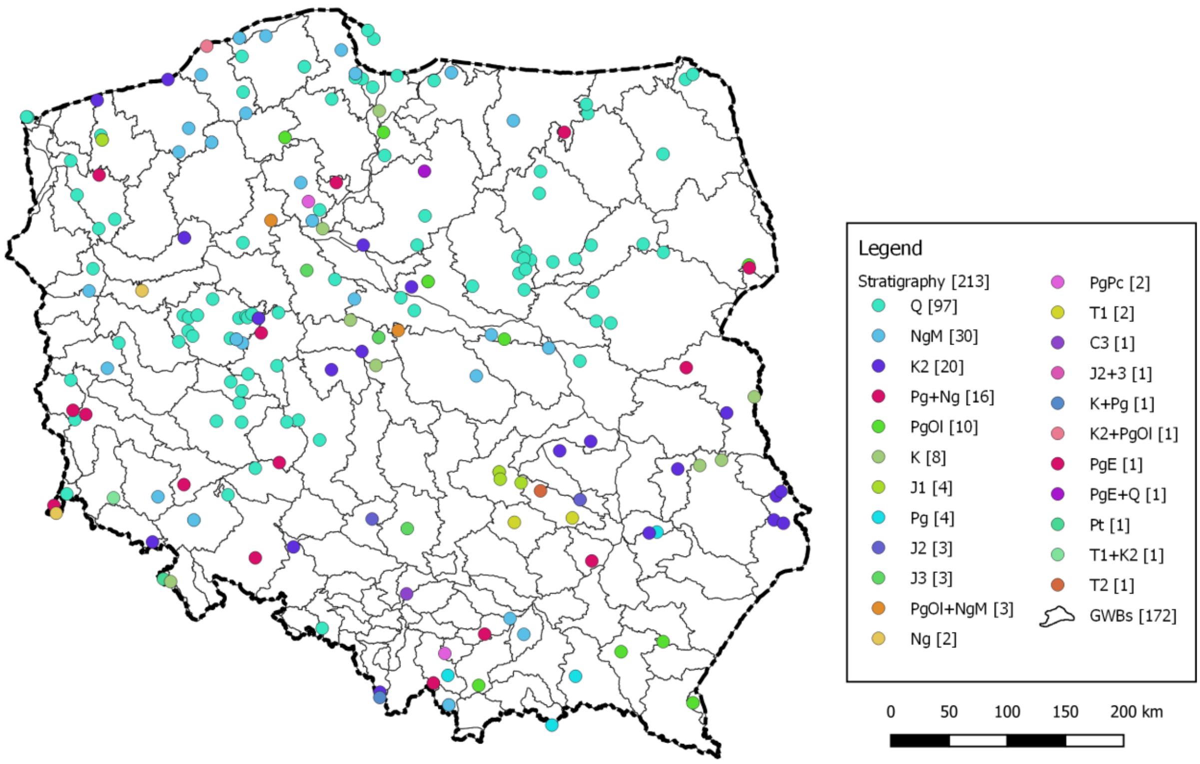

Figure 6: The distribution of wells of the groundwater observation and research network along with the data on the age of rocks in the aquifer after the first selection stage

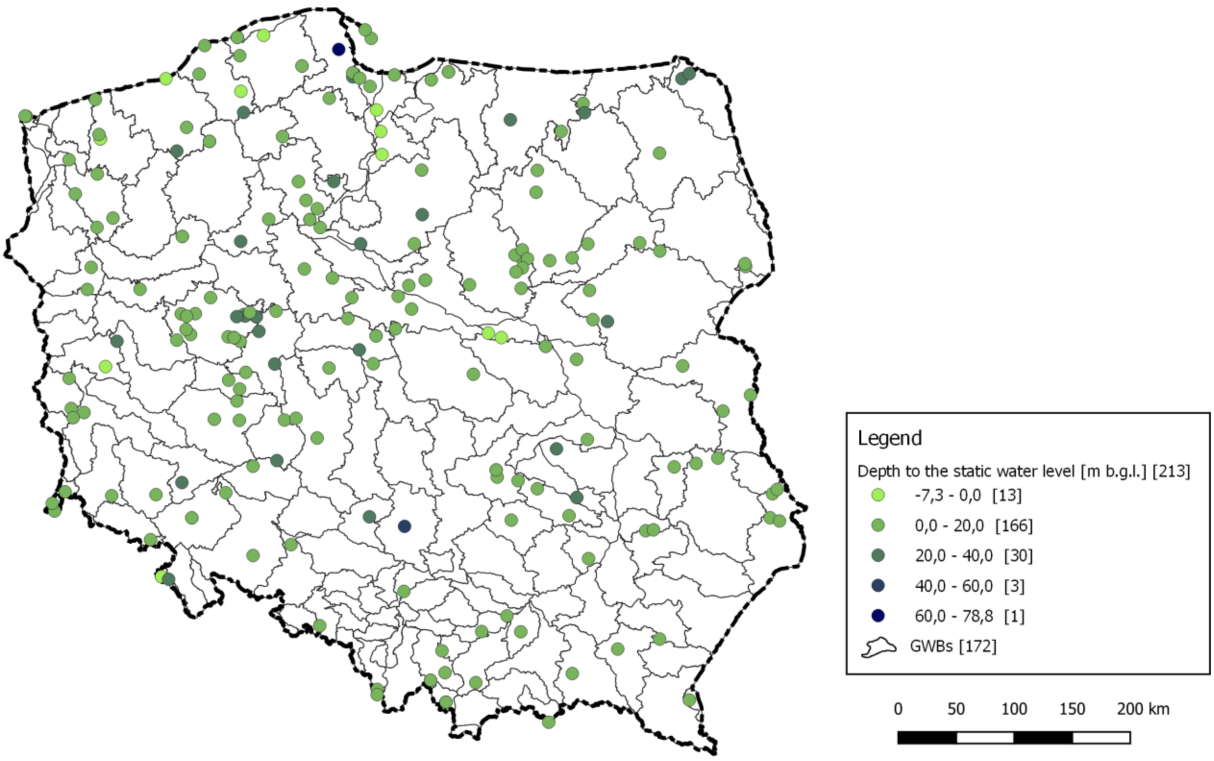

Figure 7: The distribution of wells of the groundwater observation and research network along with the information on the depth of the static water table after the first selection stage

2.2 The Second Stage of Selection

In the second stage of selection, the lithological development of the aquifers was limited to sands and gravels. As a result, 142 of the 1324 wells of the groundwater observation and research network (10.7% of the initial pool) were used for further analysis. Almost all wells are located in western and northern Poland (Fig. 8). The selected wells were presented against the map of the Groundwater Bodies (Fig. 9); while water horizons of the GWBs No. 60 (17 wells), No. 11 (6 wells) and No. 49 (5 wells) are worth special attention.

Table 1 shows the extract from the Groundwater Body No. 60 data sheet for the Quaternary lower inter-clay layer. The data sheet confirms the previously accepted criteria for the selection of boreholes and additionally supplements the information on the expected range of the hydraulic conductivity, which is higher than the threshold value (being about $3 \cdot 10^{-5}$ m/s).

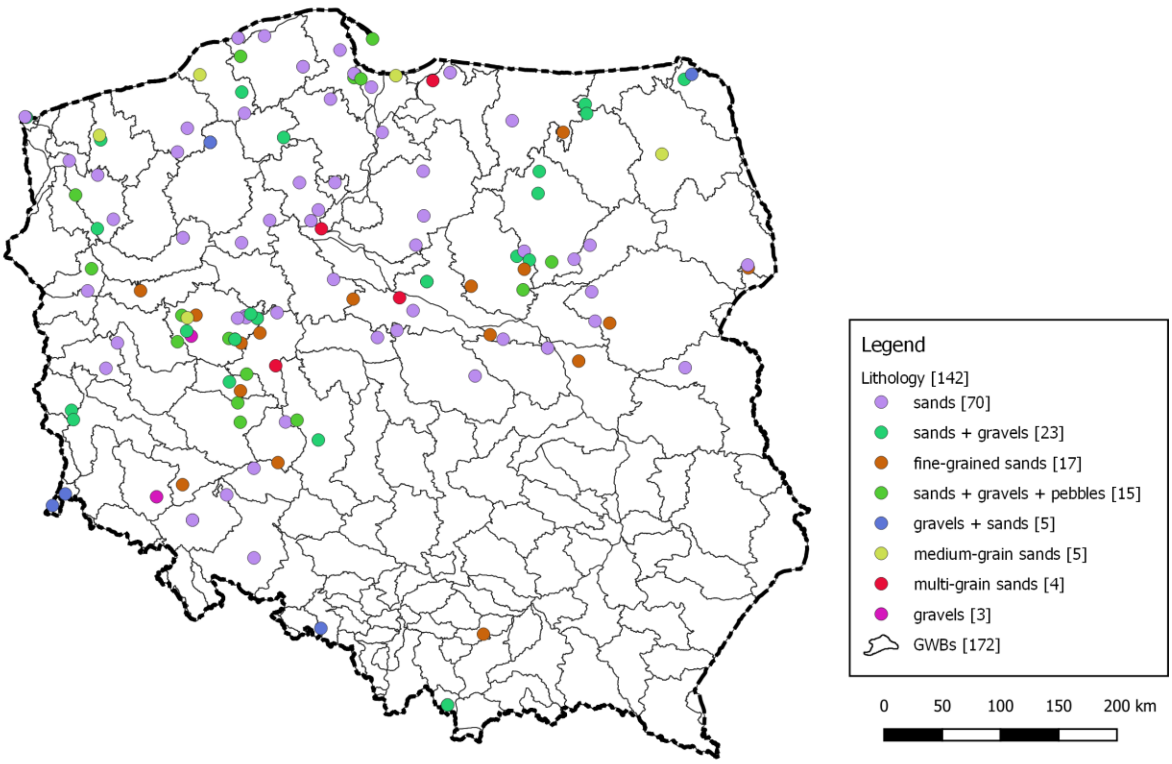

Figure 8: The distribution of wells of the groundwater observation and research network along with the data on the lithological development of aquifers after the second selection stage

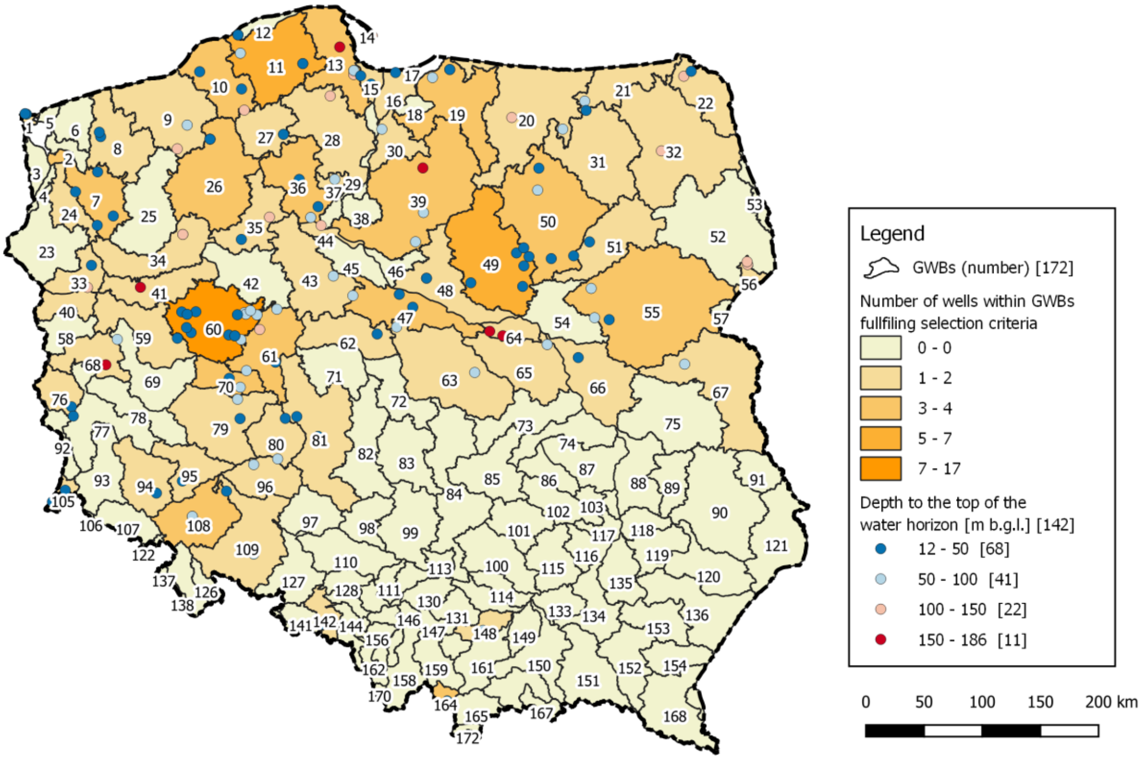

Figure 9: The number of wells of the groundwater observation and research network against the map of the Groundwater Bodies after the second selection stage

Table 1: Lower Inter-clay layer of the Groundwater Body No. 60 (PGI-NRI, PHS 2019)

lower Inter-clay layer	**Stratigraphy**	**Lithology**	**Aquifer Characteristics**	
	Quaternary (Pleistocene)	Sands, gravels	porous	
	Water table type	**Depth of occurrence of aquifers** from – to [m]		
	confined	30 - 100		
	Hydrogeological parameters of the aquifer			
	Thickness from – to	**Hydraulic conductivity** from – to	**Transmissivity** from – to	**Storage coefficient** from – to
	[m]	[m/h] [m/s]	[m^2/h] [m^2/s]	[-]
	5 - 60 (10 – 30)	0.2 – 3.0 $5.5\cdot10^{-5} – 8.3\cdot10^{-4}$	3 – 90 (10 – 35) $8.3\cdot10^{-4} – 2.5\cdot10^{-2}$	0.00012 – 0.0015
	Chemical types of groundwater (natural / deviating from natural types)			
	Natural types: HCO_3–Ca (bicarbonate-calcium water) HCO_3–Ca–Mg (bicarbonate-calcium-magnesium water) HCO_3–So_4–Ca (bicarbonate-sulphate-calcium water) Deviating from natural types: HCO_3–Ca–Na–Mg (bicarbonate-calcium-sodium-magnesium water) HCO_3–Cl–Ca–Na–Mg (bicarbonate-chloride-calcium-magnesium-sodium water) HCO_3–Ca–Na (bicarbonate-calcium-sodium water) HCO_3–Ca–Mg–Na (bicarbonate-calcium-magnesium-sodium water)			

2.3 The Third Stage of Selection

Considering the fact that ATES systems are most often used in commercial facilities, public utility buildings, and residential buildings, the criterion was assumed that ATES systems must be located in areas where the population density is at least two times higher than the average population density in Poland, i.e. around 250 persons/km^2. A vector map with precisely applied demographic information (grid node distance of 1 km) was downloaded from the Geostatistics Portal (CSO 2019) to perform spatial analysis.

As a result of the third stage of selection, 29 wells meeting all previous criteria were determined (Fig. 10). These wells are located, among others, in the following cities: Warsaw, Gdańsk, Wrocław, Bydgoszcz, Słupsk, Stargard, Racibórz, Szczytno, and Mrągowo, from which the first four are major cities in Poland with over 350,000 inhabitants at least.

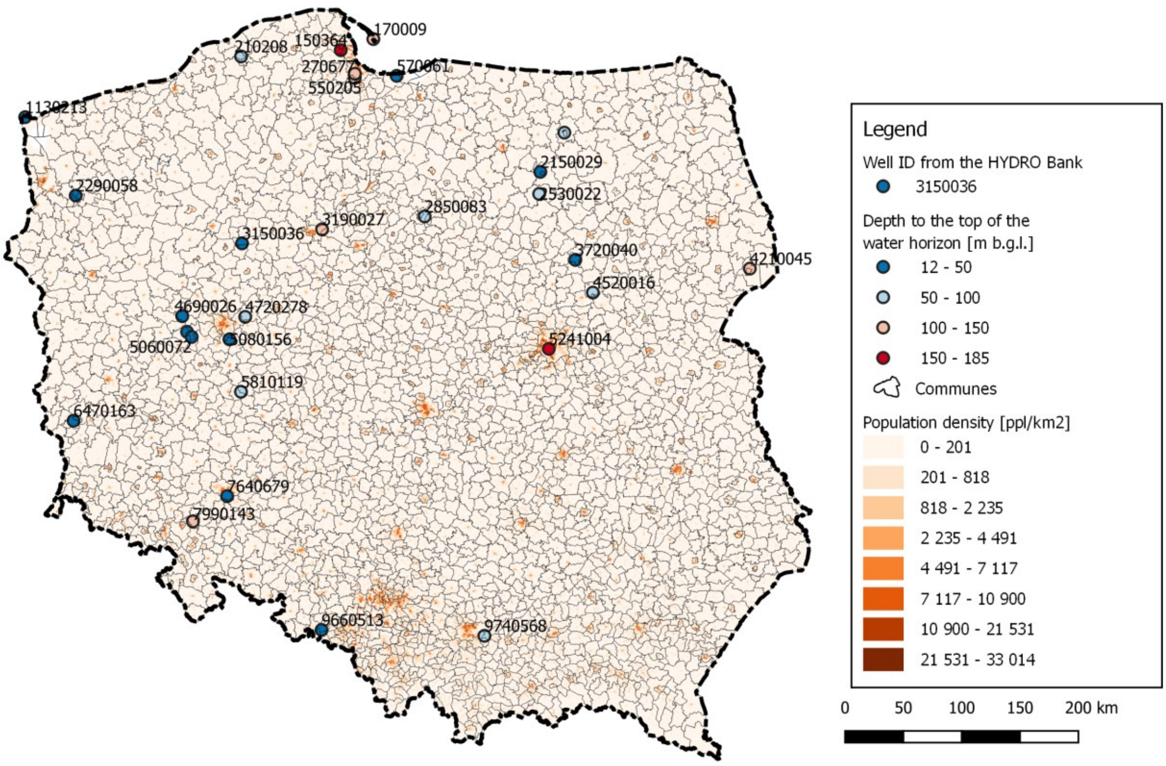

Figure 10: The distribution of wells of the groundwater observation and research network against the population density of Poland (CSO 2019) after the third stage of selection

4. CONCLUSIONS

The aim of this work was to initiate analytical studies on the possibility of heat storage in shallow aquifers (ATES) in Poland. The purpose of this technology, particularly popular in the Netherlands (90% of all systems in the world), is to provide heat and cold for low-temperature consumers, i.e. those whose supply temperature typically does not exceed 50°C, and at the same time they require cooling during summer season. The world experience, mainly from the Benelux and Scandinavia, indicates that low-temperature heat storage in shallow aquifers is a proven technology that does not pose significant technical difficulties, provided regular monitoring of groundwater quality, early detection and prevention of colmatation of wells, and the ongoing maintenance of the system. A well-designed ATES system is characterized by a very short payback time - even below 5 years with a heating/cooling demand of several MW (Miecznik 2016, Fleuchaus et al. 2018).

At this stage of the research, the authors used publicly available data of the groundwater observation and research network and the Groundwater Bodies data sheets (GWBs). As a result of the three-stage selection carried out based on the requirements set for ATES systems, preliminary locations for the first installations for heat and cold storage in shallow aquifers were pre-determined. The analysis shows that aquifers with the desired reservoir parameters are located primarily in northern and western Poland, including the main cities: Warsaw, Gdańsk, Wrocław, or Bydgoszcz. The mentioned areas require much deeper hydrogeological analysis before taking further steps, in particular: verification of the capacity of the wells, the hydraulic conductivity and natural groundwater flow velocity within the aquifer, as well as the analysis of the chemical composition of the waters. Only after positive verification of reservoir parameters of the aquifer, it is advisable to perform computer simulations showing the long-term exploitation of the aquifer under heat storage conditions.

The analysis of the literature on the experience of countries leading in the implementation of ATES indicates that the main obstacles in the initial stages of development are the lack of awareness about technology itself, the lack of interest from central and local authorities, the lack of (or unclear) legal regulations regarding obtaining permits for the development of groundwater heat storage facilities, and technical failures during the implementation of pilot installations. The development of a comprehensive study on the applicability of ATES system in Poland and maps in the GIS environment (available publicly via the Internet) could be an impulse for the development of this technology in Poland.

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