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Review

Geothermal Water Management Using the Example of the Polish Lowland (Poland)—Key Aspects Related to Co-Management of Drinking and Geothermal Water

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Abstract: Over the last few years, there has been an upsurge in the demand for drinking water and for water used in agriculture, industry, and others. Consequently, research is needed to find new technologies and methods for the comprehensive use of geothermal water sources, to provide for new resources of water. The paper shows the results of preliminary recognition in the case of the possible exploitation of the Jurassic aquifer in the Polish lowlands, considering the security of the adjacent layers. The considerations are based on experience in the exploitation of the resources of the Paris basin in France. Initial conclusions point to a high potential for such a solution, also in the Paris basin scientists are considering the use of previously unmanaged Jurassic resources.

Keywords: geothermal water; water management; Lower Jurassic; Lower Cretaceous

1. Introduction

In the past, the locations of water resources determined the areas that were possible for human settlements. In many parts of the world, the limitation still exists, and the widespread availability of drinking water for all social classes is still a challenge. This problem is exacerbated by increasing population numbers, dwindling water resources, increasing frequency, and duration of droughts, as well as economic and urban development [1]. Due to lack of freshwater resources the geothermal water gains more and more value and attention as efficient source of energy and also as drinking water resource or can be evaluated for other uses comprising bathing, agriculture, balneology [2,3]. To encourage Member State to take actions to protect water environment European Union has established Water Framework Directive 2000/60/EC (WFD) of the European Parliament and Council on 23 October 2000. The main aim of Directive is to regulate and unify European Union Water Policy and union actions to determine a mutual framework [4–7].

In Poland, as in other EU countries, many actions are being implemented due to the obligation imposed by overarching strategic objectives of EU water policy and the unified management of water resources. Polish law on water management and protection had already been adapted in 2001, initially in the Water Law of 18 July 2001 (Journal of Laws of 2015 item 469 as amended) [8,9]. The Polish Water Law Act and the Water Framework Directive require development and implementation of groundwater protection programs to achieve and maintain good groundwater status. Similar to the situation in the world, also in Poland the growing water deficit is observed and is a subject of numerous research [10–12]. The problem with deficit regions is correlated with: (1) the usage of water resources (including high mineralized water which can threaten the sustainable use of surface water and groundwater resources), (2) the expanding ratio of consumption of groundwater resources, mostly in intensively exploited areas, and (3) the lack of possibilities for recharging municipal water supply systems. Therefore, works are undertaken to upsurge the efficiency of resource use while maintaining the safety of the resources [13–16].

One of the methods of broadly understood groundwater protection, potentially constituting a source of water intended for consumption in Poland, is the developed and implemented concept of documenting and protecting the most valuable resources of these waters—the main groundwater reservoirs (GZWP in Polish). According to contractual separation criteria, due to high water quality, abundance, and potential productivity, the GZWP are the most valuable parts of hydro-structural units and aquifers, requiring special protection of the groundwater chemical and quantitative status and control of resource management, with priority being given to collective water supply for consumption and satisfaction of necessary economic needs [17]. In the area of Poland, mainly the Polish Lowland, relatively rich geothermal water resources have been identified. Some of them occur in protected areas due to the presence of waters intended for consumption in shallower aquifers, which may hinder the exploitation of geothermal waters.

The analysis of threats linked to the exploitation of geothermal waters of the Lower Jurassic will be carried out on the example of the designed borehole Konstantynów Łódzki GT-1, which is to be performed in the area of GZWP No. 401, in Mogilno-Łódź Trough and has been designated in Cretaceous formations.

The purpose of establishing the Cretaceous formation Protection Area of the GZWP No. 401 (GZWP 401) pursuant to Article 51 of the Water Law Act is to protect the water resources used to supply the population with water intended for consumption and to supply plants requiring high quality water. The need to establish the Protection Area results from the Water Management Plan for the Vistula River Basin [4,17], determines the programs of activities concerning groundwater bodies threatened with failure to meet the environmental objectives by 2015, included in the Water and Environment Program of the country. This area, as with the entire Mogilno-Łódź Trough (Figure 1), is the region with the deepest freshwater zone in Poland. The water-bearing level of the Lower Cretaceous, despite its deep occurrence, is of strategic importance for the supply of water for human consumption. At present, approximately 24% (approx. 35,000 m^3/d) of the groundwater exploited by the GZWP 401 originates from the Lower Cretaceous, 95% of which is recorded for the area around Łódź (Figure 1) [18,19]. A characteristic feature of the waters of the analyzed water-bearing system of the Łódź Basin is a significantly lower value of total mineralization of waters from the Lower Cretaceous level than observed in the higher water-bearing system levels (for example in Lower Jurassic) [19].

Due to such intensive exploitation of Lower Cretaceous waters and the planned use of Lower Jurassic geothermal resources, it is necessary to conduct a comprehensive analysis to determine the size of resources. Moreover, it is important to indicate the directions and size of the Lower Cretaceous level feeding. Due to the deep deposits of the reservoir, it is not exposed to pollution from the surface of the area, and no hazards associated with the ascension of salt waters have been observed. The main problem is the maintenance of good quantitative and chemical condition of the examined reservoir. The first step was to prepare hydrogeological documentation defining the protective area of the GZWP 401, within the framework of which the examined area was initially identified using model tests [19]. Different aspects of geothermal water exploitation and global experience will be presented to assess the potential risks.

2. Construction of Geothermal Wells—Potential Threats

The topic of geothermal energy sector is presented by many researchers from all over the world, who indicate various aspects (e.g., exploration, drilling, exploitation or use), existing problems and possible solutions for further development [20–22]. The problem that needs to be solved in terms of water management of this region is to determine the interaction of geothermal water levels, often in direct contact with the usable levels of groundwater. In the case of the exploitation of ordinary and geothermal water, in order to limit the amount of geothermal brine injected into the rock mass, account should be taken of the opportunities for the efficient use of cooled, spent geothermal waters for drinking and economic purposes (use a membrane processes for water treatment—desalination) [13–15]. Moreover, the renewability of geothermal energy resources should be considered when designing installations for heating purposes, to maintain the hydrodynamic balance between water intake and basin supply. A reliable assessment of the conflicting nature of the intake of both groundwater and geothermal water requires further research including the preparation of numerical models that consider their mutual influence. Due to fragmentary recognition of geothermal conditions (Lower Jurassic and Lower Cretaceous formations), spatial assessment of potential impacts of geothermal and groundwater resources exploitation in the discussed structure is very difficult. Also, the element of effective exploitation of geothermal resources seems to be one of the most important issues, it is also worth noting the aspect of environmental protection [23,24] and the economic factor [25]. The geological and technical uncertainty, as well as instability of national market and legislative situation must be considered.

In 2016–2018, six geothermal heat plants are operated in Poland, in Podhale and in the Polish lowlands (in Mszczonów, Poddębice, Uniejów, Pyrzyce and Stargard) regions (Figure 1) [26]. In addition, in Poland are 17 recreation centers, where geothermal water is used both for supplying recreational pools and other facilities, as well as for preparing domestic hot water. Geothermal water is also used in 12 spas for therapeutic and rehabilitation purposes [26,27]. A crucial aspect of any geothermal investment is the drilling phase of a borehole, including design of its appropriate technology and well construction, which consequently will directly influence the cost of the investment. Drilling phase may amount to approximately 40–60% of the total investment cost (depending on the depth of the boreholes) [28].

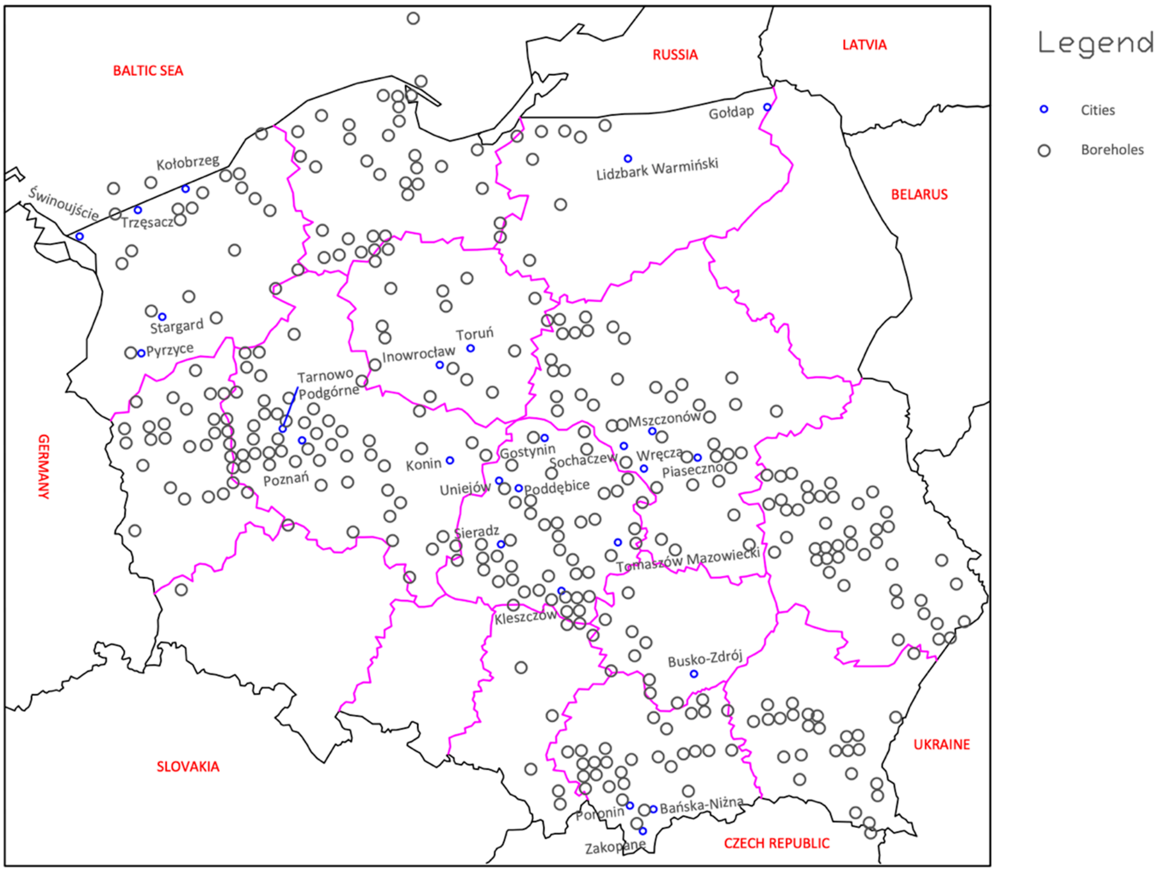

Figure 1. Research boreholes made in Poland with a depth of over 2500 meters below ground level, based on [29].

The construction of geothermal wells depends on several aspects, including geological conditions, the pressure in the well, its purpose (production or injection) and whether it is a completely new well or a reconstructed well (reconstructed object previously destroyed or decommissioned, renovated existing object, repaired a fully or partially existing facility) [20]. Within the available aquifers, the following factors are of decisive importance both for the construction and equipment of geothermal boreholes: expected water flow rate (production and injection), depth, and location of the reservoir horizon, compactness of aquifers, permeability, fracturing, designed final diameter of the boreholes and expected (planned) time of the boreholes' operation. To achieve the drilling goal, it is necessary to design the borehole structure correctly for the local parameters. An important element is also the need to comply with internal (Polish) law regulations [30].

In general, a geothermal well consists of the following components: (1) a casing with a suitable diameter, (2) a construction element that allows access to the water in reservoir (a filter, for example) and, if necessary, (3) technical equipment such as deep well pump, special operational wellhead, etc. As in the case of oil wells, the geothermal well can be vertical or directional [31]. Geothermal boreholes can operate in single-well systems (primarily for freshwater production), two-well systems (consisting of a production and injection well), and multi-well systems. There are five main types of casing columns in geothermal boreholes: (1) preliminary column, (2) conductor column, (3) technical column, (4) a production column and (5) a losing column. When designing a well, it is important to pay attention to the length and diameter of the casing, which is selected based on the parameters of the medium, information on geology, lithography, and hydrogeology, and pressure conditions. Depending on the technological situation, tension, compression, crushing, bending, and tearing loads may occur in the opening for the cladding columns. [32].

To ensure the safety of the well-being designed, drilling operations are generally divided into two main stages: (1) establish a piping scheme and (2) examine the strength of individual casing columns due to the possibility of different geotectonic conditions and pressures that will determine the final construction of the well. This is necessary for the well to be safe for other (adjacent) aquifers. The issue of drilling construction in the horizon zone of a geothermal deposit is of great importance, especially in the context of hydrothermal resources exploitation and ensuring the safety of adjacent layers. Various solutions are available to gain access to the horizon, namely a structure without a filter—the so-called "open-hole" type, a filter construction made by putting the filter into the hole, a filter construction with a widening of the borehole and a gravel packing, as well as a filter structure made by perforation of casing pipes—the so-called "cased-hole" type (to open a closed aquifer) [31].

Open-hole constructions are used for compact rocks, mainly of the fractured type, which are characterized by maintaining stability of the borehole walls. In this case, the final casing ends above the ceiling of reservoir horizon, remaining it uncased (open). Such a construction of the casing system is characterized by low manufacturing costs and potentially good hydrodynamic properties. It is also possible to widen the opening in the reservoir level interval, which allows the obtaining of better extraction and injection parameters (increase in output) [31]. Filter construction made by placing the filter in the section of the reservoir level is a solution used in case of lack of stability of drilling walls (e.g., sandstone horizon). Within this type of construction, a method can be distinguished which consists of placing the last column of cladding pipes in the ceiling reservoir level and drilling through a selected reservoir interval. Then, a filter column is placed in the un-piped part of the borehole, under the last column of cladding pipes, in the part of the reservoir level, which is usually made of perforated or pressed pipe section, and additional braiding is possible. The diameter of the plugged-in filter column limits the outer filtration surface, which may therefore have a maximum value of ø 6 5/8″ or ø 7″, for the last column of casing pipes ø 9 5/8″[31].

In the case of the "cased-hole" structure, which makes closed reservoir horizons available for exploitation, it is necessary to make perforation holes preceded by piping of the depth intervals of the reservoir level and their cementation. Hydrodynamic contact of the borehole space with the reservoir level is ensured by borehole drilling in the so-called blockade between the reservoir collector and the borehole. Due to the construction of the filter is made in this way, it is burdened with low hydrodynamic efficiency, which results from relatively small contact area of perforation boreholes with reservoir rock and from damage to the borehole zone by cement leaven and drilling slurry. Appropriate activation procedures can reduce the effect of damage to the well zone. Additionally, the possibility of occurrence of significant flow resistance should be considered, which directly influences the amount of mining expenses both in the case of water extraction and water injection. Appropriate activation procedures can reduce the effect of damage to the well zone. Additionally, the possibility of occurrence of significant flow resistance should be considered, which directly influences the amount of mining expenses both in the case of water extraction and water injection. In some cases, adaptation of unused boreholes for geothermal purposes is only possible by perforating the casing pipes and cement stone ring as a filter structure [31]. Kępińska and Bujakowski [33] indicate that the proper choice of construction may minimize the failure rate of the geothermal system. The construction and equipment of a geothermal well (production and injection) within the horizon is mainly determined by the estimated capacity of the well, depth of the aquifer, parameters of the reservoir and the expected time of operation [34]. The preliminary column protects the borehole outlet from being washed out by the drilling slurry and from contamination of its walls in poorly compact layers. The conductor column provides isolation of different water-bearing levels (from each other) and additionally in the exploitation holes it serves as a pump chamber. The technical column makes the deposit accessible and serves for water intake from the deposit level (enables their exploitation/injection). In turn the technical column also is used to close the inflow of water (large quantities) to the drilling hole, as well as to cover the areas where there are difficulties with further drilling (e.g., leakage of drilling slurry, its disappearance, loosening, etc.). It should be noted, however, that there may be many technical columns in a hole, and in the case of an injection well, the column usually leads to the surface. To prevent the borehole from backfilling and to prevent solid particles from entering the geothermal water from the aquifer, a filter is placed in the pipes of the technical column in the reservoir zone. In the case of water extraction from fractured formations of a stable nature, a borehole can be left barefoot (unfiltered). In addition, to prevent solid particles from entering the water cycle, a gravel packing is used [35].

3. Characteristics of the Area

Poland is an area with potentially large low-enthalpy geothermal energy resources, more than half of the area covers a Permian-Mesozoic reservoir, within which there are smaller separations with geothermal water collectors. The average hydrogeochemical gradient for the Polish lowlands is 5.7 g/dm^3/100m [16]. Calculations of geothermal energy resources in the Polish lowlands have shown that available geothermal resources of Mesozoic reservoirs in this area are $7753 \times 10^{22} \times$ J, which is equivalent to $185 \times 10^{12} \times$ TOE (1 ton of oil equivalent = 41.868 GJ). The most abundant reservoir in this category is the Lower Jurassic reservoir $299 \times 10^{21} \times$ J. Relatively smaller energy resources are accumulated in the Lower Cretaceous reservoir $423 \times 10^{20} \times$ J. As a standard, model tests of geothermal system operation were carried out for the perspective of 50 years and more. The extraction and exploitation of water in a closed system, i.e., with water injection into a rock mass, enables the recovery of energy, and the carrier of this energy is not impoverishing during time [22]. The geothermal energy resources from Lower Jurassic formations have been exploited for about 30 years in the north-western part of Poland, in 2 geothermal plants, without causing any disturbances. The production prospects, regulated by concessions, assume further exploitation for at least 50 years. [16,21]. Due to the increasing drinking water demand and shrinking surface water resources the exploitation of Jurassic formation should be considered to be investment in the coming years, even should begin forthwith [16,31].

As mentioned earlier, there are 6 geothermal heat plants in Poland, which extract geothermal water from sandy and sandy-muddy Cretaceous formations and Lower Jurassic formations in the Polish lowlands (a system of underground basins extending from the Szczecin area through the Mogilno-Łódź region to Mazovia) and carbonates from Eocene in the Podhale region (Figure 2) [16]. In the case of Mszczonów, Uniejów and Podhale region (nine boreholes in total), the water-bearing horizon was made available through perforation of the casing (boreholes in the region of: 1) Mszczonów city—Mszczonów IG-1; 2) Uniejów city—Uniejów PIG/AGH-1, Uniejów PIG/AGH-2, Uniejów IGH-1; 3) Bańska Niżna/Biały Dunajec city—Bańska IG-1, Bańska PGP-1, Bańska PGP-3, Biały Dunajec PGP-1, Biały Dunajec PGP-2). In the case of the wells in Pyrzyce (Pyrzyce GT-1, Pyrzyce GT-2, Pyrzyce GT-3, Pyrzyce GT-4 one additional drilled in 2018) and one well in Stargard, a filter construction with a widening of the borehole with a gravel packing was made, while in the other two wells the intervals between the reservoirs are not cased (Figure 1) [35].

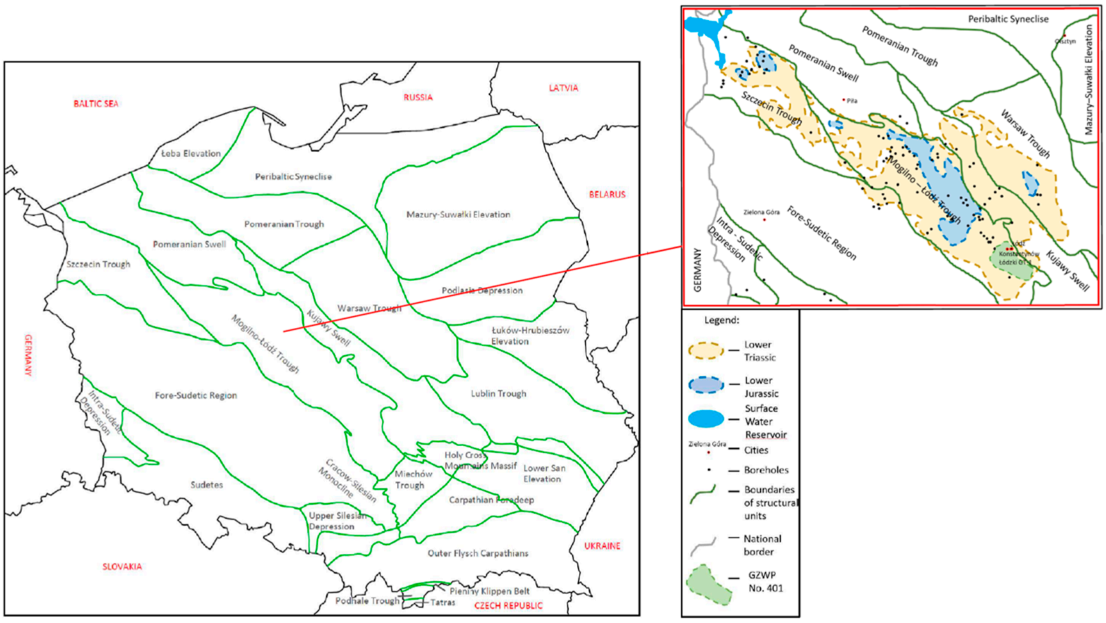

Figure 2. Map of borehole locations with a depth of over 2500 meters below ground level, mainly for the Polish lowlands, based on [21].

The heat plant in Mszczonów was launched in 1999, geothermal water is extracted by one production borehole, with no injection well, which supplies heat to the central heating network and heat and water to the Mszczonów Baths. After cooling, the geothermal water is directed to the municipal water supply system as drinking water. Exploited geothermal water from the Lower Cretaceous formations on the outflow has a temperature of 42 °C. The surplus of water (max. 30 m^3/h) is injected with a special well to the quaternary level located about 100 m below the ground level.

The heat plant in Podhale, as the first in Poland, has been operating since 1993. Geothermal water is exploited from three production wells with a max. total capacity of 960 m^3/h at a temperature of 80–86 °C, the system is complemented by two injection wells. The geothermal central heating network covers 35% of the heat demand in Zakopane and supplies buildings in several other locations, including Bańska Niżna, Biały Dunajec and Poronin (Figure 1). Most of the geothermal water stream that has been cooled in the heat exchangers is injected back into the reservoir from which it was extracted. After additional cooling, part of the water is discharged to a nearby surface watercourse. At present, further expansion of the heating network is being carried out. The heat plant in Poddębice operates based on one well, there is no injection borehole, the approved production capacity is 252 m^3/h and the temperature of geothermal water at the outflow is 71 °C. The heat plant supplies heat to the surrounding public buildings, schools, hospitals, multi-family buildings, and a part of the stream is directed to recreational swimming pools and for rehabilitation purposes in the district hospital.

Further development of both the geothermal complex and the geothermal energy and water use are being carried out. The heat plant in Pyrzyce (Figure 1) was launched in 1997, since 2017 the exploitation of geothermal water was carried out by two production wells and two injection ones. The geothermal water flowing out is at a temperature of 61 °C and the total approved water output is approximately 370 m^3/h. At the turn of 2017/2018, the system was extended by a new production borehole with approved exploitation resources of 200 m^3/h and water temperature at the outflow of 65 °C. At that time, the four aforementioned wells started to work as injection wells. The heat plant supplies heat through the central heating network for about 90% of all inhabitants of the city of Pyrzyce (Figure 2), which has about 13,000 inhabitants. The Stargard (Figure 1) heat plant has been operating since 2005, and in 2017 it operated on the basis of three boreholes: a production borehole GT-2 (directional, extended, barefoot) and two injection wells GT-1 and GT-3 (made in 2016) (vertical, filtered). The system is to provide 200 m^3/h of operation/enabling. Currently, works are being carried out to enlarge the system with additional four new geothermal boreholes. Approved exploitation resources are about 180 m^3/h, with geothermal water temperature at the outflow of 87 °C. The heat plant sells the heat produced to the local Heat Distribution Company (PEC) in Stargard.

The heat plant in Uniejów, on the other hand, has been operating since 2000. The installation consists of three openings, one for production and two for injection (Figure 1). The temperature at the outflow of exploited geothermal water is about 68 °C, and the approved exploitation resources are about 120 m^3/h. The heat plant supplies heat to the geothermal central heating network, which supplies heat to about 80% of the buildings in the city. Apart from supplying the central heating network, the geothermal water also supplies the Uniejów Thermal Baths, provides heating for the football field and the walking path, and further research is being conducted on the further multi-variant use of geothermal waters.

Apart from using geothermal waters for heating purposes in Poland, these waters are also used in several recreation centers, in farming centers (an Atlantic salmon farm near Trzęsacz), for drying wood (in the MERI PAS Geothermal Laboratory in Podhale), in food processing (e.g., cucumber pickling in Uniejów), in the cosmetics industry and in order to recover iodine-bromine salts and carbon dioxide [26].

In the total area of the Polish lowlands over 2000 deep boreholes were drilled, including 266 boreholes of the Polish Geological Institute, which reach different depths [10]. Currently, there are over 20 geothermal boreholes in the area of the Polish lowlands, most of them were made especially for this purpose, only a few of them (including Mszczonów IG-1 and Uniejów IGH-1) are old, reconstructed boreholes. In the area of the Polish lowlands, the exploitation of geothermal waters for heating purposes was initiated over 20 years ago, in 1997 a geothermal heat plant was launched in Pyrzyce. Two geothermal doublets were drilled here (two production wells Pyrzyce GT-1, Pyrzyce GT-3, and two injection Pyrzyce GT-2, Pyrzyce GT-4). Previously, geothermal waters were used only for balneological and therapeutic purposes in geothermal spas. The plant in Pyrzyce was established as the second one in Poland after the plant in Podhale (designed and launched in 1993 by MEERI PAS). In Pyrzyce, another well was drilled in 2018 to support the process of injection and will cooperate with the first four. After 2001, in Poland some new boreholes were made. The Stargard GT-1 and GT-2 was drilled in 2001-2003 and the Stargard GT-3 in 2016 (near Stargard city, Figure 1). Since 2008, several new geothermal boreholes have been drilled in the Polish lowlands, among others exploitation wells in: Toruń (Toruń TG-1), Kleszczów (Kleszczów GT-1), Gostynin (Gostynin GT-1), Tarnowo Podgórne (Tarnowo Podgórne GT-1), Lidzbark Warmiński (Lidzbark Warmiński GT-1), Piaseczno (Piaseczno GT-1) and Trzęsacz (Trzęsacz GT-1) were made in order to capture the water-bearing layers of the Lower Jurassic. The exploitation well in Poddębice (Poddębice GT-2) captures the Lower Cretaceous layers. The wells in Sieradz (Sieradz GT-1) and Tomaszów Mazowiecki (Tomaszów Mazowiecki GT-1) were drilled in order to intake the Lower Jurassic layers; however boreholes in Sochaczew (Sochaczew GT-1) and Wręcza (Wręcza GT-1) capture Lower Cretaceous layers (Figure 1). The injection wells in Toruń and Kleszczów (Toruń TG-2 and Kleszczów GT-2) reach the level of the Lower Jurassic. In the case of Toruń TG-1 well, due to its construction, it was possible to test two water-bearing levels: the Lower Jurassic and the Middle Triassic. Initially only the samples from the Lower Jurassic were examined, then, after protecting the analyzed water-bearing layer, an additional technical column was made and sealed (with a pacer) in order to deepen the hole to the water-bearing layer of the Middle

Triassic. Based on the conducted research it was found that in a given location the shell limestone formations are characterized by worse hydrogeological conditions than the formations of the Lower Jurassic. Due to the applied construction, it was possible to abolish the hole in the Middle Triassic formations and make the Lower Jurassic aquifer accessible again. A similar construction was used in the Piaseczno city (Piaseczno GT-1 borehole). In this case, the recognition of the Lower Cretaceous and Lower Jurassic formations was made [35].

In the region of the Mogilno-Łódź Trough, the Lower Cretaceous formations are lying at various depths, in the coastal zones of the Basin from several dozen meters above sea level to over 2500 meters above sea level in the area north-east of Konin (Figure 1). The thicknesses of the Lower Cretaceous formations vary from a few to over 600 meters in the central and eastern part of the basin, while in the western-southern part of the thickness does not exceed 300 meters. The variability of the thickness of aquifers found in the Lower Cretaceous formations is similar to the distribution of the total thickness of the formations of this age. The thickness of aquifers also varies from a few meters in the marginal zone of the basin to about 400 meters in the north-eastern part (locally even 600 meters). In the region of the Mogilno-Łódź Trough, the ceiling of the Lower Jurassic formations lies at a depth of 750 meters below ground level (b. g. l.) in the region of the south-western edge of the basin up to 3750 m b. g. l. in the axial part of the basin. Locally, especially in the southern and eastern part of the basin, no formations of the Lower Jurassic were found. The thickness of the Lower Jurassic formations varies within the area of the basin from a few to even 250 meters. The lowest thicknesses are found in the southern and central zone of the basin. As in the case of the Lower Cretaceous reservoir, the distribution of the thickness of the water-bearing horizons is similar to the variability of the total thickness of these formations. The lowest thicknesses, below 100 meters, are found in the southern and central zone, while the highest ones, up to 850 meters, are found in the Kujawy Dyke zone [19,36].

In Poland, several research wells have been drilled to a depth of more than 2500 meters below ground level. From Figures 1 and 2 it can be seen that a significant part of these wells was drilled in the Polish lowlands. On the basis of the conducted research, prospective areas for both the Jurassic and the Lower Triassic were distinguished, mainly within the Mogilno-Łódź Trough, Szczecin Trough, Warsaw Trough and the Kujawy Swell (Figure 1; Figure 2). In the region of Konstantynów Łódzki, the Łódź basin is built of Permian-Mesozoic sediments. The Lower Triassic formations are composed of red clay, cherry sandstone, marl, limestone, and dolomite, Middle Triassic formations of limestone, marl, claystone, dolomite, limestone with anhydrite and corrugated limestone, and the Upper Triassic formations of clay formations with sandstone, anhydrite, and gypsum inserts. Triassic formations in the region of Konstantynów Łódzki are located at depths of over 2500 meters. The formations of the Lower Jurassic are represented by alternating clay, silty and sandy compositions, and the Middle Jurassic compositions by sandstone, fine-grained and porous formations as well as slates, mudstones, claystone and limestone, and the Upper Jurassic compositions by limestone, mainly marl and sandstone, marl with inserts and anhydrites. The Jurassic formations are located at depths of more than 800 meters. The series of claystone and silts with siderite inserts represent the Lower Cretaceous. The ceiling of the horizon is located at depths of several meters in the area of outcrops in the north and south of the GZWP No. 401, about 700 meters in the area of Konstantynów Łódzki, up to over 1000 meters along the south-western border of the reservoir. The thickness of the formations varies between 50 and 200 meters, with an average value of 100 meters. The Lower Cretaceous reservoir is characterized by good hydrogeological parameters, average filtration coefficient of 10 m/d and relatively high homogeneity and stability. Within the area of the GZWP No. 401, the static water level stabilizes at a level from 120 m above sea level to 190 m above sea level [19,37].

The water inflow to the Lower Cretaceous Water-Bearing Level of the GZWP No. 401 in the areas where the piezometric surface of this level is slightly lower than in the Upper Cretaceous is from the top, from vertical filtration and through side inflows. The amount of vertical input is relatively small and depends on local parameters and the character of poorly permeable Upper Cretaceous formations. The supply from the Upper Cretaceous water inflow amounts to 46 800 m^3/d, which constitutes 25.5%

of the total supply of the Lower Cretaceous formations. The total value of vertical and side inflows within the GZWP No. 401 was estimated at about 183 600 m^3/d [19].

4. World experience—Example of Paris Basin

Experience in the use of geothermal water for district heating in France is more than 30 years old. 50 geothermal heat plants with a total heating capacity of 345 MWt have been built [38]. Currently, 37 geothermal two- or three-hole systems operate in the area of the Paris basin (Dogger Basin), most of which were constructed in the 1970s and 1980s [39]. The Paris basin is a perfect example of an intracratonic basin which is characterized by decreasing thermal subsidence in an extensional setting since its genesis [40]. Since 1998, in France the geothermal energy exploitation has been concentrated in four main regions, including Paris basin which consist most of installed geothermal plants [41]. Paris basin is large aquifer and covers around 100,000 km^2 from the Vosges mountains to Britannia (east-west) and Belgian border to Massif Central (north-south). The thill of the formation was drilled only in a few oil and gas exploration boreholes. Consequently, in the basin area was established several aquifers with geothermal potential: Triassic formation (made of sediments with sandstones and clays), Dogger (Jurassic) formations (made mainly of limestone) are considered to be very rich layers for geothermal purposes, Oxfordian (Jurassic) made of limestone, is characterized by comparable flow rate to Dogger aquifer and lower temperature (about 15 °C), and Lower Cretaceous formation (made mainly of Albien sands) have been exploited for drinking purposes since 150 years in Paris area [42]. What is important is that the exploitation of geothermal heat within the Parisian basin is carried out with the maintenance of sustainable management and the use of the most technologically safe techniques for drilling geothermal wells. The experience in operating the Dogger reservoir dates back to 40 years. The need to assess the impact of Dogger operation to maintain the favorable parameters of the reservoir in further operation is emphasized [43]. The Paris basin is a good example of a sustainable approach to regional geothermal management, where the geothermal and ordinary water intakes function in a collision-free coexistence. Geothermal energy of the aquifer from Dogger has been obtained for over 40 years and has not caused any apparent changes in the hydrodynamic parameters of the reservoir. Further studies are being carried out to increase the efficiency of tank resource use through the use of new techniques [44–46]. Castillo et al. [47] proposed an option of re-injected cooled Triassic brines into the Dogger aquifer to exploitation of the low-enthalpy geothermal resources. Application of such a solution in the case of the Polish low-water level would allow reduction of the costs of brine management and increase the efficiency of geothermal water use. However, as Castillo et al. [47] points out, further research is needed to assess the risks associated with this solution (despite promising preliminary results). The deep geothermal resource of the center of the Paris basin (Ile-de-France region, France), as was mentioned before, has been exploited since the mid-1980s. The main target of this exploitation has been the Dogger aquifer (1500–2000 m deep, 55–80 °C). At present, in the Paris basin the Triassic sandstone units below the Dogger aquifer are envisaged as new targets and sources of geothermal heat [47].

In the region of Paris basin, the first sub-horizontal geothermal borehole was drilled. The special design of the geothermal well was established with the open-hole drain in the Dogger/Bathonian, Mid-Jurassic, oolithic limestone, target reservoir, at a 1550 meters true vertical depth. This new geothermal doublet was first in the world, which reached over 1000 meters in the groundwater of the Dogger at 1600 meters depth. Moreover, it is the first time that this technique has been used for geothermal purposes (previously only for oil drilling). This new doublet replaced two existing doublets (four wells). It is predicted to gain 400 m^3/h of hot water from a single doublet, against 300 m^3/h from old four wells. Sub-horizontal drilling also significantly reduces the duration of the work: four months against eight to drill two doublets. The wells drilled and the plant planed will cover the heating and hot water needs of more than 7000 housing equivalents (public facilities, apartment buildings and businesses) [48]. In following years, the new doublet has been performed and tested. The results gained indicated that proposed solution achieved technical and economic viability of sub-horizontal well proposition. Moreover, the authors highlighted the importance of the concept and technology during study phase [47–50]. Geothermal energy of the aquifer from Dogger has been obtained without noticeable changes in aquifer properties. This was undoubtedly influenced using doublet technology and the geological structure of the basin, which makes it difficult for freshwater levels to connect with mineralized brines, without the prevalence of halo-kinetic structures.

Taking the above into account, the observed similarity between the characteristics of the Formation of the Polish Lowland and the Paris basin can be used in designing further installations and analyzing potential risks at all stages of operation. Based on experience in management of geothermal waters of the Paris basin it seems possible to use Jurassic formations within the Polish lowlands. Moreover, the possibility of using the low-temperature geothermal resources of the Lower Cretaceous (within Polish lowlands) for district heating purposes was also explored by Pająk et al. [51]. The authors underlined the potential of these formations; however, they indicated that the future development of the geothermal investment will depend on economic and environmental conditions. In the Paris basin, research/actions are also underway to exploit the so far undeveloped Jurassic resources using appropriate equipment and thus the safety of the adjacent layers (Figure 3) [45]. The potential risk of exploitation exists, but these formations may be a source of additional geothermal resources if appropriate tests and modeling are carried out and suitable drilling technology will be applied.

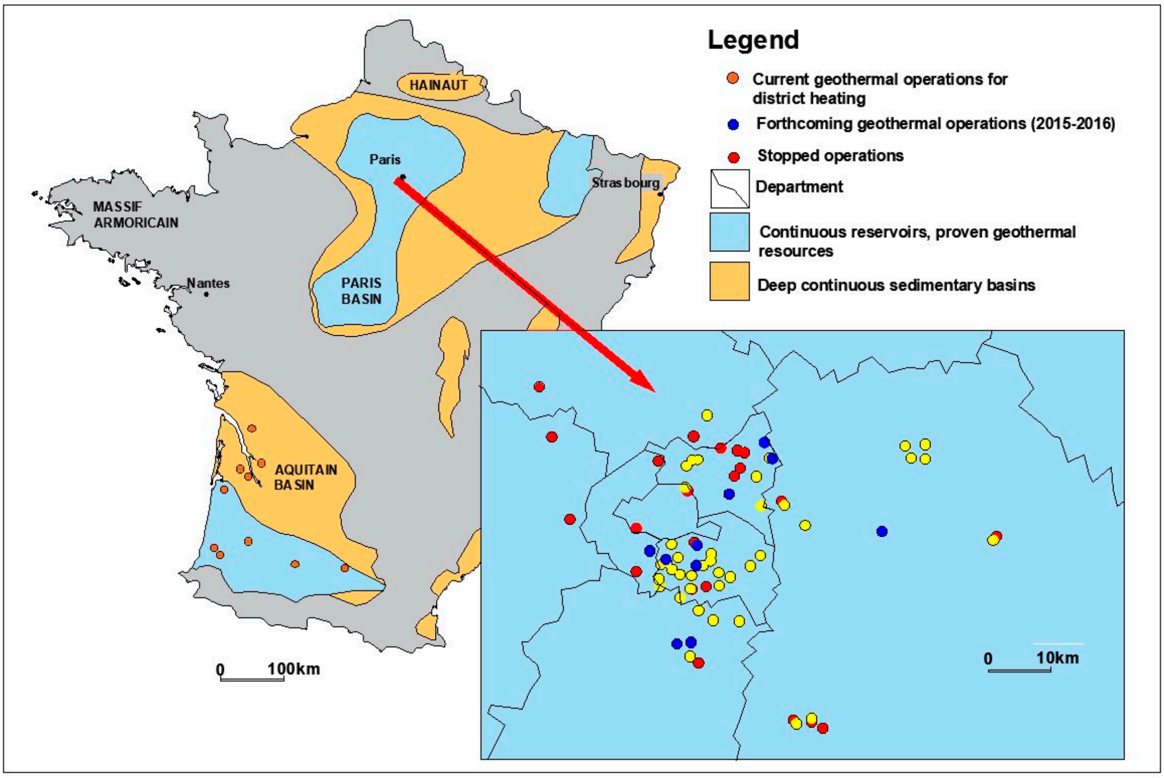

Figure 3. The map of locations of deep geothermal operations (for district heating) within two main sedimentary basins in France (zoom in Ile-de-France) based on [45].

5. Conclusions

The aim of this work was to present consideration of the possibility of exploiting geothermal waters of Jurassic levels within the Polish lowlands. The analysis was carried out based on literature data of the studied area and the current management of geothermal water resources. Due to the present exploitation of Lower Cretaceous waters as drinking water, this factor consists the main limitation of the possibility to extend the exploitation in this area. The analysis was also enriched with experiences related to the use of the resources of the Paris basin.

Generally, the assay has shown that proper recognition of local area (including modeling the local area), the selection of appropriate drilling technology, and thus the implementation of a proper well casing allows for the exploitation of the lower-lying (Jurassic) formations. An important element is also the proper recognition of the directions of supply of the adjacent reservoirs and the adjustment of the capacity of the Jurassic formations. So far, the geothermal resources in the Polish lowlands have been exploited without any problems with the tightness of the boreholes, and the quaternary formations have not been threatened. In this area, the design of boreholes for deeper aquifers with higher temperatures than those recorded in the Lower Cretaceous should consider the high reservoir pressures under which these waters occur and their relatively high mineralization, increasing in north-western direction, as a result of halo-kinesis. In view of the potential risks involved and the impending objective of ensuring drinking water, the exploitation of Jurassic formations should be preceded by additional research to select an appropriate technology and borehole construction ensuring safe exploitation of Lower Jurassic (considering above-laying Lower Cretaceous formation). Moreover, the creation of regional hydrochemical and hydrodynamical models, considering the whole natural conditions in the studied region, would allow the obtaining of more precise information on potential conflicts.

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