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Assessment of the potential for low-temperature aquifer thermal energy storage (LT-ATES) in Poland

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Low-temperature aquifer thermal energy storage (LT-ATES) is a growing heat management method in western and northern Europe, which enables underground storage of thermal energy utilizing groundwater. The Polish Geological Institute – National Research Institute, in collaboration with the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences and the AGH University of Science and Technology, jointly undertook a comprehensive investigation into the hydrogeological potential for deploying LT-ATES technology in Poland. The two-year project titled "Preliminary assessment of thermal energy storage potential in aquifers in Poland", enabled the evaluation of major usable aquifers based on LT-ATES boundary conditions specific to Poland. A number of hydraulic parameters were carefully assessed, including as most critical: depth to the top of the aquifer; potential yield from a single well; and groundwater velocity. Finally, the total area identified as suitable for LT-ATES in Poland is ~141,000 km², representing around 45% of the country's territory. A classification of LT-ATES potential based on the estimated heating and cooling capacities indicated that ~19% of Poland is suitable for large-scale ATES systems and another 20% of the country has conditions that may offer high capacities but their hydraulic regime is comparatively less favourable.

Key words**:** thermal energy storage, LT-ATES, potential mapping, major usable aquifers, Poland

Introduction

The development of aquifer thermal energy storage (ATES) technology dates back to the 1960s in China. At that time, to prevent land subsidence, water was injected into aquifers. It was quickly noticed that the injected water maintained a fairly stable temperature for many months. The textile industry around Shanghai quickly realized that this method could effectively store cold in large quantities to air-condition their factories during the summer season (Lee, 2010; Fleuchaus et al., 2018). Early industrial ATES systems in China reached their peak deployment in the 1970s and early 1980s, although systematic documentation of these installations remains limited in the international literature (Lee, 2010).

In Europe, intensive development of ATES technology took place in northwestern Europe and southern Scandinavia between the second half of the 1980s and the beginning of the 21st century. By 1978, one of the earliest demonstration systems was built in Uppsala, Sweden, designed to store solar heat in summer and recover it for space heating in winter (Andersson et al., 2003; Lee, 2010; Lund et al., 2011; Fleuchaus et al., 2018).

At that time, many research and demonstration installations were built, and over time, ever more commercial installations were launched, on an increasingly large scale. Currently, it is estimated that there are ~3,000 ATES installations in operation worldwide, of which ~85% are located in the Netherlands and another 10% in Belgium, Sweden, and Denmark (Fleuchaus et al., 2018; Stemmle et al., 2025).

One of the most compelling drivers for future ATES development in Europe, and in Poland in particular, is the need to decarbonize the heating sector, which is largely dependent on fossil fuels. Rising energy prices, combined with European Union mandates to reduce greenhouse gas emissions, are pushing both policymakers and energy providers to explore renewable and decentralized heat sources. High-temperature ATES (HT-ATES) systems look promising as an efficient and long-term solution for storing excess heat from solar thermal collectors, industrial waste, or geothermal plants for later use in winter, potentially reducing the demand on fossil fuel-based district heating. In this context, HT-ATES systems – designed for storage at temperatures above ~70 °C – present promising opportunities for coupling with sources of industrial excess heat, and concentrated solar thermal and geothermal energy (Dobson et al., 2025; Herrmann et al., 2026). However, HT-ATES systems are very rare, with only a few known installations worldwide. Therefore, their long-term performance and economic profitability have not been established by a sufficient number of installations (Herrmann et al., 2026).

On the other hand, LT-ATES facilities with a supply temperature ≤25 °C – account for ~99% of the market (Fleuchaus et al., 2018; Schüppler et al., 2019). This predominance is primarily attributable to the greater accessibility of suitable aquifers, substantially lower capital investment and a short payback period, which is usually between 2 and 10 years and 7 years on average (Fleuchaus et al., 2018; Schüppler et al., 2019).

Low-temperature ATES systems are well-suited for a broad spectrum of large-scale buildings with seasonal heating and cooling demand. Such bidirectional exchange of thermal energy enables the setting up of a temperature gradient between wells located in the warm and cool zones, thereby maximizing the utilization of the technology and shortening the payback time. Typical end-users include public buildings (e.g., universities, hospitals, airports, museums), commercial buildings (such as shopping centers, office complexes, and hotels), as well as industrial and agricultural applications (e.g., greenhouses, data centres) equipped with low-temperature heating systems (Miecznik, 2016; Fleuchaus et al., 2018). Among underground thermal energy storage (UTES) technologies, ATES systems offer the largest storage capacities, both in terms of water volume and energy content. Notably, some LT-ATES installations in Europe achieve capacities exceeding 20,000 MWh, while the largest existing high-temperature PTES (Pit Thermal Energy Storage) system in Vojens (Denmark) has a thermal capacity below 15,000 MWh (Herrmann et al., 2026). These experiences underscore the potential for Poland to adapt and implement ATES, drawing on lessons from mature European markets while tailoring solutions to local hydrogeological and climatic conditions.

In Poland, the development of ATES remains at an early stage, despite the country's favourable conditions for seasonal thermal energy storage, as described by Bloemendal et al. (2015) in their global-scale assessment. Poland's climate profile, characterized by cold winters and warm summers, creates a certain equilibrium between strong natural demand for heating and for cooling, aligning well with the fundamental principles of ATES. Additionally, the presence of extensive sedimentary basins, particularly in central and northern regions, suggests significant hydrogeological potential for aquifer-based storage (Miecznik and Skrzypczak, 2019). Therefore, building on extensive hydrogeological research, environmental modelling, and system integration, ATES presents a promising option for contributing to climate objectives while offering reliable and scalable heating and cooling solutions. Unfortunately, despite these advantages, ATES technology has not yet been adopted on the Polish heating market.

Financial support from domestic sources – primarily the National Fund for Environmental Protection and Water Management (NFOŚiGW) – has significantly contributed to a better assessment of geothermal resources in Poland by financing numerous deep drilling projects (Dziadzio et al., 2021; Sokołowski et al., 2025). Complementary funding from EU programs (e.g., Horizon Europe, the Cohesion Fund) and the EEA and Norwegian Financial Mechanisms has further accelerated the development of geothermal heating and initiated further research. These instruments could be extended to support the development of ATES in Poland by financing feasibility studies and pilot projects. The Polish Geological Institute – National Research Institute (PGI-NRI), along with other Polish universities, including AGH University of Kraków, as well as scientific institutions such as the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences (MEERI PAS), is increasingly active in energy transition research and could play a central role in adapting ATES models to local geological and climatic conditions and overall technical concerns. Nonetheless, to effectively translate the increasing availability of financial support into the successful deployment of ATES systems, it is essential to first address the technical and legal constraints.

The significant challenge lies in aquifer characterization. Poland's publicly accessible hydrogeological mapping system is not tailored for ATES feasibility. While geothermal resource mapping is relatively well developed, it does not provide sufficient data on hydraulic conductivity, porosity, and groundwater flow characteristics, all of which are critical for successful ATES system design. This knowledge gap makes it difficult to identify viable sites and hampers the development of risk assessment protocols. To change the situation, in years 2023-2024 three of the scientific institutions noted above undertook extensive study of available data on groundwater in Poland to assess the actual potential for aquifer use as storage for thermal energy, both heat and cold. The result – a map of low-temperature ATES potential – has been published, showing at the country scale where hydrogeological conditions are favourable for ATES implementation. This means that at least one of the aquifers present down to 200 m of depth meets the boundary conditions, which make possible to store and deliver energy for heating and cooling demand in Poland's climatic zone. This area is further classified relative to the amount of energy that can be obtained from one doublet-well providing a low temperature difference of 4 K. The map, available on https://geologia.pgi.gov.pl/mapy/?page=Podziemne-magazynowanie contains approximate data of hydrogeological parameters of major usable aquifers suitable for ATES installations, such as depth, thickness, transmissivity, single well discharge rate, hydraulic conductivity, groundwater flow velocity and assumed effective porosity used in flow calculations. Additionally, the total number of identified aquifers down to 200 m is also provided. These values cannot be applied at the scale of individual installation, the proper planning of which will always require detailed site investigation. However, the project outcomes should pave the way for further ATES development in Poland. Especially so, since the project also included intensive legal system review with regard to ATES applications in usable groundwater layers. Many gaps were identified, and proposals for changes and amendments were presented to the Polish Ministry of Climate and Environment.

Therefore, to initiate the development of underground thermal energy storage, particularly low-temperature ATES, Poland must begin implementing the long-term strategy outlined by the Ministry of Climate and Environment in the national roadmap for geothermal development, published in late 2021 (Ministry of Climate and Environment, 2021). This should lead to the establishment of a regulatory framework that supports underground thermal energy storage and investments in hydrogeological surveys and digital aquifer databases. It should also incentivize early-stage ATES demonstration projects and align ATES development with the objectives of the Clean Air Programme and the National Energy and Climate Plan. With its natural advantages and growing institutional interest, Poland has the potential to become a regional leader in ATES, but only when the appropriate legal, financial and technical pathways are established.

This study presents a first comprehensive, country-scale analysis of regional hydrogeological data to assess the potential for low-temperature aquifer thermal energy storage (LT-ATES) in Poland. By integrating publicly available groundwater datasets with energy-based performance criteria adapted to Poland's climatic conditions, it provides a framework for identifying areas suitable for seasonal heat and cold storage. Unlike previous assessments that focused on a limited criterion, this work emphasizes hydraulic and storage parameters critical for LT-ATES system design and operation. The results offer a new scientific and planning reference for Poland, supporting the development of pilot projects, regulatory frameworks, and evidence-based energy policy.

Methodological approach for national scale assessment of suitable aquifers for the development of LT-ATES systems in Poland

Poland's countrywide LT-ATES potential study was conducted in 2023-2024, though the preparations for it had started already in 2018. Increasing demand for space cooling, and a reasonably good balance between heating and cooling because of the climate in Poland, allowed an assumption that the technology of seasonal storage of heat and cold in aquifers might significantly raise the efficiency of ground source heat pumps (GSHP). That is why it was so important to investigate whether, and if so where, fresh groundwater layers, historically considered only as water supply sources, could also be suitable for thermal energy storage. The project, ordered by the Ministry of Climate and Environment and funded by the NFOŚiGW, was titled "Preliminary assessment of the possibility of storing thermal energy in aquifers in Poland (ATES)".

As the research concerned freshwater aquifers with their tops situated at a depth of no >200 m, the natural hydrological conditions were examined mostly for low temperature energy storage (LT-ATES). One of the main goals was to assess the potential of shallow aquifers in Poland for thermal energy storage. Therefore, it was necessary to verify assessments made by Bloemendal et al. (2015) and Miecznik and Skrzypczak (2019), but at a much higher spatial resolution.

In Poland, most shallow groundwater-bearing layers in post-glacial sand and gravel deposits are porous. They are abundant in northern and central Poland and are used as drinking water supply sources. These layers are at various depths, have diverse thickness and hydraulic conductivity, and can be confined or unconfined. Their lithological composition and chemical characteristics are influenced by local geological conditions and, in some cases, by anthropogenic impacts. The widest range of data available are always from a major usable aquifer (*pol. abbreviation:* GUPW); information on the others is fragmented and generally scarce countrywide. Fissured and karst aquifers were excluded as potential candidates for energy storage due to the physical processes occurring within them, which make heat retention less effective compared to porous aquifers, as demonstrated by Guglielmetti et al. (2021).

The assessment of the natural potential for thermal energy storage in aquifers in Poland proceeded based on existing geological and hydrogeological data available at the national scale. The principal sources of information were the continuous database of the Hydrogeological Map of Poland (abbrev. in Polish: MHP) at a scale of 1:50,000 – Major Usable Aquifer (MHP GUPW) and the Hydrogeological Map of Poland at a scale of 1:50,000 – First Aquifer – Occurrence and Hydrodynamics (MHP PPW−WH). Supplementary data were obtained from the Central Hydrogeological Data Bank – Bank Hydro (abrev. in Polish CBDH−BH). These abbreviations, resulting from the shortening of Polish names of hydrogeological databases, are used throughout the article.

The analysis focused on the parameters of the major usable aquifer occurring down to 200 m, identified as the most promising in the context of effective thermal energy storage. In accordance with the Instructions for the Development and Digital Edition of the Hydrogeological Map of Poland at a scale of 1:50,000 (Instrukcja…,1999), the major usable aquifer is defined as the first aquifer horizon from the land surface, constituting the principal source of water supply of dominant range and capacity. In addition, the number of supplementary usable aquifers, which could serve to support the system, was determined for individual geological profiles.

Delineation of areas with ATES potential proceeded based on a set of boundary parameters relevant to Poland's groundwater layers and available in data repositories for the whole country. The boundary condition values were adopted based in part on a literature review of ATES systems in Europe, which provides recommended ranges, particularly for parameters such as aquifer transmissivity and groundwater flow velocity (Lee, 2013; Bloemendal and Hartog, 2018; Noethen et al., 2025). These conditions are given in Table 1, while the complete workflow and data used for assessing the ATES potential in Poland is shown in Figure 1.

The evaluation of the potential for aquifer thermal energy storage in Polish conditions was conducted based on three hydrogeological parameters:

- potential yield of a single borehole, representing the capacity to extract groundwater as an energy carrier,
- actual groundwater flow velocity within the aquifer, as a natural hydrodynamic factor to which the design of a given storage system must be adapted,
- depth of the aquifer, which determines formal, legal and economic aspects of system construction, in particular, drilling requirements,

Data on potential well yields and GUPW depth was derived from existing databases and had already been prepared during delineation of the ATES potential area, as described above. The number of aquifer horizons in the geological profile down to 200 m b.g.l. in the delineated area was determined based on the hydrogeological unit descriptions in the MHP 1:50,000 database and borehole profiles from the CBDH–BH. As noted above, the presence of aquifers in the geological profile additional to the major usable aquifer, which could help support the system (e.g., for backup purposes, increasing capacity, or, under favourable hydrochemical conditions, serve as an additional injection reservoir) is considered beneficial as regards aquifer storage systems. Existing national groundwater resource databases do not contain information on actual groundwater flow velocities in aquifers. Such values are usually calculated locally, e.g., during well construction or contaminant migration studies. For the present study, however, regional estimates were required for the entire ATES potential area. Therefore, approximate groundwater flow velocities were calculated on the basis of averaged hydraulic conductivity values determined for the GUPW in each hydrogeological unit of the MHP, combined with hydraulic gradients derived from GUPW groundwater table elevations. Since the MHP provides only a linear representation of groundwater levels in the form of piezometric water level contours, these contours were used to generate information on hydraulic gradients within the GUPW in areas that satisfy the boundary conditions for ATES potential.

Because the input layer had a linear topology, it was converted into a point topology, where nodes inherited the piezometric water level attribute. From these points, a continuous surface layer was generated using interpolation (kriging) in Surfer software. The interpolated grid (500 × 500 m nodes) was then exported as point data: X, Y, H, where X and Y were PL 1992 coordinate system values (EPSG 2180) and H represented the GUPW groundwater elevation.

The resulting point layer (X, Y, H) was imported into QGIS software, where the "slope" algorithm was applied to calculate the slope angle of the surface defined by X, Y, H. This produced a raster layer with the attribute "hydraulic gradient in major usable aquifer", expressed in percent and assigned to each pixel (Figure 2). These values were then aggregated spatially and assigned to a generated regular hexagonal grid with a distance of 1000 m between opposite hexagon sides covering the entire ATES potential area. Each hexagon received an average slope value from the pixels it contained.

The actual groundwater flow velocity shown in Figure 3 was calculated by multiplying the hydraulic gradient (in unitless form) by the hydraulic conductivity value, which was spatially aggregated in the same manner as the gradient, and divided by effective porosity values adopted after K. Busch and L. Luckner (in Pleczyński, 1981) for the hydraulic conductivity ranges given in Table 2.

The assessment of LT-ATES potential across Poland was conducted exclusively based on hydrogeological parameters. The primary objective was to delineate areas capable of supporting large-scale LT-ATES systems, typically delivering several to over a ten megawatts of thermal capacity, contingent upon the feasibility of drilling a sufficient number of wells. At the same time, areas with more constrained hydrogeological conditions – characterized mainly by lower anticipated yields per well – were identified as more suitable for small-scale installations. Additionally, a third class was defined for zones where the interplay of the 3 key parameters listed in Table 3 did not clearly favour either large- or small-scale installations. As a result, following three classes of aquifer suitability were established:

- Class 1 – for systems up to 175 kW per doublet, where estimated yield per well is ≤30 m^3/h;
- Class 2 – for systems above 500 kW, where estimated yield per well is ≥30 m^3/h and the hydraulic regime allows the drilling several doublets. Therefore, two or three doublets may be required to obtain such thermal power;
- Class 3 – a transition between class 1 and class 2 with mixed conditions.

The heating power of an LT-ATES installation used in the above classification was calculated using the following equation:

$$P_{ATES} = Q \cdot c_w \cdot \Delta T \cdot \frac{COP_h}{COP_h - 1}$$

where:
Q is the yield from a single well-expressed in m^3/s, c_w is the volumetric heat capacity of water and ΔT is the temperature difference of water between the warm and cold well, COP_h - heat pump coefficient of performance (in a heating mode).
For classification purposes, the following values were used:

- Q – as in Table 3, but recalculated to m^3/s;
- $c_w = 4.18 \cdot 10^6 \frac{J}{m^3 \cdot K}$;
- ΔT = 4 K;
- COP_h = 5.5, unitless.

The conservative assumption of a temperature difference ΔT of 4 K warrants clarification. This value is considerably lower than the typical ΔT observed in cyclic LT-ATES systems, where the temperature difference between warm and cold wells commonly exceeds 10°C (Herrmann et al., 2026). In our study, the adopted ΔT reflects the minimum thermal gradient expected between production and injection wells in open-loop or unidirectional ATES configurations, as described by Silvestri et al. (2025). These operational modes are particularly advantageous under conditions of elevated groundwater flow velocity – typically greater than 100 m per year – which can lead to increased thermal dispersion and reduced heat recovery. Consequently, the lower ΔT assumption aligns with realistic performance expectations in dynamic hydrogeological environments where cyclic storage may be less effective.

The coefficient of performance of a heat pump can be estimated using the Lorenz cycle approach (Jensen et al., 2018; Walden and Padullés, 2024). Assuming a heat source within the temperature range of 13-20°C – representing groundwater stored in the "warm" wells of an ATES system, a groundwater temperature difference between warm and cold wells of ΔT = 4 K, and a heat sink (heated object) characterized by supply and return temperatures of 40 and 30°C, respectively, together with a pinch-point temperature difference in both the evaporator and condenser of $\Delta T_{pp} = 3K$, and a Lorenz efficiency of $\eta_{Lorenz} = 0.5$, the resulting COP_h is expected to range between 5.2 and 6.8, with higher values corresponding to higher groundwater temperatures. If the temperature difference between the warm and cold wells increases to ΔT = 8 K, COP_h decreases to ~4.9-6.2. To maintain methodological transparency while ensuring accessibility for readers of a geological journal, a fixed COP_h value of 5.5 was adopted.

Results

The GIS-based analysis on a fine grid, consisting of 162 786 uniform hexagons, allowed for the designation of areas meeting the boundary conditions listed in Table 1. It was found that ATES systems of various capacity can be implemented in an area of nearly 141,100 km^2, which constitutes 45.1% of the area of Poland. The GIS analysis was conducted using eight parameters, each represented as a separate layer, with values constrained by the boundary conditions defined. These parameters were then divided into intervals (from 3 to 7 intervals, depending on the parameter) to illustrate their spatial variation. Statistical analysis showing the spatial occurrence of aquifers of given hydrogeological characteristics is summarized in Table 4 and Figure 4. Then, based on the four previously determined parameters – depth to the top of the major usable aquifer, groundwater flow velocity, potential well yield, and number of aquifers – these areas were classified according to their energy potential.

Additionally, the spatial distribution of six base hydrogeological parameters used in this study, namely:

- depth to the top of the major usable aquifer,
- thickness of major usable aquifer,
- transmissivity of major usable aquifer,
- estimated yield from a single well tapping a major usable aquifer,
- hydraulic conductivity of major usable aquifer,
- number of aquifers in geological profile down to 200 m below the ground level,

is shown on individual maps in Appendix 1.

The following description provides a summary of each parameter.

Depth to the top of the major usable aquifer: a great majority (~84%) of major usable aquifers, identified as suitable for ATES systems, have their tops between 50 and 100 m below the ground level. This corresponds to 118,402 km^2 or almost 38% of the territory of Poland. This finding is particularly favourable in light of the additional regulatory requirements applicable to drilling operations exceeding depths of 100 m. The rest of the major usable aquifers have their tops between 100 and 200 m (9.1% of the total identified ATES area), followed by a depth interval from 10 to 50 m (7%).

Number of aquifers: ~40% of the area suitable for ATES systems contains a single aquifer, with a limitation that the top of any water-bearing layer is located no deeper than 200 m below ground level. In another 54% of cases, two aquifers are present, while three or four aquifers were identified in the remaining 6% of the ATES-suitable area.

Aquifer thickness: ~82% of identified aquifers have a thickness not exceeding 40 m. There is no visible trend in the geographical distribution of this parameter.

Aquifer transmissivity: Noethen et al. (2025), in their study dedicated to identifying ATES key locations for hospitals in Lower Saxony, Germany, decided to set the threshold value for transmissivity at 20 m^2/h (480 m^2/d), which allows separating unfavourable from good transmissivity. In the case of our study, only around 18.7% of the identified ATES-suitable area meets this criterion (~26,300 km^2); however, in our opinion, such a threshold value is too restrictive, excluding the possibility of installing smaller-scale ATES systems.

Single well potential yield: high-capacity wells (>50 m^3/h) can be drilled in nearly 50% of the areas identified; however, no distinct spatial distribution pattern is observed.

Hydraulic conductivity: ~99.5% of the identified aquifers have estimated hydraulic conductivity in the range from 0.8 to 70 m/d with a mean value of 17.9 m/d.

Hydraulic gradient: hydraulic gradients >1% are mainly associated with drainage zones in river valleys, but can also be observed in the Kashubian Lake District and in the northwestern part of Poland.

Groundwater velocity: low groundwater velocity is considered favourable for efficient ATES installations. In their recent study, Noethen et al. (2025) proposed a threshold of 0.05 m/d (18.25 m/y) to define such optimal conditions, while velocities ranging from 0.05 to 0.5 m/d (182.5 m/y) were classified as moderate. In our analysis for Poland, groundwater velocity below 200 m/y in the major usable aquifer is estimated to occur at over 85% of the area suitable for ATES installations.

As anticipated, the spatial distribution of ATES classes within the aquifers analysed showed a heterogeneous, mosaic-like pattern (Fig. 5). This reflects the inherent variability in hydrogeological conditions across Poland.

Aquifers classified as Class 1 are characterized by relatively low well yields (≤ 30 m^3/h), slow to moderate natural groundwater flow, and shallow depths not exceeding 100 m. These aquifers cover ~21,438 km², which accounts for 15.2% of the total area identified as having LT-ATES potential in Poland. This also corresponds to 7.0% of the country's inland territory. Due to their limited hydraulic performance, class 1 aquifers are more suitable for the development of LT-ATES systems with relatively small thermal storage capacities.

Aquifers belonging to Class 2 are located in regions with higher well yields and faster natural groundwater flow: conditions that are favourable for the development of larger-capacity LT-ATES systems. In such settings, high extraction and injection rates can locally modify the hydraulic regime, potentially suppressing convective heat losses and enhancing thermal storage efficiency. These aquifers span nearly 58,000 km², representing over 41% of the total area identified as suitable for ATES deployment in Poland. This coverage also corresponds to ~18.9% of the country's territory.

Aquifers assigned to Class 3 exhibit highly variable hydrogeological conditions and have been categorized as areas where LT-ATES storage potential is strongly dependent on site-specific design parameters. Key factors influencing feasibility include the number of wells, their spacing, as well as the technological configuration adopted by the heating and cooling end-user. These mixed conditions were found to be the most widespread in Poland (though closely followed by Class 2 – large installations), covering ~61,600 km². This represents 43.7% of the total area identified as suitable for LT-ATES deployment across the country.

Discussion

Our assessment of the suitability of shallow groundwater aquifers for storing low-temperature heat and cold was based primarily on the serial Hydrogeological Map of Poland (MHP) at a scale of 1:50,000, which provides a broader interpretation of the major usable aquifer (MHP GUPW), the most important source of water supply, as well as the First Aquifer Level (MHP PPW). The MHP was developed between 1996 and 2004 and consists of 1,069 sheets. However, in 1999, an update to the "Instructions for the Development and Computer Editing of the Hydrogeological Map of Poland at a Scale of 1:50,000" was issued, updating, among other things, the method for calculating potential well yield. Due to the scale of the project – executed over eight years by multiple contributors – and the interim revisions to map development guidelines, noticeable discontinuities in selected parameters describing major usable aquifers are clearly evident at sheet boundaries. This is visible, for example, in the maps of thickness, hydraulic conductivity, and the number of aquifers – as included in Appendix 1. Therefore, it should be emphasized that the nationwide assessment for Poland is of an indicative nature only, and the design of each ATES installation must begin with a detailed investigation of local conditions. This investigation should cover both hydrodynamic and hydrochemical aspects, as these may exert a decisive influence on the performance and operational lifespan of storage systems utilizing groundwater.

The approach to defining boundary conditions, such as aquifer transmissivity, thickness, groundwater velocity, and the thickness of isolating layers, also varies among authors. However, it is generally accepted that most favourable conditions for the development of LT-ATES systems require a porous aquifer with a transmissivity of at least 100 m²/d, coupled with a low groundwater velocity, i.e., <100 m/yr, and ideally, <25 m/yr (Bloemendal et al., 2018). Such conditions create an opportunity to exploit groundwater with high yields, and at the same time having a limited radius of thermal influence. Furthermore, the methodology employed in this study for the country-scale classification of LT-ATES systems in Poland provides an estimate of the potential thermal capacity of these systems (Table 3; Fig. 5). Its principal objective, however, is to delineate regions where hydrogeological conditions are most conducive to the development of large-scale installations, as opposed to areas characterized by lower expected well yields or other less favourable hydrogeological constraints. Achieving the desired heating or cooling capacity – for instance, 500 kW – may require drilling of two or more doublets, even in cases where individual wells have very high flow rates. However, detailed calculations concerning the integration of LT-ATES installations with specific types of buildings fall beyond the scope of this paper.

The methodology applied in this study builds on established approaches commonly used in Europe, such as those by Bloemendal and Hartog (2018) in the Netherlands, Stemmle et al. (2025) in Germany, and Noethen et al. (2025) particularly in Lower Saxony. These studies evaluate hydrogeological conditions, aquifer depth, permeability, and groundwater flow at regional or national scales. European methodologies typically consider all aquifer types (porous, fractured, and karst) and apply generalized boundary values, allowing cross-regional comparisons and approximate assessments of ATES potential.

In this study, the same general framework was applied but adapted to Poland's specific hydrogeological conditions and the quality and coverage of national data. The analysis focused on porous, shallow freshwater aquifers, highlighting the major usable aquifer (GUPW) and supporting aquifers (PPW−WH), while excluding fractured and karst aquifers, which are difficult to quantify on regional maps due to their strong local variability. Boundary parameters such as hydraulic conductivity and groundwater flow velocity were adjusted based on national databases (MHP, CBDH-BH), considering the fragmented information on secondary aquifers.

A major limitation in Poland is the absence of operational data from ATES installations, since no such systems are currently in operation, unlike countries such as the Netherlands where abundant operational data allow model calibration and derivation of realistic results through multivariate modelling and iterative refinement.

The methodology applied combines established European assessment principles with practical adaptations to national conditions and data constraints and enabled a high-resolution, locally adapted assessment of LT-ATES potential in Poland.

Given the favourable hydrogeological and climatic conditions across a significant territory of Poland, the Ministry of Climate and Environment should strive to implement the plan included in the "Multi-year Program for the Development of the Use of Geothermal Resources in Poland" (Ministry of Climate and Environment, 2021), which concerns the implementation of pilot installations of underground thermal energy storage systems, as well as financial support for the construction of numerous LT-ATES installations. In its strategy, the Ministry anticipates supporting over 100 such installations until 2040, estimating the amount of funding at ~PLN 159 million (~EUR 37.4 million). It is therefore worth beginning this venture by clarifying legal and administrative uncertainties and then financing the construction of several pilot installations. This will enable Polish researchers, consulting companies, and geological service providers to acquire essential expertise and further advance their competencies in the design, implementation, and operation of ATES systems. As a result, it will contribute to accelerating the development of the underground thermal energy storage market in Poland.

Another important issue is the promotion of low-temperature heating, in which heat pumps can meet the user's temperature requirements while maintaining a high COP. This will enable a much wider use of Poland's geothermal resources and underground heat storage than is currently the case. This will result in the reduced use of peak-load boilers, thus contributing to improved air quality.

The methodology applied and analyses conducted provide a solid foundation for planning pilot projects and developing regulatory frameworks for ATES in Poland.

Conclusions

Based on the analysis presented, LT-ATES technology could be feasibly implemented across nearly half of Poland's territory – ~141,000 km² – where hydrogeological conditions are considered favourable for this form of underground thermal energy management. However, the development of heat and cold storage in aquifers requires more than that. The map of LT-ATES potential is just the beginning of a long road to the deployment of ATES installations for individual or group heating and cooling as well as into heating and cooling grids. This nationwide assessment of LT-ATES potential is indicative only and cannot be substitute for a detailed local analysis. Hydrodynamic and hydrochemical factors can significantly influence system performance and operational lifespan. Each installation must be then designed based on site-specific geological and hydrogeological conditions as well as actual heating and cooling demand for the system end-user. We must develop cost-effective methods for investigating local natural conditions in order to obtain all the information necessary to properly design efficient and reliable LT-ATES systems capable of long-term operation. Advanced technological solutions may be required to mitigate less favourable natural properties of aquifers.

Complementing these technical efforts, the establishment of clear permitting procedures, enhanced aquifer data acquisition, and the initiation of demonstration projects subsidized by the Ministry of Climate and Environment can further accelerate market readiness. Through such integrated actions, countries like Poland can begin to unlock the strategic value of ATES in decarbonization of the heat market and improvement of air quality.

Data availability: The map containing classification and hydrogeological parameters of all areas identified as favourable for the development of LT-ATES technology in Poland is available as a web-map service at: https://geologia.pgi.gov.pl/mapy/?page=Podziemne-magazynowanie

A dedicated website on the assessment of LT-ATES potential in Poland is available at: https://www.pgi.gov.pl/srodowiskowa/bloki-tematyczne/ates.html

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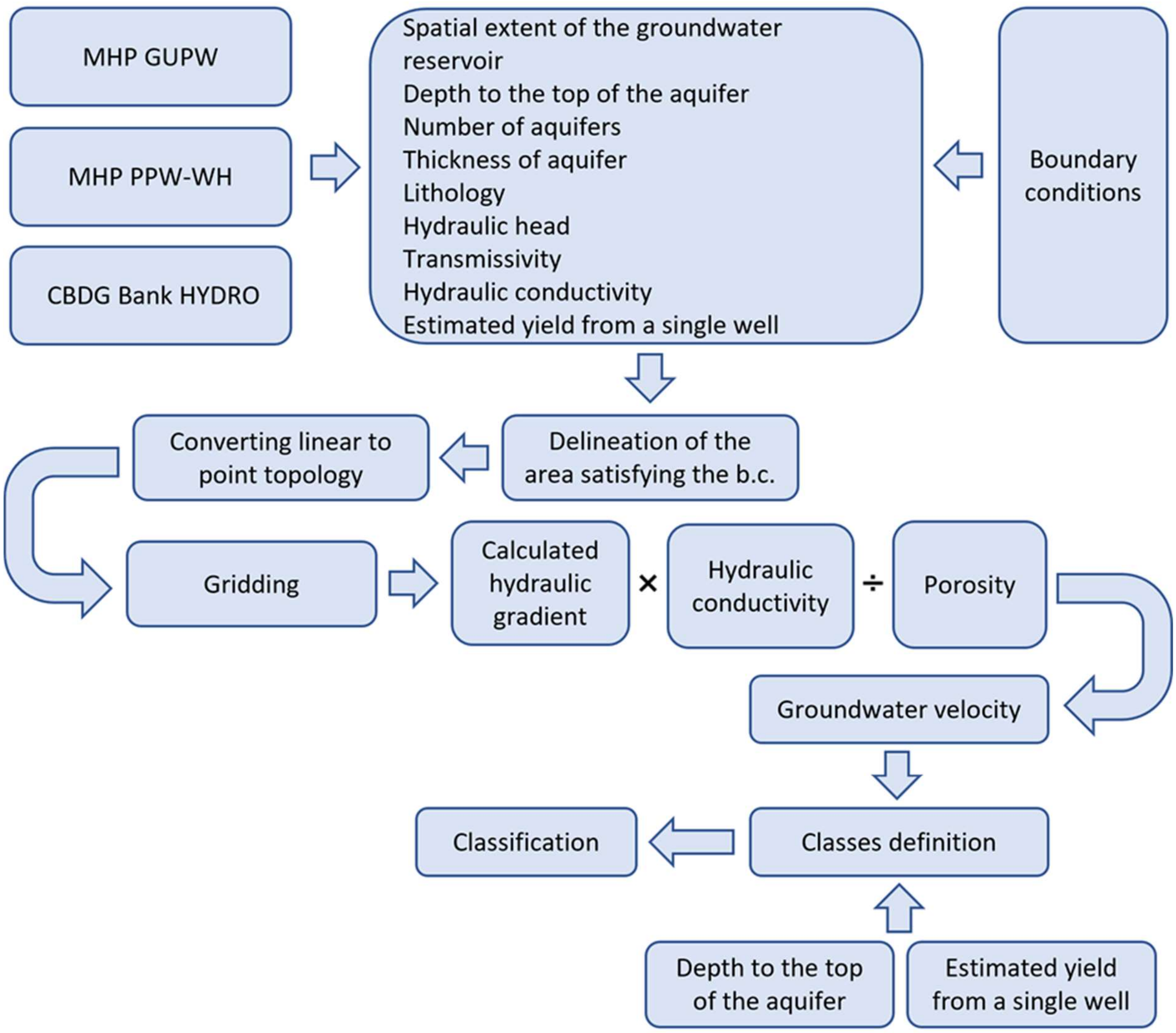

Fig. 1. Workflow and databases used for assessing ATES potential in Poland

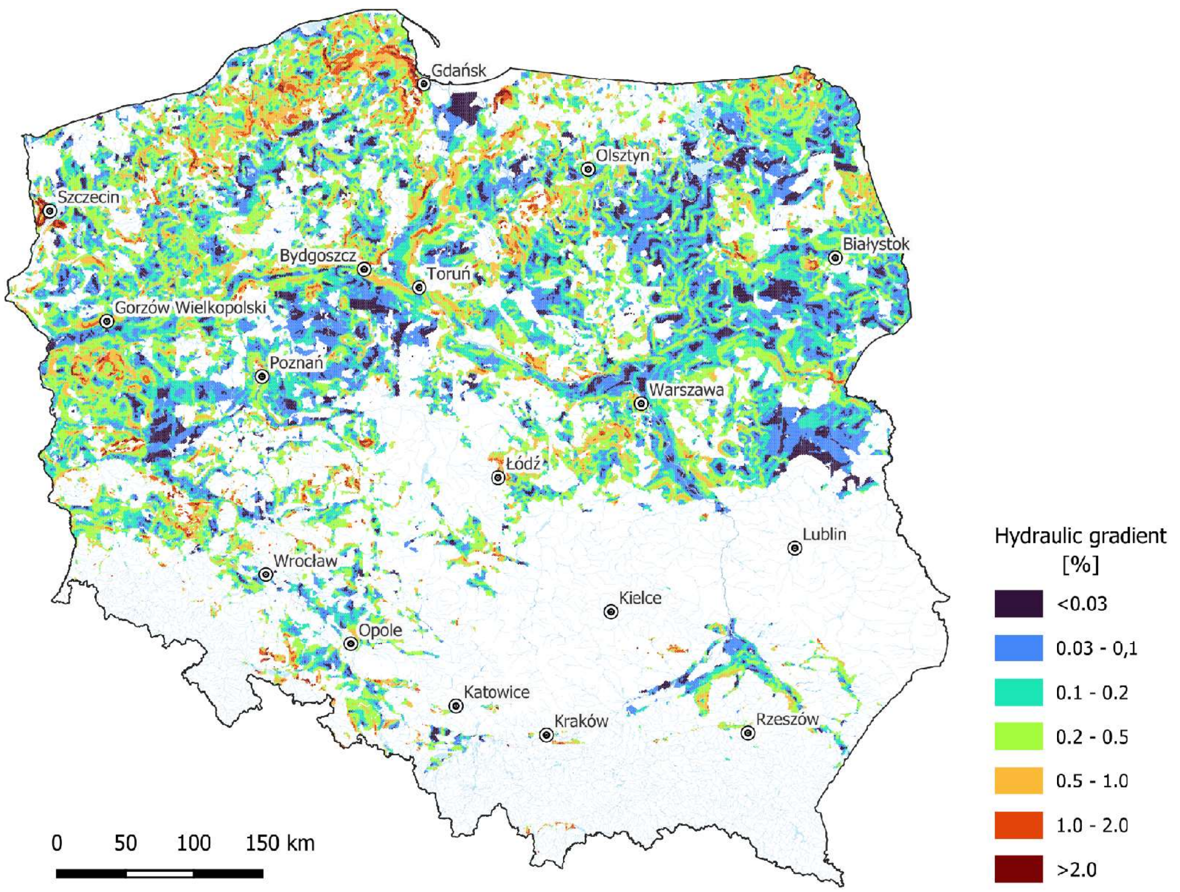

Fig. 2. Estimation of the hydraulic gradient in major usable aquifers in areas prospective for ATES development

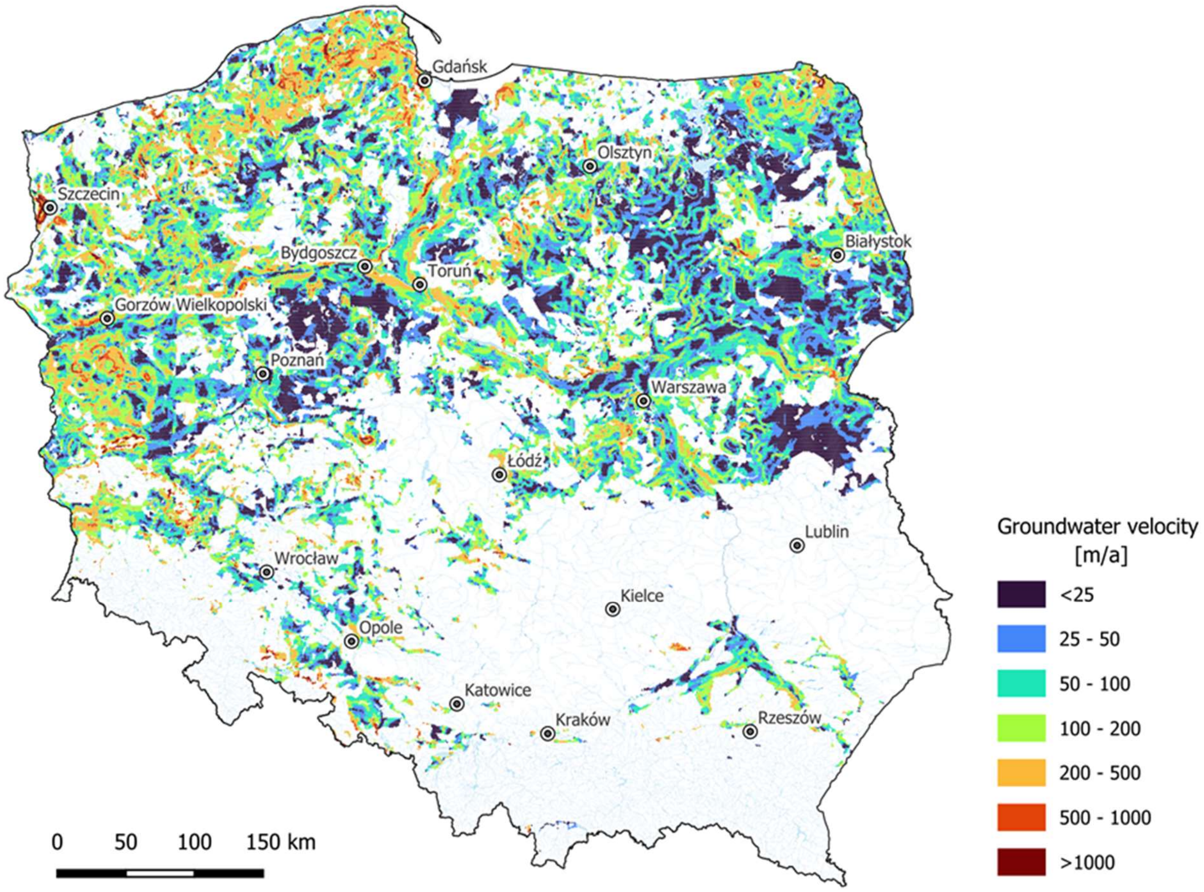

Fig. 3. Calculated groundwater flow velocity in major usable aquifers in areas prospective for ATES development

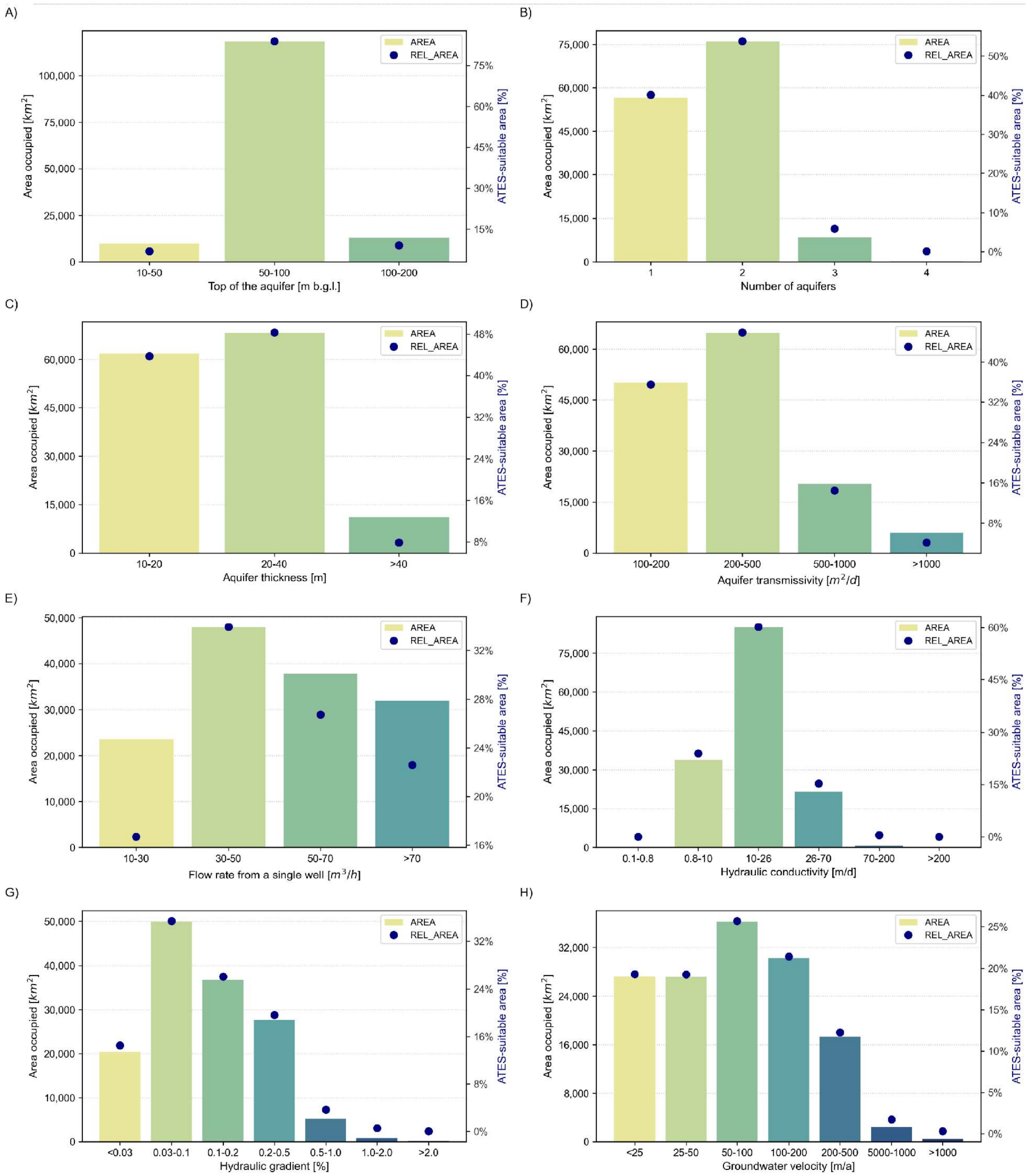

Fig. 4. Distribution of hydrogeological parameters in areas identified as favourable for ATES development

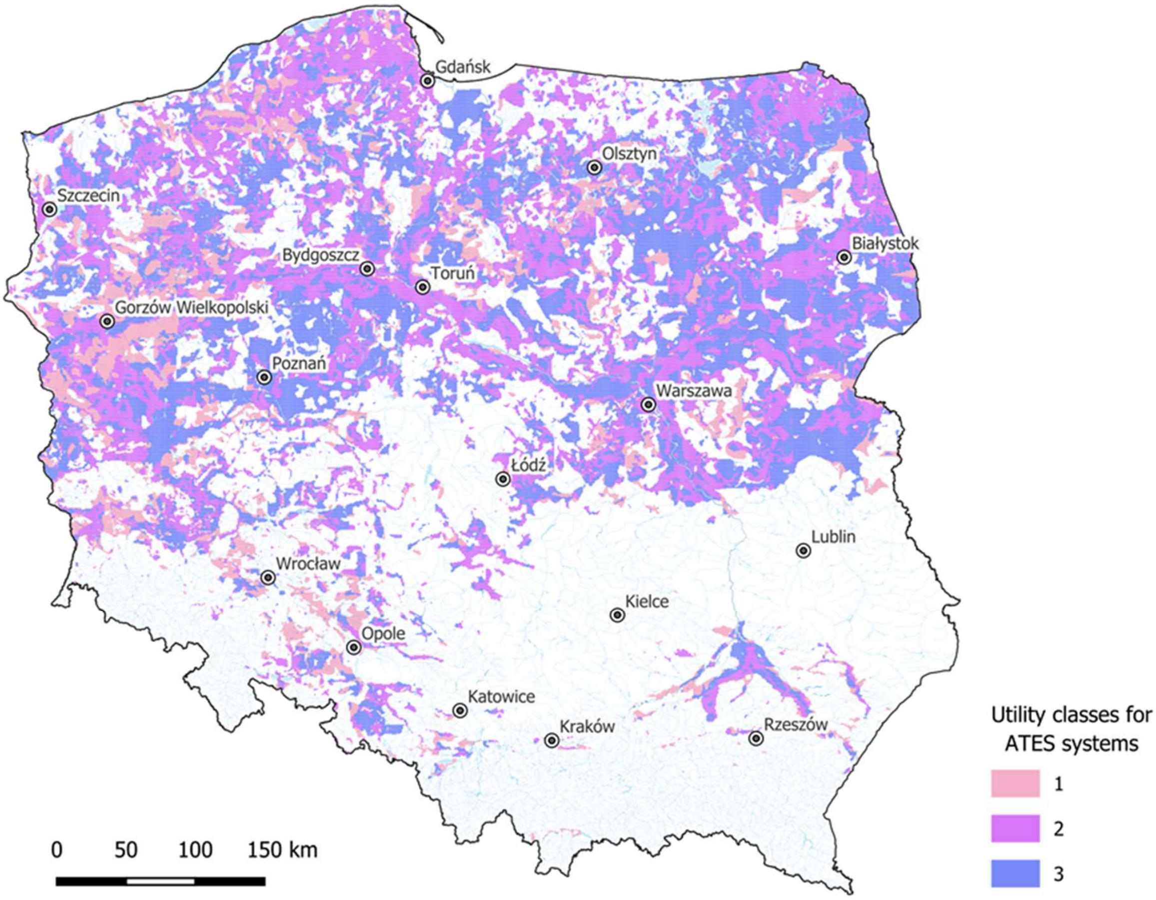

Fig. 5. Classification of LT-ATES potential in Poland (class definition and colors used as in Table 3)

Table 1. Boundary conditions for ATES adopted for groundwater in Poland

Min. aquifer thickness	Min. depth to aquifer top	Min. aquifer transmissivity	Min. yield from a single well	Aquifer type	Min. number of aquifers
[m]	[m b.g.l.]	[m^2/d]	[m^3/h]	-	-

10	10	100	10	porous, both confined and unconfined	1

Table 2. Effective porosity adopted according to hydraulic conductivity

Hydraulic conductivity range [m/d]	Adopted effective porosity [–]
0.1–0.8	0.05
0.9–10.0	0.10
10.1–26.0	0.15
26.1–70.0	0.20
70.1–200.0	0.23
>200.0	0.25

Table 3. Classes used for evaluation of ATES potential in Poland

ATES potential class	Depth of aquifer top	Single well potential yield	Natural groundwater flow velocity	Number of aquifers
	m b.g.l.	m^3/h	m/yr	1 – only one aquifer 2 – more than one aquifer
1 – for systems up to 175 kW	10 - 100	10 - 30	<= 25	2
				1
			25 - 100	2
				1
			>100	2
				1
2 – for systems above 500 kW	10 - 100	>70	25 - 100	2
				1
			>100	2
				1
		30 - 70	>100	2
				1
	100 - 200	>70	25 - 100	2
				1
		>70	>100	2
				1
		30 - 70	25 - 100	2
			>100	2
				1
3 – mixed conditions, power adjustment by installation technical design	10 - 100	>70	<= 25	2
				1
		30 - 70	<= 25	2
				1
			25 - 100	2
				1
	100 - 200	>70	<= 25	2

				1
		30 - 70	<= 25	2
				1
			25 - 100	1
		10 - 30	<= 25	2
				1
			25 - 100	2
				1
			>100	2
				1

Table 4. Summary of the distribution of hydrogeological parameter ranges in Poland that meet the boundary criteria for ATES system suitability

Class / Interval	Area occupied	Relative to the total ATES area	Relative to the area of Poland
	[km^2]	[%]	[%]
Depth to the top of the major usable aquifer			
10-50 m b.g.l.	9,825	7.0	3.1
50-100 m b.g.l.	118,402	83.9	37.9
100-200 m b.g.l.	12,834	9.1	4.1
Number of aquifers			
1	56,560	40.1	18.1
2	75,954	53.8	24.3
3	8,350	5.9	2.7
4	197	0.1	0.1
Aquifer thickness			
10-20 m	61,761	43.8	19.7
20-40 m	68,160	48.3	21.8
>40 m	11,139	7.9	3.6
Aquifer transmissivity			
100-200 m^2/d	50,076	35.5	16.0
200-500 m^2/d	64,703	45.9	20.7
500-1000 m^2/d	20,396	14.5	6.5
>1000 m^2/d	5,885	4.2	1.9
Yield from a single well			
10-30 m^3/h	23,528	16.7	7.5
30-50 m^3/h	47,905	34.0	15.3
50-70 m^3/h	37,729	26.7	12.1
>70 m^3/h	31,899	22.6	10.2
Hydraulic conductivity			
0.1-0.8 m/d	62	0.0	0.0
0.8-10 m/d	33,838	24.0	10.8
10-26 m/d	84,978	60.2	27.2
26-70 m/d	21,519	15.3	6.9
70-200 m/d	661	0.5	0.2
>200 m/d	3	0.0	0.0
Hydraulic gradient			
<0.03%	20,475	14.5	6.5
0.03-0.1%	49,931	35.4	16.0
0.1-0.2%	36,765	26.1	11.8
0.2-0.5%	27,693	19.6	8.9
0.5-1.0%	5,238	3.7	1.7
1.0-2.0%	794	0.6	0.3
>2.0%	78	0.1	0.0
Groundwater velocity			
<25 m/yr	27,215	19.3	8.7
25-50> m/yr	27,182	19.3	8.7
50-100 m/yr	36,248	25.7	11.6
100-200 m/yr	30,227	21.4	9.7
200-500> m/yr	17,277	12.2	5.5
500-1000 m/yr	2,475	1.8	0.8

>1000 m/yr	437	0.3	0.1
Utility classes			
Installations <175 kW	21,438	15.2	7.0
Installations >500 kW	57,992	41.1	18.9
Mixed conditions	61,630	43.7	20.1

APPENDIX 1

Selected hydrogeological parameters of major usable aquifers in areas suitable for LT-ATES deployment

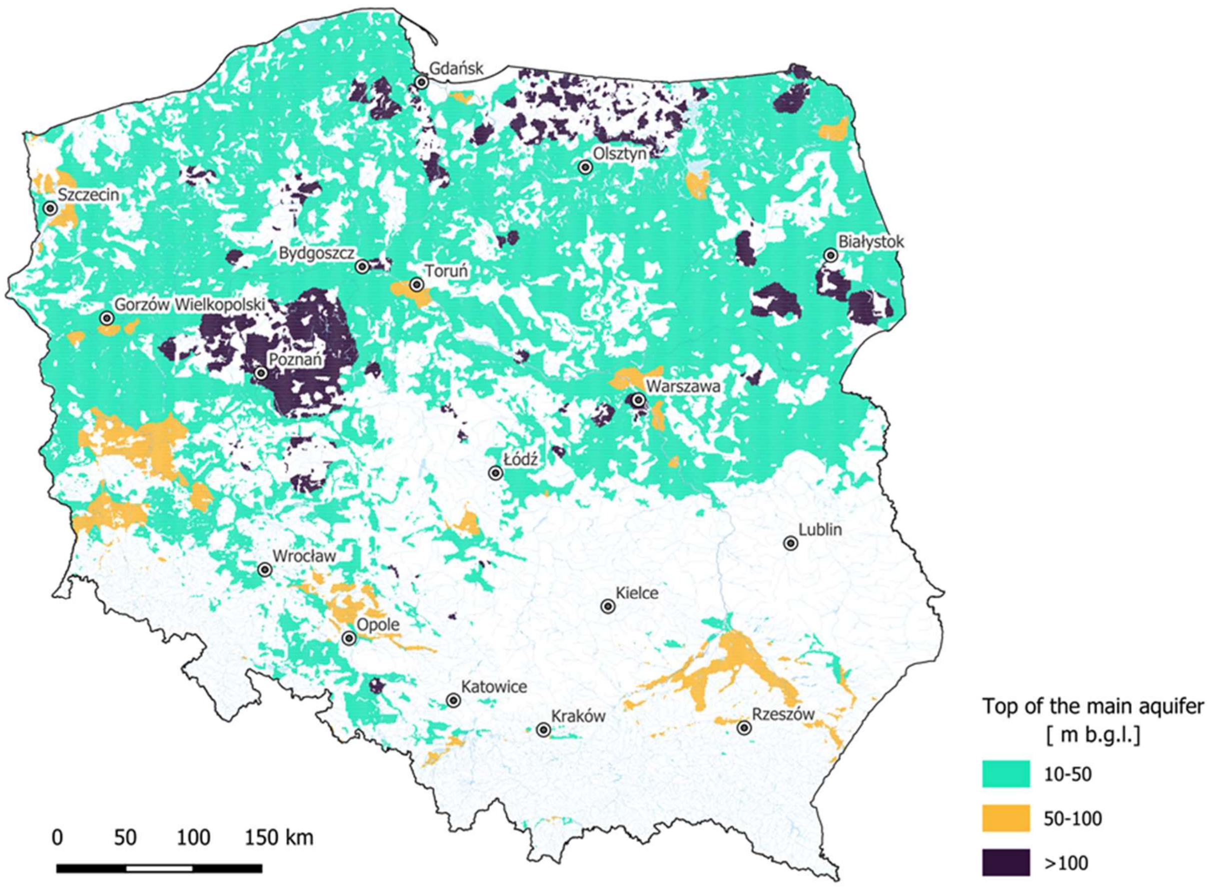

Figure A1. Depth to the top of major usable aquifers in LT-ATES-suitable areas, based on the Hydrogeological Map of Poland at 1:50,000 scale

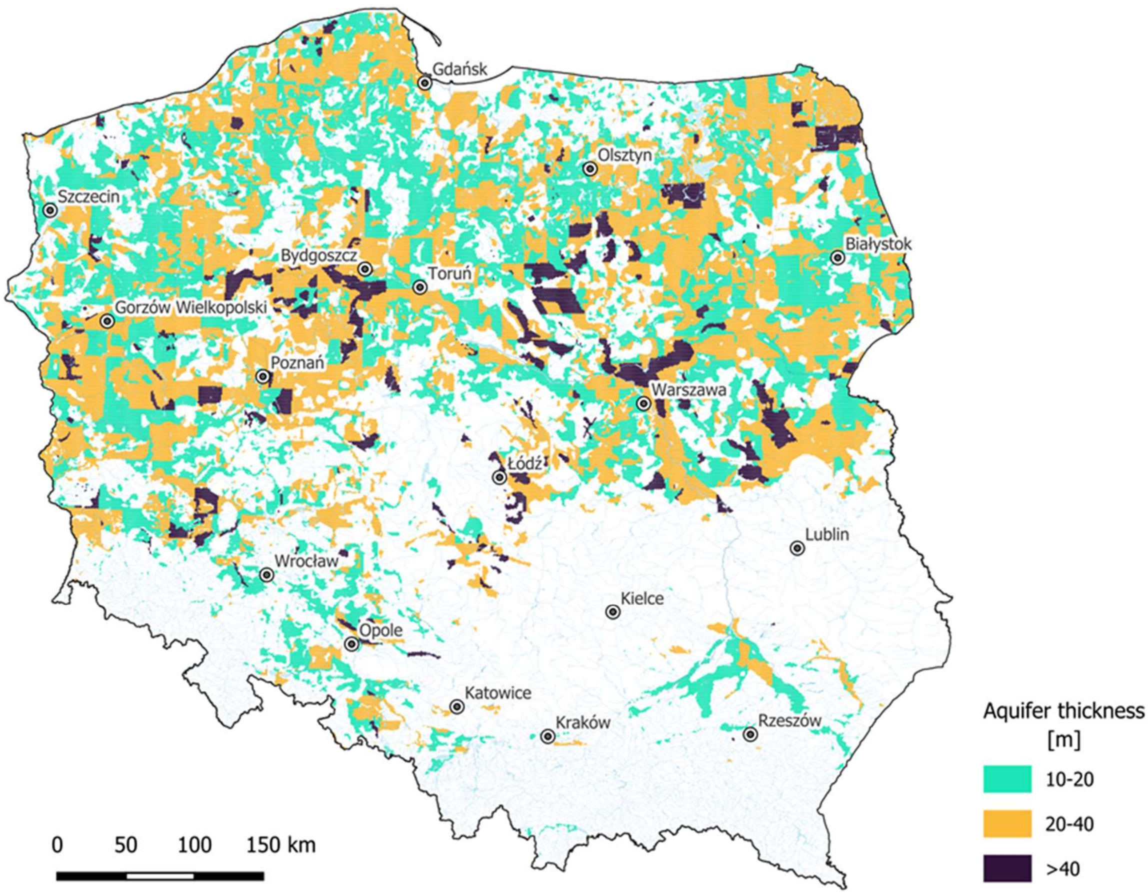

Figure A2. Thickness of major usable aquifers in LT-ATES-suitable areas, based on the Hydrogeological Map of Poland at 1:50,000 scale

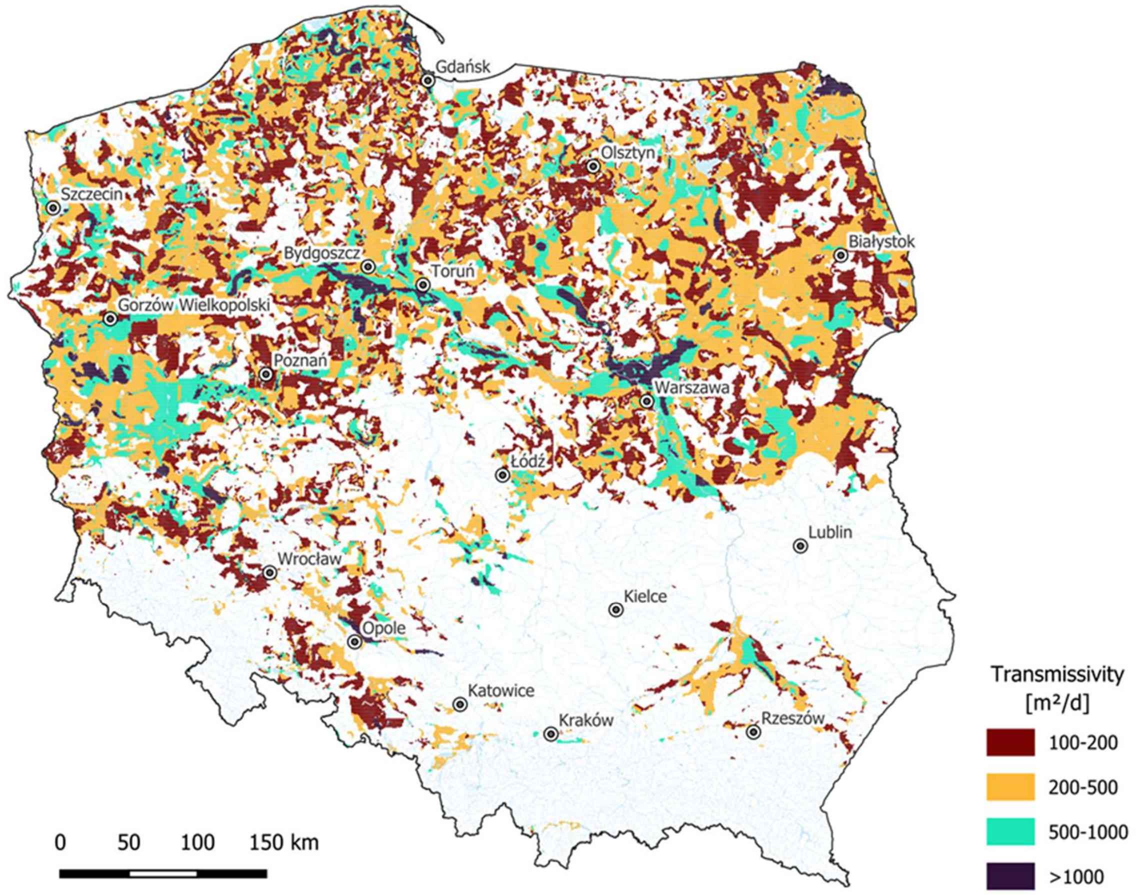

Figure A3. Transmissivity of major usable aquifers in LT-ATES-suitable areas, based on the Hydrogeological Map of Poland at 1:50,000 scale

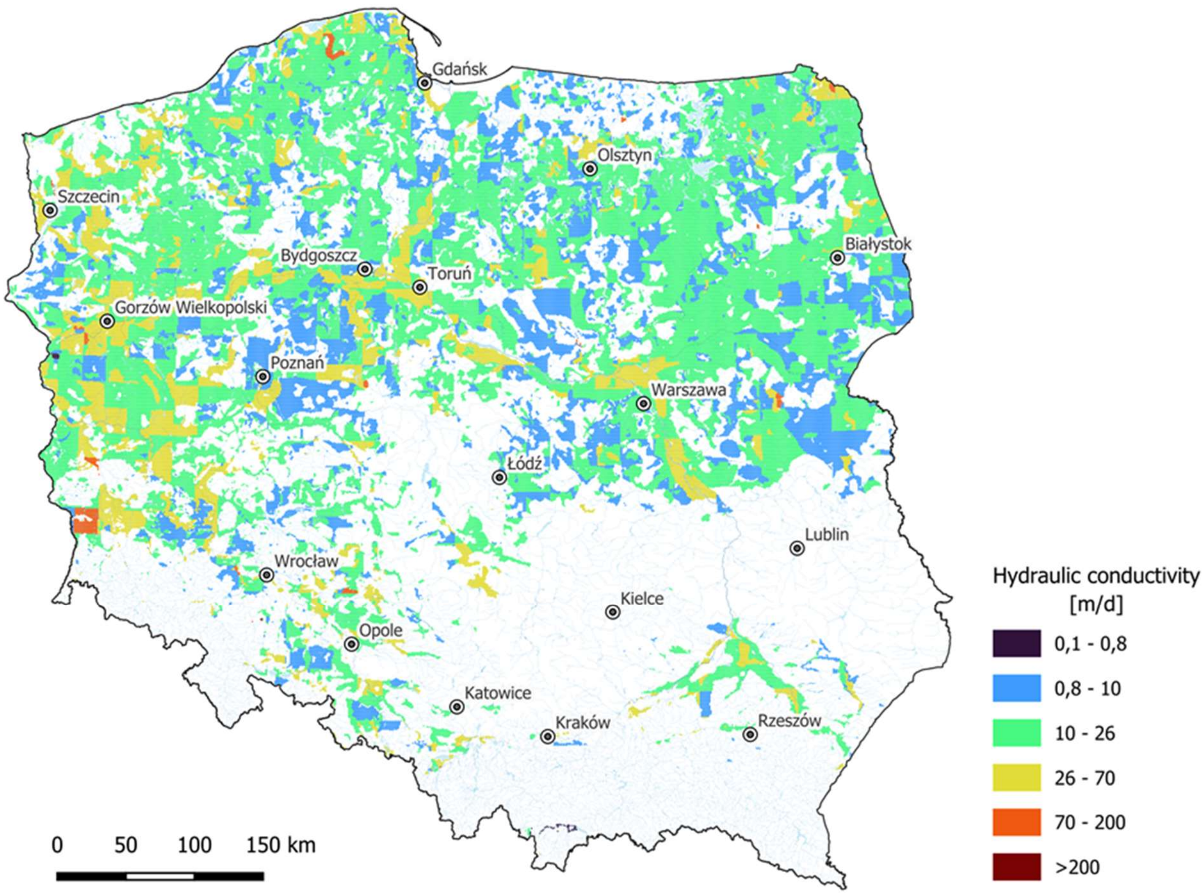

Figure A4. Hydraulic conductivity of major usable aquifers in LT-ATES-suitable areas, based on the Hydrogeological Map of Poland at 1:50,000 scale and the Bank Hydro database.

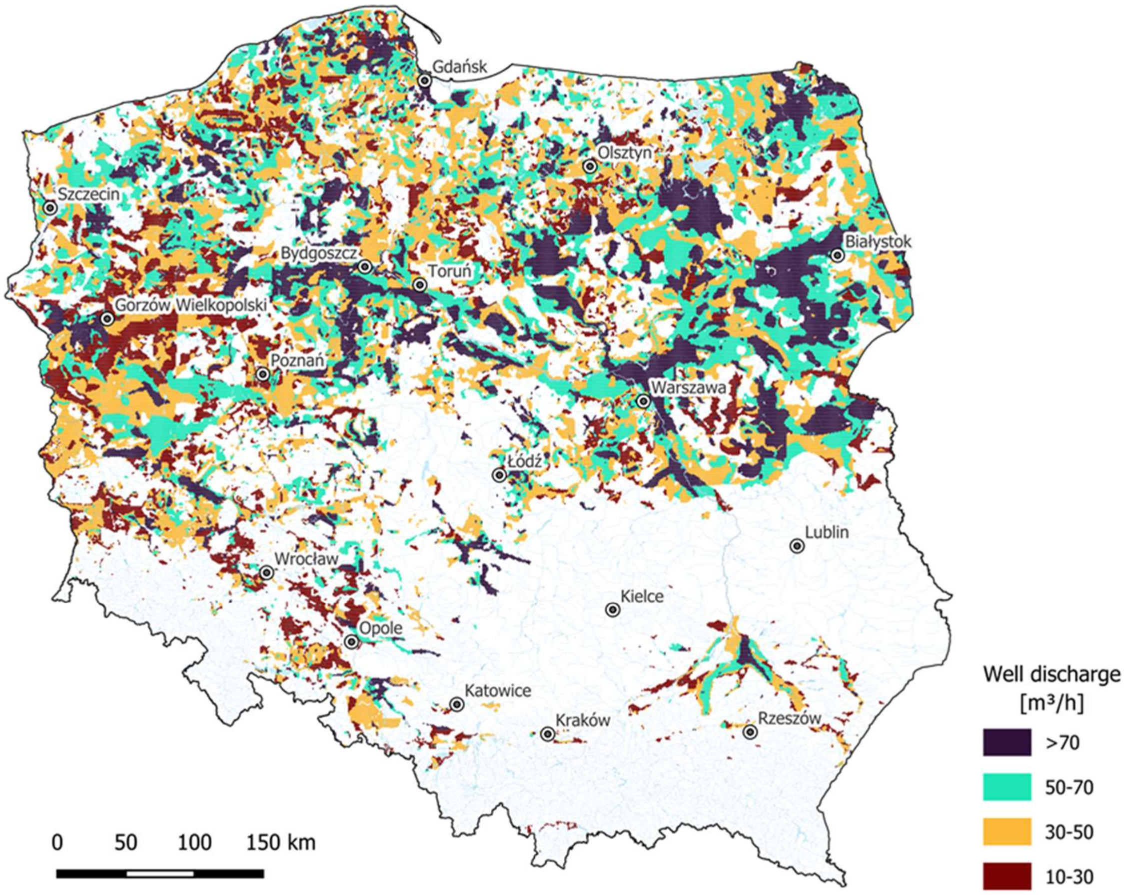

Figure A5. Potential yield from a well tapping a major usable aquifer in LT-ATES-suitable areas, based on the Hydrogeological Map of Poland at 1:50,000 scale

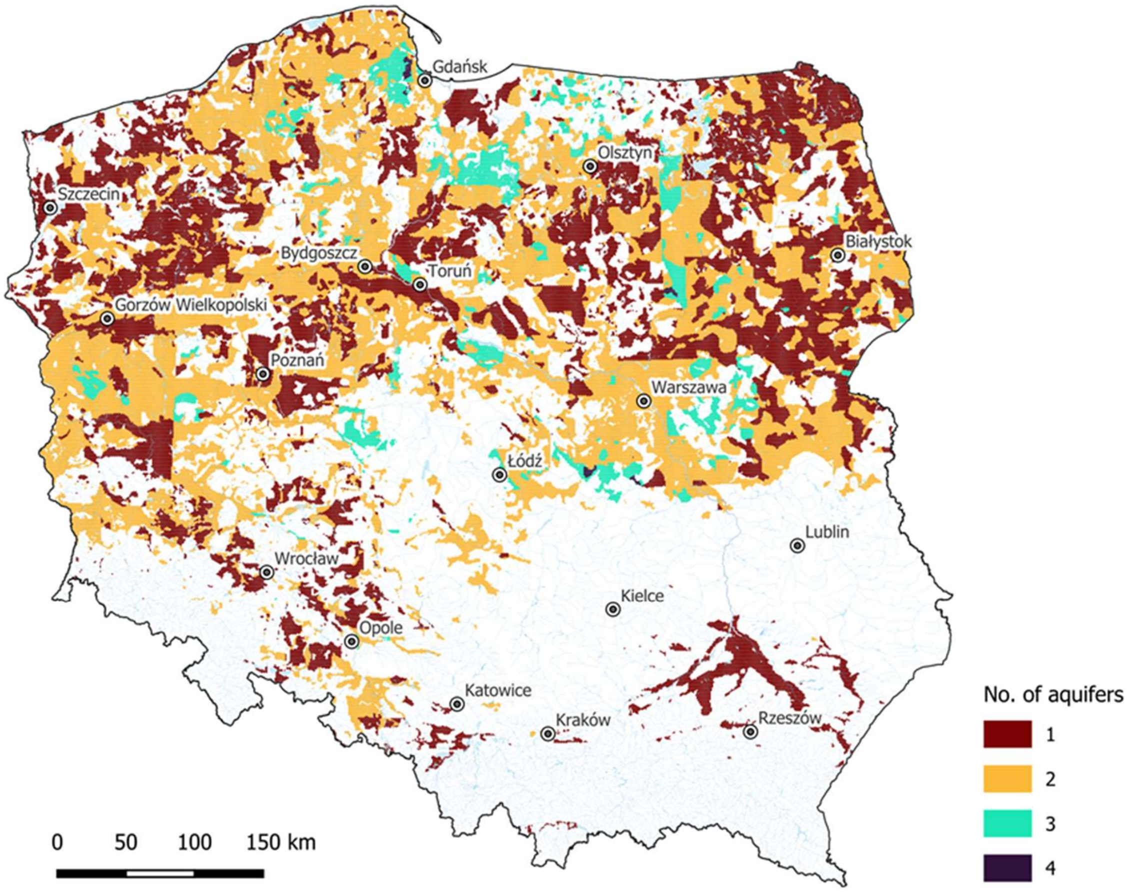

Figure A6. Number of identified aquifers down to a depth of 200 m in LT-ATES-suitable areas, based on the Hydrogeological Map of Poland at 1:50,000 scale and the Bank Hydro database.