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Coal Mine Drainage as a Source of Drinking and Industrial Water—The Upper Silesian Coal Basin, Poland

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Abstract: Water is one of the most important resources found on Earth, essential for all forms of life. Both the quantity and quality of water resources are crucial for the health of the population and for economic sectors, making water a factor in determining a society's standard of living. Mine water serves as an appealing source of both drinking and technological water. Regardless of the exploitation method, it must be pumped to the surface and, usually, treated to meet environmental standards. In most cases, it is discharged to rivers. In this article, we present a model of the use of mine water from three pumping stations of decommissioned coal mines in the Upper Silesian Coal Basin—Jan Kanty, Saturn, and Boże Dary. Water from these pumping stations is characterized by good qualitative and quantitative parameters. The results of the physico-chemical composition analyses carried out in the years 2012–2022 did not reveal any excessive amounts of toxic components or treatment difficulties. Given the long operational lifespan of these pumping stations and their existing water extraction infrastructure, they emerge as promising sources of both potable and industrial water supply, demanding minimal treatment efforts.

Keywords: mine water; mine dewatering; water management; sustainable mining; water quality

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1. Introduction

Poland is one of the countries with the lowest water resources in Europe [1]. According to Eurostat data [2], its annual water resources per capita is about 1500 m^3, while the European multi-year average stands at around 8000 m^3. This places Poland, along with the Czech Republic (1400 m^3/capita), Cyprus (400 m^3/capita), and Malta (200 m^3/capita), in the group of European countries with freshwater resources below the limit of 1700 m^3/capita, which the World Health Organization (WHO) recognizes as below the safe level of water.

In 2022, almost 9.4 km^3 of water was used in Poland, with the vast majority coming from surface intakes. Surface intakes accounted for 80.83% of the total water consumption, while groundwater intakes accounted for 18.76%. Only 0.41% of the water use was from water pumped from mines. A total of 754,869,000 m^3 of water was discharged from active and inactive mining facilities in 2022, of which only 5.1% (38,400,000 m^3) was managed in a way other than being discharged into surface watercourses [3].

The issue of obtaining water for potable and technological purposes from mines has already been widely addressed in the literature [4–6]. In Poland, promising results for the use of saline waters, originating from the dewatering of mines, for drinking-water purposes have been reported [7], together with the use of water for cooling in air-conditioning systems [8]. Other articles have presented the possibility of utilizing waters from the Saturn coal mine for drinking purposes [9] and from the decommissioned zinc and lead ore mine, Olkusz-Pomorzany, for technological purposes in ore-processing plants [10]. Acid mine drainage water has also been used in Africa [11–13] and in Spišsko-gemerské

Rudohorie Mts., Slovakia, where water from a closed metallic mine was proposed as a drinking source [14]. Much attention has been paid to abandoned coal and metal ore mines in Spain, whose waters, once treated, could be suitable for industrial purposes [15–17]. Mine waters are also employed in the cooling systems of power plants [18,19]. They are also proposed for use in underground pumped-storage hydropower (UPSH) [20–25], energy storage [26,27], and geothermal heat pumps [28–31].

Mine waters are also utilized for technological purposes within mining facilities. Water derived from dewatering is used for backfilling [32] and, in mineral processing plants, for fire protection and in tailings ponds [33].

In general, there are not many examples of mine water use in Poland [34,35]. It is considered to be an inexpensive resource that, regardless of the type of mining, must be pumped out of the ground, and in many cases, treated to meet environmental standards before its discharge to rivers. Most water from mine dewatering comes from the Upper Silesian Coal Basin (USCB). Active and closed mines in the USCB in 2022 produced 34% of the pumped mine water in Poland [36].

This paper presents models of the management of mine water from three pumping stations of former coal mines—Jan Kanty, Saturn, and Boże Dary, which are some of the structures of the Central Mine Drainage Plant (CMDP). The favorable qualitative and quantitative parameters of these waters, the absence of heavy metal pollution, along with the extended operational lifespan of these pumping stations and their pre-existing water extraction infrastructure, make them an appealing source of both potable and technological water that requires minimal water treatment.

2. Upper Silesian Coal Basin (USCB) Geology

Coal mining is the largest sector of the Polish mining industry. Coal deposits in Poland are generally associated with the Carboniferous period, and their exploitation is concentrated in three regions: the Upper Silesian Coal Basin (USCB), the Lublin Coal Basin (LCB), and the Lower Silesian Coal Basin (LSCB). In the LSCB, coal mining was completely abandoned in 1996 due to challenging extraction conditions and high operational costs.

The largest and most resource-rich coal basin in Poland is the USCB, in which exploitation started more than 250 years ago. Located in the southern part of Poland (Figure 1), the USCB is a foreland basin that was transformed into an intermontane basin in subsequent stages of its geological evolution [37,38]. The USCB is located within the Upper Silesian tectonic block, which, together with the Brno block (Czech Republic territory), form the so-called Brunovistulicum [39]. It has an approximate triangular shape, with hypothetical vertices close to Krakow, Tarnowskie Góry, and Ostrava. The area of the USCB is about 7400 km^2, with around 5800 km^2 located in Poland and the remaining part in the Ostrava–Karviná region of the Czech Republic.

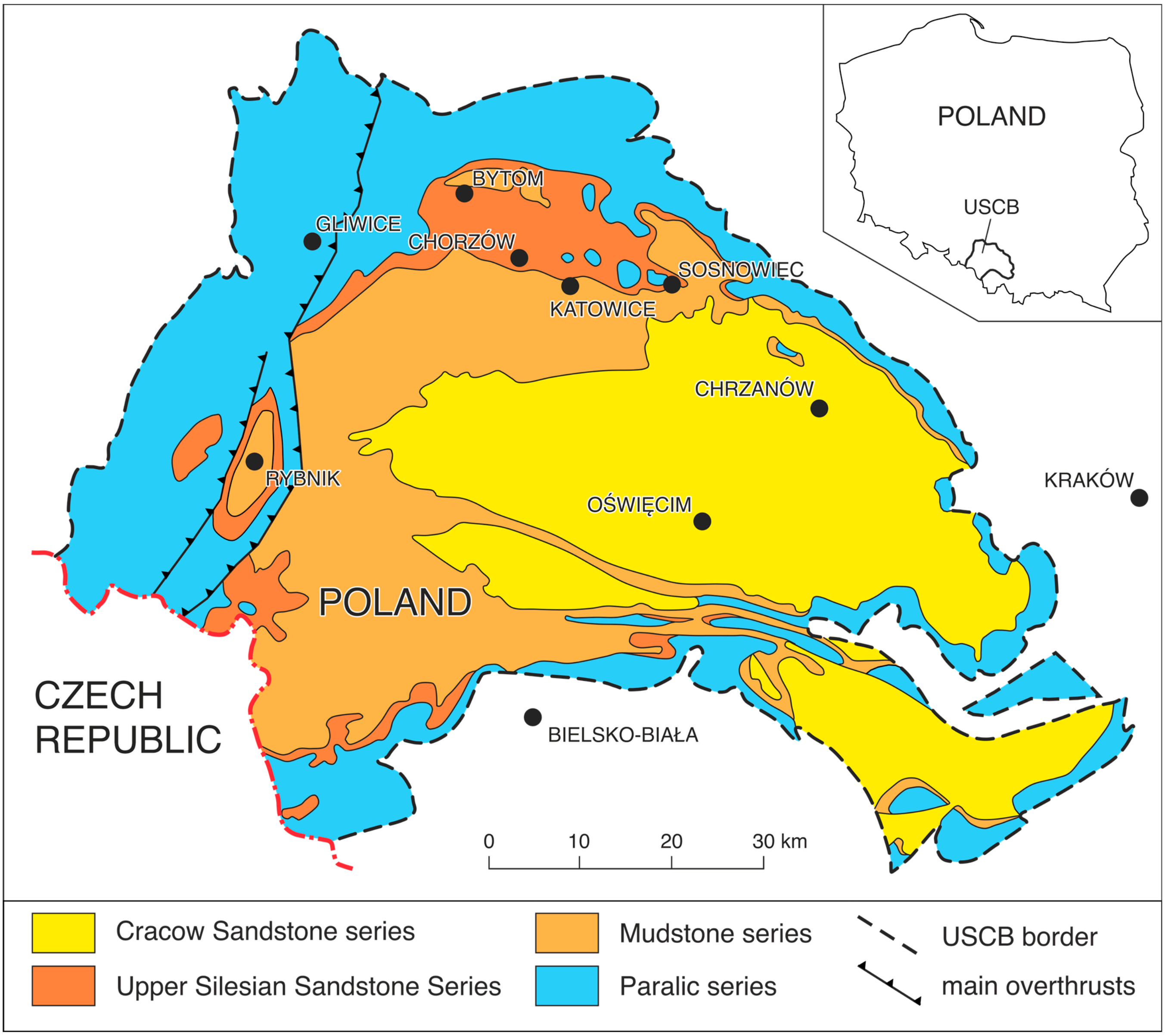

Figure 1. Geological map of the USCB—Carboniferous subcrop and sedimentation paleo-environments (based on [40], simplified).

The Upper Silesia Block is mostly composed of the Variscian Orogenesis sediments and partly of the Alpine Orogenesis sediments. On top of the Variscian sediments, there are Triassic, Jurassic, Neogene, and Quaternary sediments. Formations of orogens older than the Variscan lie at great depths and have been scarcely investigated [41].

In the profile of the coal-bearing Carboniferous formation of the USCB, a distinct bipartition is apparent. The older part is formed by lagoon and wetland paralic sediments, while the younger part consists of continental sediments. The paralic formations are clastic rocks with insets of marine sediments [42]. The USCB continental sedimentation consists of three sedimentary series. It begins with the Upper Silesian sandstone series, composed of coarse-grained sediments (sandstones and conglomerates). The second unit is a mudstone series, represented by mudstone and claystone [43]. The final continental productive Carboniferous sediments consist of a Cracovian sandstone series, formed by coarse-grained sediments, such as sandstones and conglomerates. The total thickness of the coal-bearing sediments in the USCB is 8500 m [44].

The oldest rocks in the overburden of the productive Carboniferous formation in the USCB are Permian sediments composed of calcareous conglomerates, melaphyrs, porphyrs, red sandstones, and clays. They fill depressions in the Carboniferous formation and are covered by Triassic and Jurassic sediments. The Triassic is developed in the bottom part as poorly consolidated sandstones and gravelly deposits, transitioning upwards into the marls and dolomites of the Rhaetian and then into the limestones and dolomites of the Middle Triassic [45]. The Upper Triassic is primarily composed of clayey rocks with occasional intercalations of limestones and sandstones. The lower part of the Jurassic consists of locally occurring kaolinitic clays from the Lower Jurassic. Above them, there are marls and sandstones of the Dogger, covered by carbonate formations of the Upper Jurassic [41] (Figure 2).

Figure 2. Younger deposits overlying the top surface of the Carboniferous formation (based on [41], simplified).

The Neogene stratigraphy is represented by the Miocene and, locally, the Pliocene formations. The Miocene, in the north of the USCB, is composed of sands and clays (rarely marlstones and limestones), and in the south, coarse clastic conglomerates and sandstones known as Dębowieckie conglomerates [44]. In the northwestern part of the USCB, anhydrites, gypsum, and salt are also found. The Pliocene sediments are water-saturated clays and sands.

The youngest rocks in the USCB are Quaternary sediments. They are formed by glacial and fluvial sedimentation and are composed of sand and gravel. Eolian sediments, such as loess and sand, are also locally present [45].

3. Upper Silesian Coal Basin (USCB) Hydrogeology

Normal hydrochemical zoning is a characteristic feature of the USCB hydrogeochemical environment [46]. Several aquifers with groundwater of different ages are separated by low-permeability aquitards or aquicludes [47]. From the hydrogeological stratification viewpoint, there are three hydrogeological zones in which the Carboniferous formation is covered by Quaternary sediments, Triassic and Quaternary sediments, and Neogene and Quaternary sediments [33].

The Carboniferous sediments are outcropping or are covered by the Quaternary sediments in the area of the Main Syncline (a large anticlinal structure) and the northeastern part of the USCB. The Quaternary aquifer has high storativity, but it was dewatered in some regions by mining activities. Its recharge occurs mainly by precipitation and, locally, in areas of intense mining drainage, from rivers. The hydraulic conductivity of Quaternary sediments varies from 1.13×10^{-5} to 6.5×10^{-3} m/s [48]. The Carboniferous aquifer is formed by alternating permeable and poorly permeable formations. Inflow to coal mines in this area generally does not exceed 10 m^3/min.

In Bytom and Chrzanów Basins (large synclinal structures), the Carboniferous rocks are covered by Triassic and Quaternary sediments. Triassic aquifer is characterized by high hydraulic conductivity values ranging from 1.6×10^{-7} to 4.7×10^{-3} m/s. The recharge of this aquifer occurs through precipitation on outcrops and from other, hydraulically connected, aquifers. However, mining activities have lowered the Triassic aquifer water table, due to intense drainage. Water inflow to coal mines in the Bytom Basin usually does not exceed 10 m^3/min, while in the Chrzanów Basin, it reaches up to 25 m^3/min [33].

The Carboniferous rocks are covered by a thick sequence of Neogene and Quaternary rocks in the southern and western parts of the USCB. The water inflow to mines operating beneath the Neogene is low (approximately 5 m^3/min) and linked to static reserves in the Carboniferous sandstones [33]. The Neogene aquifer is recharged by precipitation, while it is drained by numerous springs and mining activities [40].

4. Mine Dewatering Model in the USCB

Since the early 1990s, over 40 coal mines have been closed in the USCB. During the period of restructuring of the Polish mining industry, the mines underwent reorganization and ownership changes (Figure 3). However, the termination of the extraction of a deposit by an underground mine is not always equivalent to the cessation of the dewatering of its workings. This decision depends on several hydrogeological and mining factors.

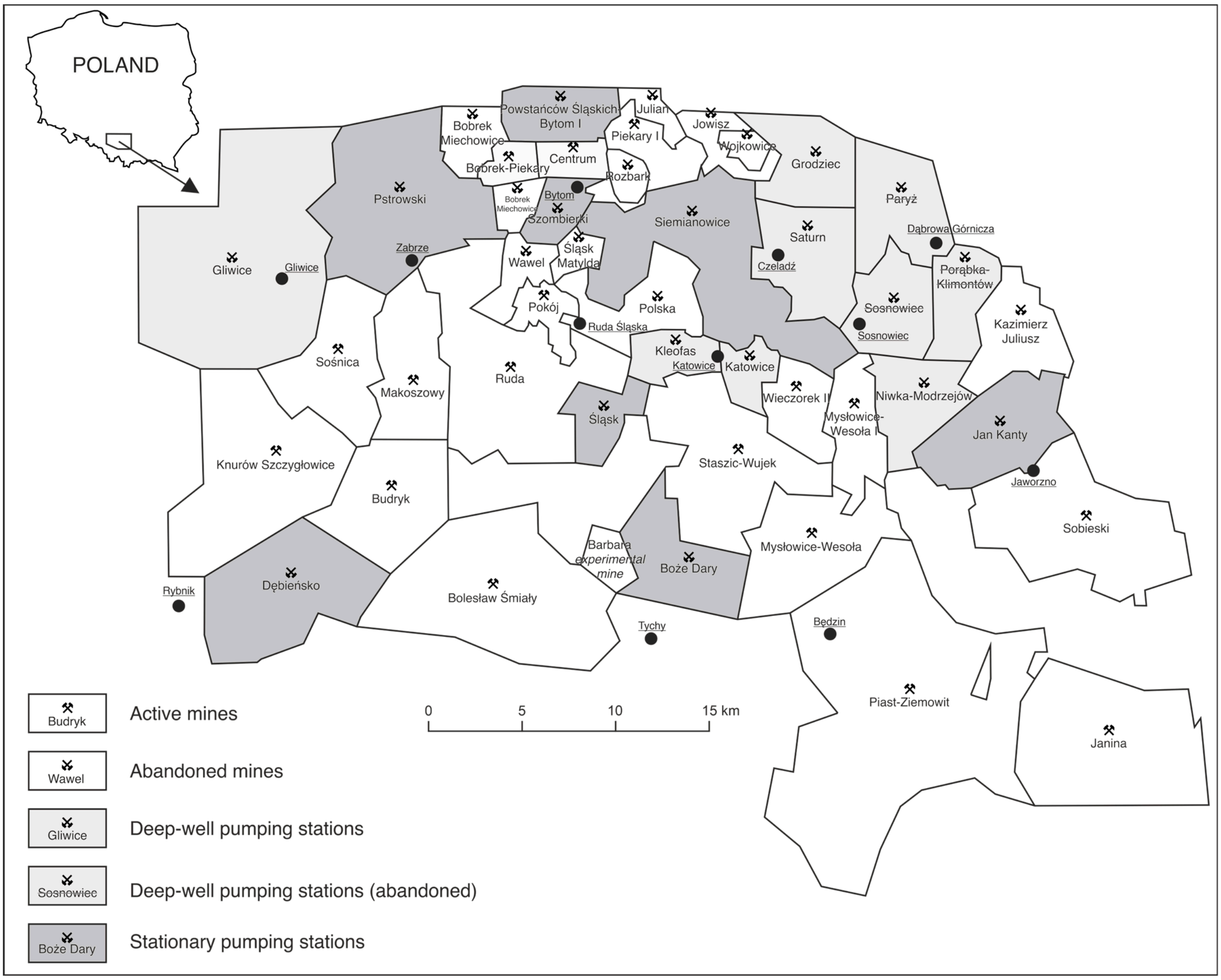

Figure 3. Map of CMDP pumping stations (based on [49]).

The Central Mine Drainage Plant (CMDP), formed in 2000, is responsible for the continuous dewatering in the decommissioned coal mines in the USCB. Currently, it manages 12 pumping stations established based on the closed coal mines. The CMDP is also working on simplifying the dewatering systems of closed mines and transitioning from stationary dewatering systems to deep-water ones. The use of submersible pumps is very beneficial for both economic and safety reasons. It is estimated that stationary dewatering at the CMDP scale is about 75% more expensive than deep-well dewatering [50]. Safety considerations primarily involve the pumping station crew, which must work in the proximity of old mining works with the potential accumulation of water and dangerous gases [51]. The use of deep-level pumping stations also allows for the smooth adjustment of the water table level depending on the local hydrogeological and mining conditions [52].

The USCB mines are interconnected. Unlike isolated mines, they have controlled or uncontrolled hydraulic connections to other mines. When dewatering is stopped at one of the group mines, it is flooded to the level of the lowest hydraulic connection with the neighboring mine. Once this connection is reached, water begins overflowing into that neighboring mine, reaching its drainage system. If this system can handle the additional inflow, the water level stabilizes at the overflow level. Otherwise, the dewatering in the adjacent mine must also be shut down, and both mines become flooded until the water level aligns with that of another neighboring mine, restarting the whole process.

Hydraulic connections between active and abandoned mines can be divided into direct and indirect connections. Direct connections are potential water flow paths, while indirect connections are paths of possible groundwater seepage [53]. Among direct connections, there are open connections (not backfilled corridor workings, shafts, or boreholes) and closed connections (compressed or backfilled workings). The flow resistance of open connections is very low, and their permeability generally depends on the size of the connections, while the permeability of closed connections is much lower and limited by flow resistance. Direct connections are also the pillars, shelves, or belts of coal seams up to about 4 m thick, which do not form a permanent barrier to water flow and can be opened at any time.

Indirect connections include various contacts between workings through remaining coal walls, rock shelves, or pillars with a thickness usually up to 20 m. They also include fault zones, potential fracture zones, and layers of highly permeable sandstone. These connections have a strictly seepage characteristic [53].

The dewatering model adopted in the 1990s in the USCB is based on not allowing an active mine to be subjected to a water hazard from a rising water level in an adjacent decommissioned mine. In some of the decommissioned mines, drainage systems are still functioning to protect active mines from a water hazard, which is defined as the possibility of an uncontrolled inrush of water or a mixture of water and loose rock material into the mine workings [33]. For example, in 2022, in the NE part of the USCB, two of the six liquidated mines were dewatered: the Saturn pumping station (formerly the Saturn coal mine) and the Niwka-Modrzejów pumping station (formerly the Niwka-Modrzejów coal mine) (Figure 4).

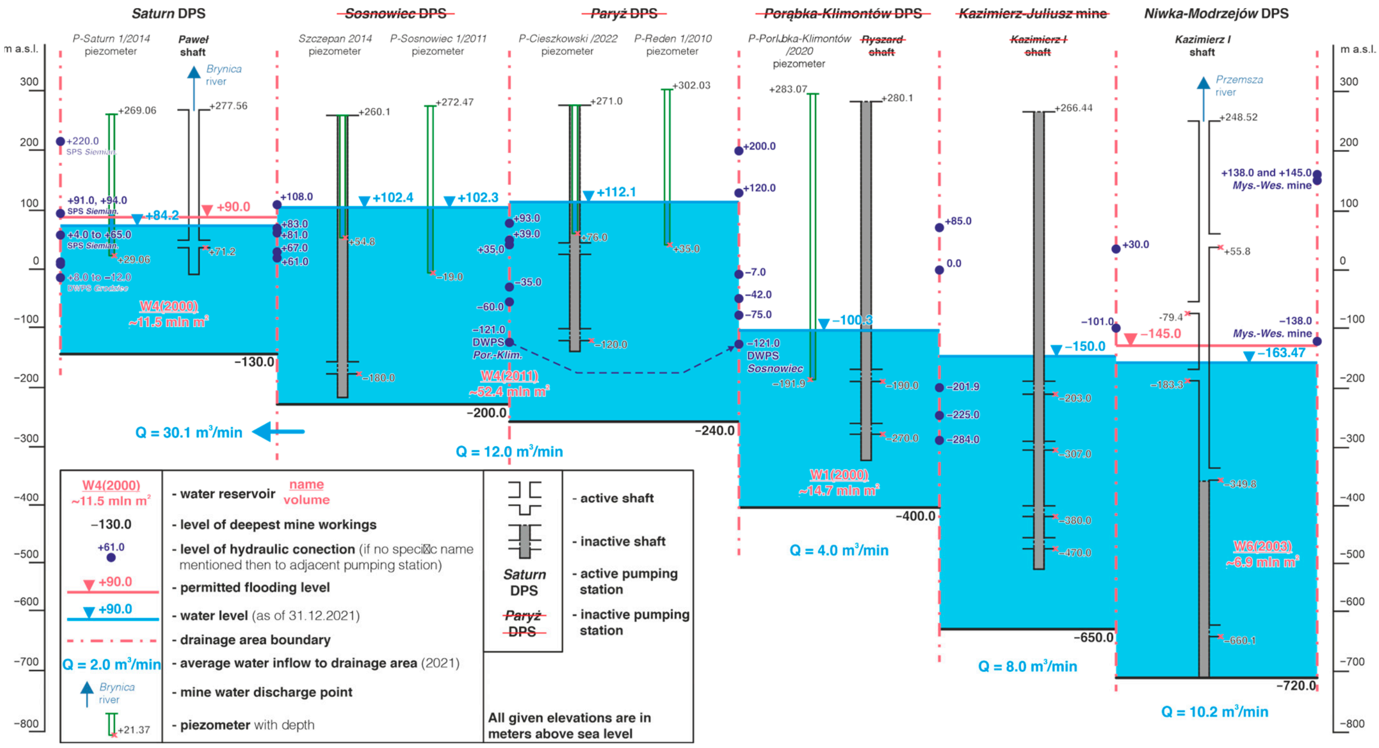

Figure 4. Schematic cross-section of the abandoned mines in the NE part of the USCB.

The CMDP uses two dewatering systems at its pumping stations: a deep-well pumping system (DPS) and a stationary pumping system (SPS). The DPS is implemented in mines where the hydrogeological conditions allow for the stabilization of water at a certain level. The formation of a water reservoir in mining works must be based on the previous detailed analysis of direct and indirect connections and determination of the stability of the boundary pillars between adjacent mines.

The DPS requires a shaft adapted into a pumping well with at least two completely submerged pumps, keeping the water level below dangerous connections between mines (Figure 5). According to the regulations in Poland, the DPS must guarantee pumping out the maximum daily inflow in less than 20 h.

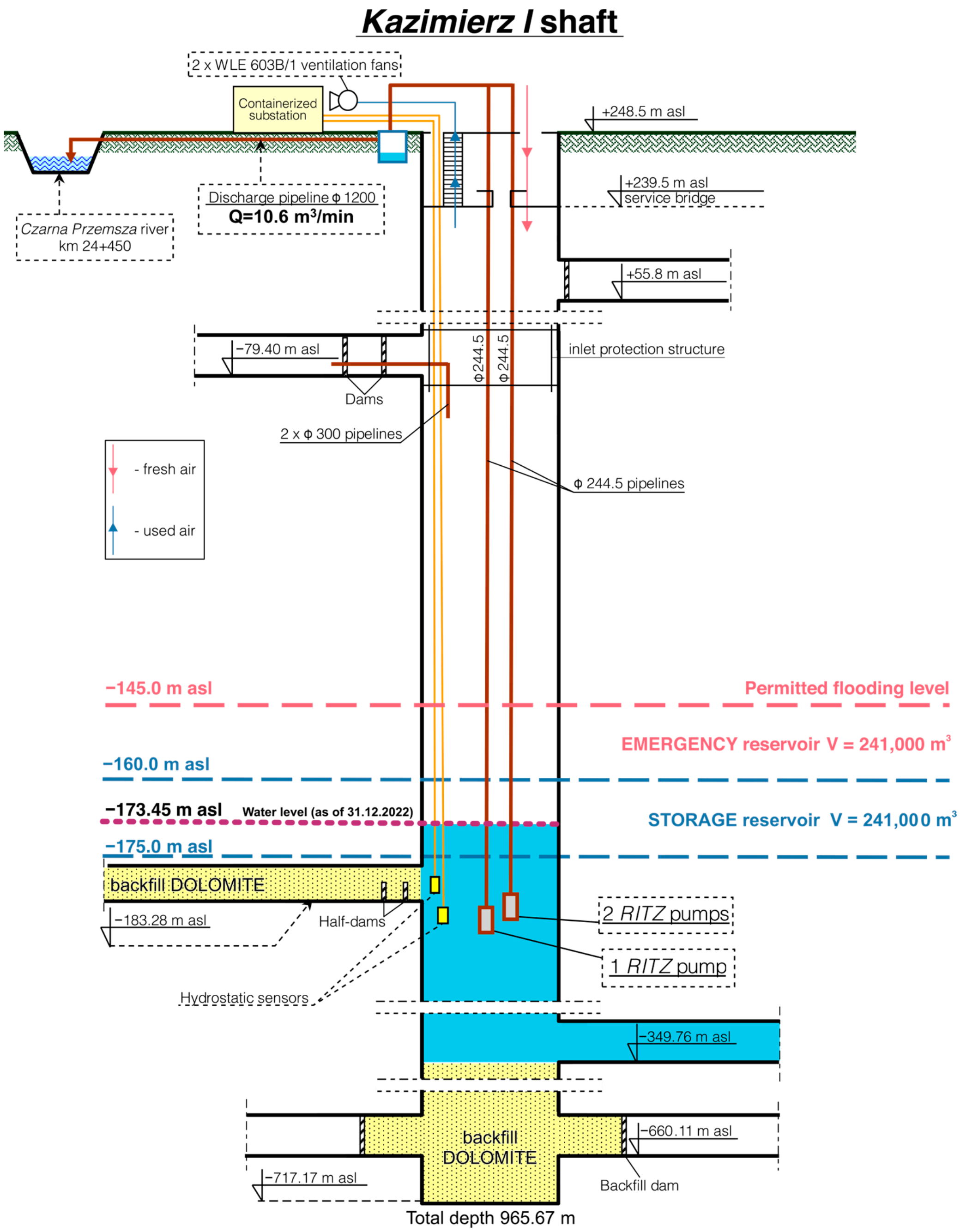

Figure 5. Scheme of the DPS in the example of the Niwka-Modrzejów DPS.

The DPS is composed of several key elements. At a depth of several meters below the entry of a shaft, a service bridge is built for submersible pump maintenance. The presence of the bridge requires ventilation of the shaft to at least its level. The water level in a shaft is controlled by hydrostatic sensors. They are installed at pre-determined depths and measure the hydrostatic pressure, enabling the direct determination of the current water level (the height of the fluid column above the sensor).

The conversion of a mine into a DPS and its flooding to a specified level create favorable conditions for the accumulation of water in mining levels and the formation of reservoirs of a large volume. There are two types of reservoirs—storage reservoirs and emergency reservoirs. A storage reservoir is used for the accumulation of water flowing into mine works. It has a precisely defined damming level, which can be achieved without increasing the water hazard level for nearby mines.

The emergency reservoir should only be flooded in situations of an emergency rise in the groundwater table. Its volume is determined based on the longest possible time of water inflow necessary for fixing or replacing the drainage pumps. This ensures that the water level in the shaft does not exceed the permitted flooding level (Figure 5).

The SPS requires the maintenance of the underground and surface technical infrastructure of at least two shafts and mine corridors at one or several levels, allowing for sufficient mine ventilation of the pumping station (Figure 6).

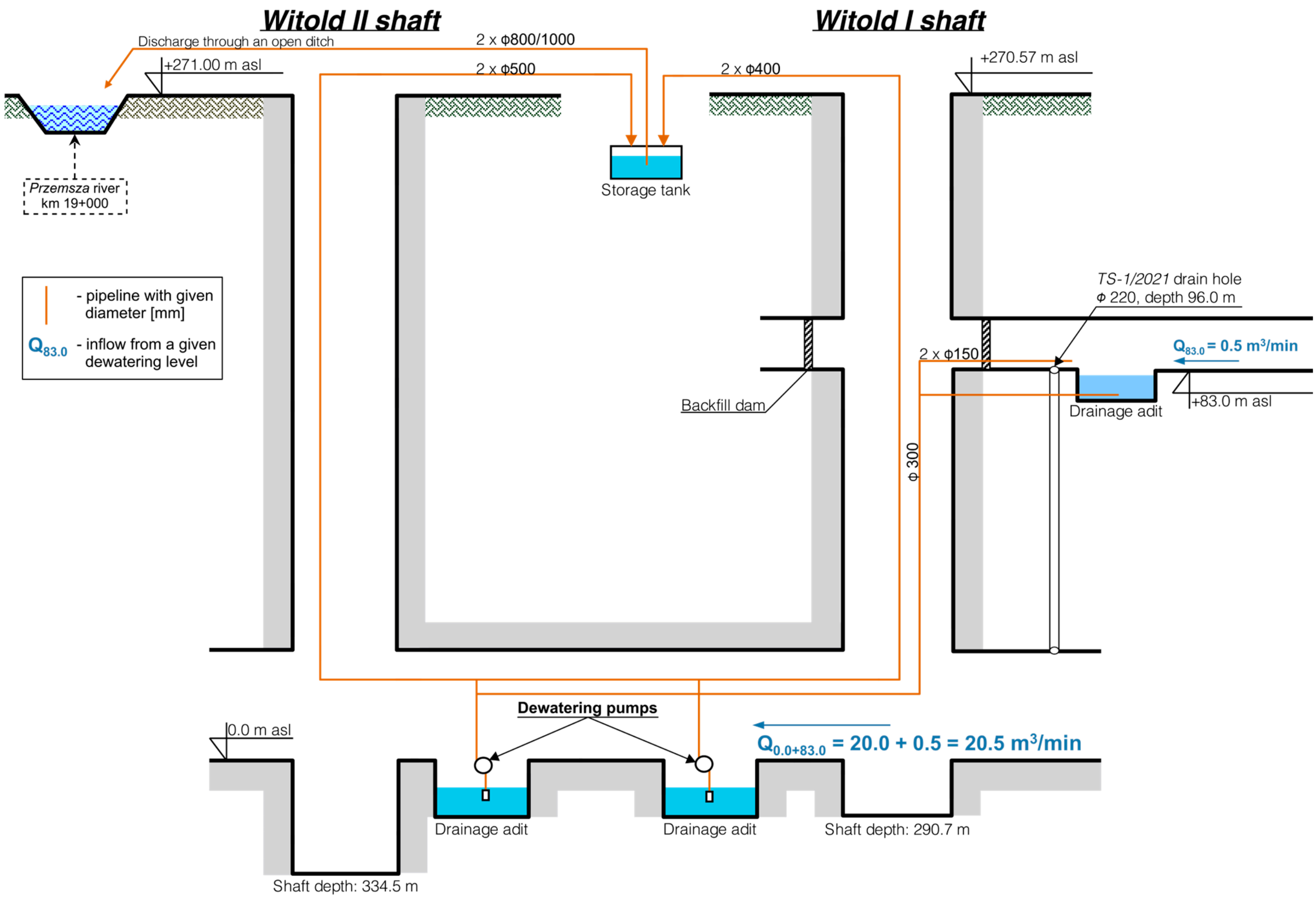

Figure 6. Scheme of the SPS in the example of the Jan Kanty SPS.

Water entering the mine gravitationally flows through water galleries to the main pumping station, from which it is pumped to the surface through pipelines. SPSs are "inflexible" because they are sensitive to unforeseen increases in water inflow and rises in the water table level. In the event of a sudden inflow of water exceeding the pumping reserve or the capacity of the water galleries, the pumping station may be at risk of flooding. Such occurrences cannot be ruled out, especially in cases where several decommissioned mines are linked through uncontrolled connections [51].

5. Characteristics of the CMDP Pumping Stations

This section discusses the possibility of using mine water from three pumping stations in the structures of the CMDP, which have long-term utility perspectives—Saturn, Jan

Kanty, and Boże Dary. The waters from these pumping stations are characterized by good qualitative and quantitative parameters.

Saturn Pumping Station. The task of the Saturn DPS is to protect the active mines in the Bytom and Main basins of the USCB from water hazard. It is adapted to serve as the main drainage center for decommissioned mines in the northeastern part of the USCB. The pumping station also receives water from neighboring decommissioned mines, i.e., Paryż, Sosnowiec, Porąbka-Klimontów, and Kazimierz-Juliusz (Figure 4). In the Paweł shaft, there are seven pumping units, but it is designed to accommodate nine pumps. They are installed in Hobas-type pipes with a diameter of 700 m. The spaces between the pipes are filled with dry concrete. The dewatering in the Saturn DPS is maintained in the elevation range of 83.00 to 86.00 m asl, with a permitted flooding level of 90 m asl. In the flooded mine workings, an underground W4(2000) water reservoir was created with an estimated volume of 11,500,000 m^3. Since January 2017, the pumping station has received an additional inflow of 12.00 m^3/min from the Paryż and Sosnowiec mines. The total inflow to the Saturn DPS in 2021 was 30.07 m^3/min. The mine water is discharged into the Brynica River (Figure 4).

Jan Kanty Pumping Station. The mine workings of the closed Jan Kanty mine are being dewatered to protect the active Sobieski coal mine from water hazard. At the time of the mine closing, its excavations were flooded at levels from −116.00 to 19.00 m asl, with a water volume of about 1,400,000 m^3. The Jan Kanty dewatering system includes the main drainage pumping station at an elevation of 0.0 m asl. The permitted flooding level of the workings is 30.00 m asl. Water from the dewatering level is pumped to the surface through pipelines located in the Witold I and Witold II shafts and then discharged into the Przemsza River. About 12% of the pumped water is used in the Jaworzno Power Plant. In 2021, the average inflow into the workings of the closed Jan Kanty mine was 21.1 m^3/min. By the end of 2023, the CMDP plans to complete the construction of a deep-well pumping station and convert the Jan Kanty SPS to a DPS.

Boże Dary Pumping Station. The principal function of the Boże Dary SPS is the protection from water hazard of the Staszic-Wujek and Mysłowice-Wesoła coal mines. It maintains a stationary dewatering system at an elevation of −123.73 m asl. Gravitational drainage boreholes allow the water to flow into the dewatering level from higher mine levels. Then, water is pumped to the surface through pipelines installed in Shaft II and discharged into the Mleczna River. In 2021, the Boże Dary SPS discharged over 7.5 million m^3 of water, averaging 14.55 m^3/min. Approximately 14% of this water was sold to two neighboring industrial factories, where it was used for the production of paper and cardboard.

6. Methods

The water samples were collected and measured directly at the point of discharge from the collective pipelines of the pumping stations. The electrical conductivity (EC) and pH were measured using the WTW 330i unit equipped with pH and SenTix ORP electrodes.

In the laboratory, the alkalinity was determined by titration with HCl to an endpoint of 4.5, and the concentration of Cl^- was determined by the argentometric method. In the accredited testing laboratory of the Hydrogeology and Engineering Geology Department at the AGH University of Krakow, the Ca, Mg, Na, K, Fe, and Zn were measured using the ICP-AES Plasma 40. Major anions were analyzed by ion chromatography using the Dionex DX-120. Trace element concentrations were measured by the ICP-MS (Perkin-Elmer, Shelton, CT, USA, Elan 6100). QA/QC was performed using certified materials.

The categorization of mine water as a source of drinking or industrial water involves a comprehensive assessment based on Polish law regulations. The assessment of the suitability of mine water for drinking purposes was carried out based on the provisions of the regulations on the quality of water intended for human consumption issued by the Minister of Health in Poland (Tables 1–3) [54].

Table 1. Aggregate results of water analyses from the Saturn pumping station.

Parameters		Values					
		Minimum	Maximum	Mean	Median	Standard Deviation	MPL [1]
-	pH	7.00	7.5	7.19	7.15	0.15	6.5–9.5
mg/L	TDS	1001.55	1758.88	1473.82	1489.27	214.54	-
	Turbidity	6.0	24.0	15.07	16.5	5.94	-
	GH	549.0	1046.0	773.9	788.0	152.62	60–500
	Cl^-	95.0	400.0	173.4	154.0	80.05	250
	SO_4^{2-}	130.0	473.0	359.2	380.0	94.78	250
	HCO_3^-	472.0	560.0	517.7	516.5	24.19	-
	Fe^{2+}	0.0016	9.93	4.9	4.76	3.85	0.2
	Mn^{2+}	0.12	1.51	1.114	1.23	0.36	0.05
	Na^+	16.00	181.00	121.23	123.5	44.95	200
	K^+	2.44	26.8	12.89	12.35	5.88	-
	Ca^{2+}	145.0	248.0	193.6	198.0	32.39	-
	Mg^{2+}	32.7	104.0	70.63	71.4	18.74	7–125
	Cr^{3+}	<0.003	0.006	0.0039	0.003	0.0011	0.05
	Zn^{2+}	<0.02	0.157	0.0559	0.0345	0.0525	-
	Cu^{2+}	<0.004	0.012	0.0069	0.005	0.003	2
	Cd^{2+}	<0.0002	<0.0002	-	-	-	0.005
	Ni^{2+}	<0.004	0.018	0.0086	0.009	0.0044	0.02
	Pb^{2+}	<0.01	0.014	0.0096	0.01	0.0028	0.01

[1] Maximum permissible level in Polish drinking water standards. “-“, in this column, means that the lawmaker has not specified an MPL value. Applies also to Tables 2 and 3.

Table 2. Aggregate results of water analyses from the Jan Kanty pumping station.

Parameters		Values					
		Minimum	Maximum	Mean	Median	Standard Deviation	MPL
-	pH	6.9	8.7	7.59	7.5	0.47	6.5–9.5
mg/L	TDS	860.0	1300.0	1059.53	1052.74	105.19	-
	Turbidity	9.6	31.0	17.29	15.0	6.57	-
	GH	426.0	849.0	594.91	583.0	120.75	60–500
	Cl^-	110.0	190.0	152.73	150.0	19.62	250
	SO_4^{2-}	250.0	350.0	317.36	320.0	30.67	250
	HCO_3^-	217.0	264.0	238.55	239.0	14.42	-
	Fe^{2+}	0.01	12.9	5.05	4.75	4.3	0.2
	Mn^{2+}	0.0186	1.62	1.2	1.29	0.43	0.05
	Na^+	39.7	108.0	73.7	73	17.85	200
	K^+	5.13	15.0	9.67	9.35	2.32	-
	Ca^{2+}	99.4	206.0	140.85	132	28.79	-
	Mg^{2+}	42.7	133.0	64.38	56.1	24.1	7–125
	Cr^{3+}	<0.003	<0.003	-	-	-	0.05
	Zn^{2+}	<0.02	0.084	0.0237	0.01	0.0256	-
	Cu^{2+}	<0.003	0.021	0.007	0.005	0.0059	2
	Cd^{2+}	<0.0002	<0.0002	-	-	-	0.005
	Ni^{2+}	<0.004	0.12	0.0172	0.007	0.0326	0.02
	Pb^{2+}	<0.001	0.025	0.0105	0.01	0.0005	0.01

Table 3. Aggregate results of water analyses from the Boże Dary pumping station.

Parameters		Values					
		Minimum	Maximum	Mean	Median	Standard Deviation	MPL
-	pH	7.2	8.1	7.72	7.7	0.28	6.5–9.5
mg/L	TDS	877.44	3095.15	1618.09	1407.53	768.73	-
	Turbidity	5.2	39.0	18.37	15.0	10.44	-
	GH	206.0	433.0	321.43	312.0	72.04	60–500
	Cl^{-}	120.0	982.0	408.43	335.0	292.18	250
	$SO_4{}^{2-}$	125.0	372.0	246.14	220.0	88.7	250
	$HCO_3{}^{-}$	300.0	739.0	475.86	440.0	149.05	-
	Fe^{2+}	0.06	5.97	1.86	1.38	1.99	0.2
	Mn^{2+}	0.06	1.08	0.47	0.41	0.36	0.05
	Na^{+}	96.5	900	365.93	202.0	273.64	200
	K^{+}	10.4	27.9	18.49	17.0	5.32	-
	Ca^{2+}	18.3	94.3	61.5	63.0	22.86	-
	Mg^{2+}	24.8	55.4	38.39	39.6	10.09	7–125
	Cr^{3+}	<0.002	<0.002	-	-	-	0.05
	Zn^{2+}	0.00003	0.091	0.039	0.035	0.031	-
	Cu^{2+}	<0.003	0.02	0.009	0.005	0.006	2
	Cd^{2+}	<0.001	<0.001	-	-	-	0.005
	Ni^{2+}	<0.01	0.011	0.01	0.01	0.00035	0.02
	Pb^{2+}	<0.001	<0.001	-	-	-	0.01

In the case of industrial water, the assessment was carried out using the common classification of mine-water quality in Poland [33,55]. This classification serves as a reference point, providing a systematic approach to evaluating the potential of water for various industrial applications. Equally important is the individual assessment carried out for the waters under consideration, taking into account the specific requirements for the proposed use of the waters, which can vary greatly.

7. Water Quality

Active coal mines and the CMDP pumping stations are the main drainage bases in the USCB. Groundwater mineralization in the USCB varies greatly, ranging from fresh water to extreme brines [56]. The water quality depends on the depth of drainage, the area covered by mine workings, and the permeability of surrounding layers [35]. With increasing depth, there is a normal hydrogeochemical zonation, characterized by an increase in the chloride and sodium concentrations with depth [57].

Saturn Pumping Station. The water from the Saturn DPS can be classified as Ca-Mg-Na-SO_4-HCO_3-type water with mineralization not exceeding 2 g/L. In the past, part of the pumped water was directly (without treatment) used as a water supply in Czeladź. However, its periodically fluctuating quality parameters and more strict water standards caused it to be discontinued for drinking purposes without the proper treatment necessary to meet the Polish drinking water standards [9]. The results of physical and chemical analyses performed in 2014–2023 showed that water from the Saturn pumping station is characterized by low turbidity (on average, 15.07 mg/L, with the constant presence of iron and manganese). A characteristic feature of this water is very high total hardness at an average level of about 770 mg/L, of which carbonate hardness accounts for about 55% of the total hardness (Table 1).

Jan Kanty Pumping Station. The decommissioned Jan Kanty coal mine belonged to the group of mines with the highest inflows in Poland [58], with maximum values reaching 30 m^3/min at the time of its active exploitation [59]. Based on the analysis of discharge waters from the Jan Kanty SPS from 2012 to 2022, it was observed that the water exhibits relatively stable physicochemical parameters and mineralization below 1.5 g/L. Its geochemical type is either Ca-Mg-Na-SO_4-Cl-HCO_3 or SO_4-Cl-HCO_3-Ca-Mg-Na, depending on minor fluctuations in the calcium and sulfate ion concentrations. Just like in the Saturn DPS, in the Jan Kanty SPS, there is also a constant presence of iron and manganese, low turbidity, and high total hardness, of which 33% is carbonate hardness (Table 2).

Boże Dary Pumping Station. Mine water from the Boże Dary SPS in the years 2016–2022 showed variable quality parameters, with mineralization ranging from approximately 870 to about 3100 mg/L (Table 3). The most common geochemical water type was Na-Cl-HCO_3. Unlike the previously discussed pumping stations, the total hardness in the Boże Dary SPS is lower, with an average value of 321.43 mg/L, predominantly consisting of non-carbonate hardness. The analysis results also indicate lower concentrations of iron and manganese, with similar turbidity (an average of 18.37 mg/L). However, the discharge water from the Boże Dary SPS is characterized by the highest salinity, with an average chloride content of approximately 408 mg/L, which results from the lowest dewatering level among the three discussed pumping stations.

8. Discussion about Possibilities of Mine-Water Usage

A commonly used classification of mine-water quality in Poland [33,55] defines four basic groups: potable water, industrial water, brackish water, and brine (Table 4). Each type of water can be used for different purposes.

Table 4. Classification of mine waters (based on [33,55]).

Group	Water Type	Mineralization [g/L]	Cl^- + SO_4^{2-} Concentration [g/L]
I	Potable	<1.0	<0.6
II	Industrial	1.0–3.0	0.6–1.8
III	Brackish	3.0–70.0	1.8–42.0
IV	Brine	>70.0	>42.0

Group I can be divided into two subgroups: water complying with the Polish water quality standards for drinking water, and water not suitable for direct drinking. The latter may contain above-standard concentrations of certain undesirable components, such as iron, manganese, or other metals, or may be contaminated with organic compounds, nitrogen compounds, or bacteria. Before using these types of water for drinking purposes, they must undergo appropriate treatment processes.

The treatment of Group I water is based on the removal of iron and manganese by oxidation, followed by filtration and disinfection, usually by the application of chlorine. In justified cases, pH correction of the water should be carried out before chlorination (Figure 7).

Industrial water (Group II) almost always requires the removal of iron and manganese, followed by the removal of suspended solids [33]. A further treatment process depends on the intended water use. For example, industrial water used for fire protection and coal sprinkling in coal mines must be chlorinated. Water for the power plants' cooling systems must be decarbonized with lime, and water intended for use in heat distribution networks must be softened and demineralized (Figure 8).

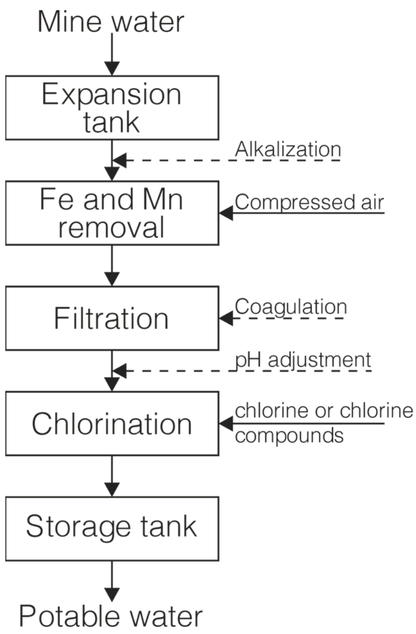

Figure 7. Water treatment process for Group I mine water [60].

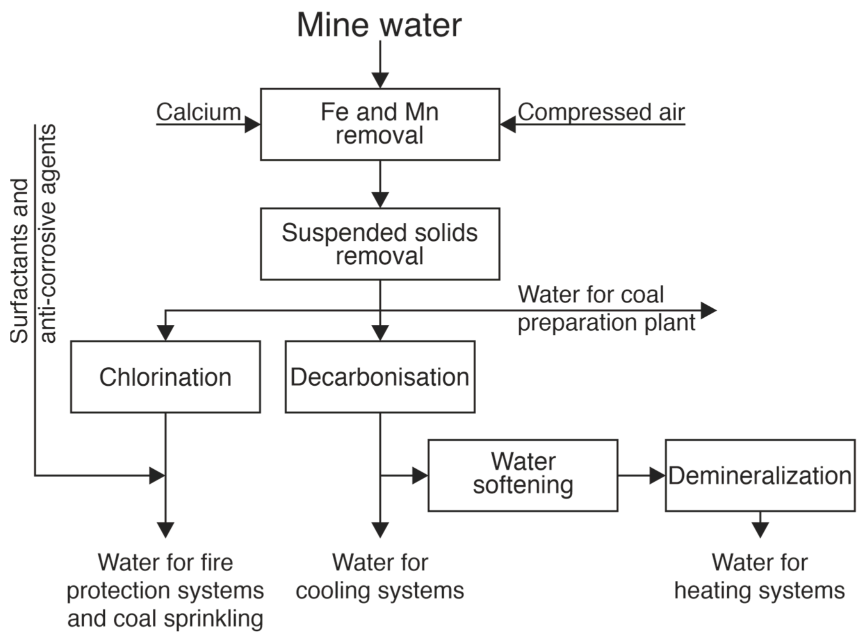

Figure 8. Water treatment process for Group II mine water [60].

Group III and IV waters are the most challenging to manage. Moderately saline waters have only very limited industrial use and can mainly be used for concentrating into saline waters [33]. Saline waters with mineralization exceeding 70 g/L can be used in graduation towers, as is the case in the Wieliczka [61] and Bochnia Salt Mines [62].

According to the presented classification, waters from the Saturn, Jan Kanty, and Boże Dary pumping stations belong to Group II, i.e., they are industrial waters. However, because analyses of the physicochemical composition of the water did not show any exceedances of toxic components (e.g., heavy metals) or difficulties related to treatment (e.g., high concentrations of SO_4^{2-} ions), waters from the discussed pumping stations should also be considered in the category of drinking waters.

The use of water from the Saturn DPS for drinking purposes has already been proposed by Sawiniak and Kłos [9]. They showed that water from dewatering can be a cost-effective and quality water source, with simple water treatment technology (Figure 9). Tests of water treatment technology at the Saturn DPS showed that the concentration of iron decreased to less than 0.1 mg/L, and the concentration of manganese to less than 0.05 mg/L.

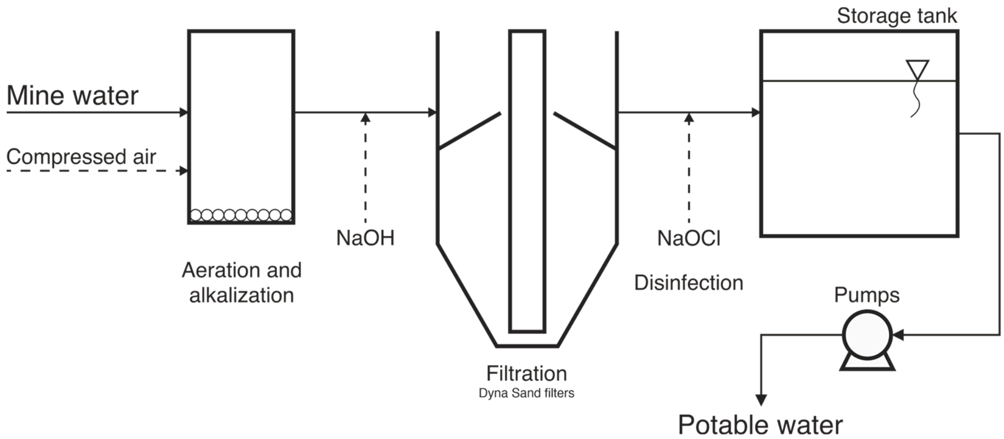

Figure 9. Scheme of the Saturn DPS water treatment system (based on [9]).

During the transition from a stationary to a deep-well pumping system in 2011, a project to recover heat from mine water was implemented at the Saturn pumping station [49]. The obtained energy is used to heat the CMDP administrative building in Czeladź, located near the Paweł shaft. The installation consists of two two-stage water-to-water heat pumps with a total heating capacity of approximately 117.8 kW, fulfilling the building's heating needs and serving as a cooling generator during the summer. This serves as an excellent example of utilizing mine waters for technological purposes. Coupled with the construction of a water treatment plant for obtaining municipal water, the Saturn DPS could serve as a model for best practices in dewatering abandoned mines.

The water from the Jan Kanty SPS is characterized by very good-quality parameters (Table 2). After possible treatment or mixing with water of lower mineralization, the mine water could be an alternative source of water supply for the city of Jaworzno, within which the pumping station is located. Currently, there are plans to construct a water treatment facility near the Jan Kanty pumping station. The purified waters from this plant could be directed to both the municipal water supply network for drinking purposes and serve as industrial waters for the nearby Jaworzno Economic Zone and to supplement the water systems in the Jaworzno Power Plant. Implementing such a solution would allow for the diversification of the city's water sources and the economic utilization of high-quality water, which, regardless of its intended use, must be pumped to the surface.

Similar to the Jan Kanty SPS, the waters from the Boże Dary SPS could be directed toward a similar management direction. In June 2023, a pilot water treatment station was launched at the Boże Dary pumping station. Initially, tests will be conducted on the water from the 183 m asl level, which has lower salinity. In the next step, water from −123.73 m asl level (Table 3), representing the storage reservoir, will be analyzed. In the case of positive results and after additional environmental and economic analyses, a decision to build a mine water treatment plant and supply the municipal water network with mine water may be made.

In addition to providing drinking water, the Boże Dary SPS is a promising source of industrial water. In 2021, 1,097,264 m^3 of water was sold to two production plants. In October 2023, a hydrogenerator was installed at a level of −123.73 m asl. The operation of the unit reduces the external electricity consumption and cost of dewatering. Between 16 October and 24 October 2023, the generator produced almost 26 MWh of electrical energy.

Water from the discussed pumping stations can also be used for neighboring mines' purposes. Drinking water can be used for sanitary purposes, as observed in mines such as the Olkusz-Pomorzany Zn-Pb ores mine. Industrial water can be used in coal-processing plants, primarily in the coal-washing and flotation processes. They can also be used for fire protection, as well as for hydraulic backfilling and material transport through pipelines.

9. Conclusions

In recent years, researchers have increasingly focused on the issue of the efficient utilization of mine waters, which are still primarily treated as industrial wastewater. Water extracted from mines as a result of mining activities often exhibits specific chemical and physical compositions, presenting both challenges and potential benefits for various economic sectors.

In the context of ongoing climate changes and decreasing water reserves worldwide, the use of mine waters is becoming a strategic issue, not only at the local level but also for sustainable water resource management globally. Faced with more frequent extreme weather events, dry periods, and alterations in precipitation cycles, the exploration of alternative water sources has become extremely crucial. However, examples of mine-water use on a large scale in the world are still limited, despite their attractiveness as a resource that must be pumped to the surface.

In the present article, the concept of the use of mine waters from three closed coal mines in the USCB: Saturn, Jan Kanty and Boże Dary, is discussed. These waters are characterized by good qualitative and quantitative parameters, with physico-chemical analyses revealing no exceedances of toxic components (e.g., heavy metals) or difficulties associated with treatment (e.g., high concentrations of SO_4^{2-} ions). A long perspective of the usage of these pumping stations and already available pumping installations make them a promising source of both potable and industrial water with a low level of purification.

After potential treatment, mine waters from the Jan Kanty SPS can be successfully used for drinking and industrial purposes, as they are already used in the Jaworzno Power Plant. A similar approach to water management can be adopted at the Boże Dary SPS, where ongoing studies assess the groundwater quality for municipal purposes. Furthermore, water from this pumping station is already sold to two industrial plants. In October 2023, an underground hydrogenerator began to operate in Boże Dary SPS, providing energy for the pumping station's operational needs.

Also, water from the Saturn DPS can be used for urban water supply with simple water treatment technology. These waters are already technologically managed—heat pumps have been installed in the shaft, which are used to heat and cool the administrative building of the CMDP in Czeladź.

Despite the promising prospects, there are significant challenges and limitations related to the use of mine water. One of the main limiting factors may be the reluctance of local authorities and the need to overcome entrenched water management practices. Decision makers often prefer traditional, proven water acquisition methods, and the implementation of innovative solutions, such as mine-water usage, may encounter resistance. The use of water from active mines may also be difficult for technical reasons. The functioning of a mine may result in periodic fluctuations in quality parameters, due to, e.g., uncontrolled inrushes of water into the workings, accidents, the leaching of poor-quality water from backfill, etc.

In summary, the use of mine water has a promising perspective in the context of water management in times of climate change. The presented concepts demonstrate the potential of both drinking and technological water supply. The implementation of practical solutions based on the analyses of qualitative and quantitative parameters may result in efficient water management and contribute a significant step in the direction of sustainable development.

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References

1. Gutry-Korycka, M.; Sadurski, A.; Kundzewicz, Z.; Pociask-Karteczka, J.; Skrzypczyk, L. Water Resources and Their Use. *Nauka* **2014**, *1*, 77–98. (In Polish)
2. Water Statistics. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Water_statistics#Water_as_a_resource (accessed on 23 January 2024).
3. Statistics Poland. *Environment 2023*; Statistics Poland: Warsaw, Poland, 2023. (In Polish)
4. Banks, D.; Younger, P.L.; Dumpleton, S. The Historical Use of Mine-Drainage and Pyrite-Oxidation Waters in Central and Eastern England, United Kingdom. *Hydrogeol. J.* **1996**, *4*, 55–68. [CrossRef]
5. Wolkersdorfer, C. *Water Management at Abandoned Flooded Underground Mines: Fundamentals, Tracer Tests, Modelling, Water Treatment*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2008; ISBN 9783540773313.
6. Schultze, M. Maximising Use of Waters Produced by Mining. In Proceedings of the International Mine Water Association Symposium, Bunbury, Australia, 30 September—4 October 2012; pp. 11–19.
7. Machnicka, A. Drinking Water in PGG S.A. Branch of HCM „Piast-Ziemowit" Ruch Ziemowit. *Bezpieczeństwo Pracy Ochrona Środowiska Górnictwie* **2021**, *5*, 14–19. (In Polish)
8. Kłos, M.; Gumińska, J. The Use of Saline Mine Water for Production of Potable and Process Water. *Instal* **2016**, *11*, 49–5052. (In Polish)
9. Sawiniak, W.; Kłos, M. Utilisation of Mine Waters for Municipal Purposes. *Wiadomości Górnicze* **2003**, *54*, 223–225. (In Polish)
10. d'Obyrn, K.; Postawa, A.; Cień, D. Flooded Ore Mine as a Potential Source of Water for Industrial Purposes. *Instal* **2023**, *1*, 47–52. (In Polish)
11. Karakatsanis, E.; Cogho, V. Drinking Water from Mine Water Using the HiPRO Process-Optimum Coal Mine Water Reclamation Plant. In Proceedings of the International-Mine-Water-Association Symposium on Mine Water and Innovative Thinking, Sydney, NS, Canada, 5–9 September 2010.
12. van Zyl, H.; Maree, J.; van Niekerk, A.; van Tonder, G.; Naidoo, C. Collection, Treatment and Re-Use of Mine Water in the Olifants River Catchment. *J. S. Afr. Inst. Min. Metall.* **2001**, *101*, 41–46.
13. Hutton, B.; Kahan, I.; Naidu, T.; Gunther, P. Operating and Maintenance Experience at the Emalahleni Water Reclamation Plant. In Proceedings of the International Mine Water Conference, Pretoria, South Africa, 19–23 October 2009; pp. 415–430.
14. Bajtos, P. Actual and Potential Utilisation of Mine Waters in the Spissko-Gemerske Rudohorie Mts., Slovakia. In Proceedings of the 10th International-Mine-Water-Association Congress, Karlsbad, Czech Republic, 2–5 June 2008; pp. 87–89.
15. Marques, A.; Garcia-Ordiales, E.; Loredo, J. Potential for Mine Water Reuse in an Abandoned Coal Mine in Northern Spain. In Proceedings of the International-Mine-Water-Association Symposium on Mine Water and Innovative Thinking, Sydney, NS, Canada, 5–9 September 2010; pp. 309–312.
16. Hidalgo, C.; Rey, J.; Martinez, J.; Benavente, J. Evolution of Mine Water Uses in the Abandoned Sulphide Mines of the Province of Jaen, Spain. In Proceedings of the International-Mine-Water-Association Symposium on Mine Water and Innovative Thinking, Sydney, NS, Canada, 5–9 September 2010; pp. 301–304.
17. Jardón, S.; Ordóñez, A.; Álvarez, R.; Cienfuegos, P.; Loredo, J. Mine Water for Energy and Water Supply in the Central Coal Basin of Asturias (Spain). *Mine Water Environ.* **2013**, *32*, 139–151. [CrossRef]
18. Gao, Y.; Liu, K.; Hou, W. Mine Dewatering Water Reuse in Large Scale Thermal Power Plant. In Proceedings of the 2016 International Conference on Mechatronics Engineering and Information Technology, Melbourne, Australia, 30 November–3 December 2016; Atlantis Press: Paris, France, 2016.
19. Hoffman, A.; Jankowski, J.; Rozwadowski, J.; Sokólski, W.; Szukalski, J. Anticorrosion Protection of Water and Wastewater Installations in Big Industrial Plants Using Cathodic Protection Technology. *Ochrona przed Korozją* **2008**, *8*, 296–300. (In Polish)
20. Barszcz, T.; d'Obyrn, K.; Korbiel, T. Experimental Underground Pumped-Storage Hydropower (UPSH). *Rynek Energii* **2022**, *1*, 55–61. (In Polish)
21. Menéndez, J.; Schmidt, F.; Konietzky, H.; Fernández-Oro, J.M.; Galdo, M.; Loredo, J.; Díaz-Aguado, M.B. Stability Analysis of the Underground Infrastructure for Pumped Storage Hydropower Plants in Closed Coal Mines. *Tunn. Undergr. Space Technol.* **2019**, *94*, 103117. [CrossRef]
22. Menéndez, J.; Fernández-Oro, J.M.; Galdo, M.; Loredo, J. Efficiency Analysis of Underground Pumped Storage Hydropower Plants. *J. Energy Storage* **2020**, *28*, 101234. [CrossRef]
23. Ali, S.; Stewart, R.A.; Sahin, O. Drivers and Barriers to the Deployment of Pumped Hydro Energy Storage Applications: Systematic Literature Review. *Clean. Eng. Technol.* **2021**, *5*, 100281. [CrossRef]

24. Kitsikoudis, V.; Archambeau, P.; Dewals, B.; Pujades, E.; Orban, P.; Dassargues, A.; Pirotton, M.; Erpicum, S. Underground Pumped-Storage Hydropower (UPSH) at the Martelange Mine (Belgium): Underground Reservoir Hydraulics. *Energies* **2020**, *13*, 3512. [CrossRef]
25. Brücker, C.; Preuße, A. The Future of Underground Spatial Planning and the Resulting Potential Risks from the Point of View of Mining Subsidence Engineering. *Int. J. Min. Sci. Technol.* **2020**, *30*, 93–98. [CrossRef]
26. Menéndez, J.; Loredo, J.; Galdo, M.; Fernández-Oro, J.M. Energy Storage in Underground Coal Mines in NW Spain: Assessment of an Underground Lower Water Reservoir and Preliminary Energy Balance. *Renew. Energy* **2019**, *134*, 1381–1391. [CrossRef]
27. Montero, R.; Niemanm, A.; Wortberg, T. Underground Pumped-Storage Hydroelectricity Using Existing Coal Mining Infrastructure. In Proceedings of the 36th IAHR World Congress, Hague, The Netherlands, 28 June–3 July 2015; pp. 3592–3599.
28. Kubski, P. Use of Underground Mine Water Energy for Heating. *Zeszyty Problemowe Postępów Nauk Rolniczych* **2002**, *486*, 101–106. (In Polish)
29. Watzlaf, G.R.; Ackman, T.E. Underground Mine Water for Heating and Cooling Using Geothermal Heat Pump Systems. *Mine Water Environ.* **2006**, *25*, 1–14. [CrossRef]
30. Digges La Touche, G.; Preene, M. The Potential Use of Ground Energy in the Mining Industry—Exploration to Closure. In Proceedings of the IMWA Congress 2011, Aachen, Germany, 4–11 September 2011.
31. Drwięga, A.; Gliklich-Kostrzewa, B. Energetical Use of Water from the Process of Mines Dewatering. *Bezpieczeństwo Pracy Ochrona Środowiska Górnictwie* **2019**, *4*, 3–13. (In Polish)
32. Strozik, G. Balance and Methods of the Utilization of Salt Waters from Active and Decommissioned Hard Coal Mines Including Their Use in Underground Mining Technologies. *Zeszyty Naukowe Instytutu Surowcami Mineralnymi Energią Polskiej Akademii Nauk* **2017**, *98*, 199–210. (In Polish)
33. Rogoż, M. *Mining Hydrogeology with Basics of General Hydrogeology*; Central Mining Institute: Katowice, Poland, 2004; ISBN 8387610631. (In Polish)
34. Magdziorz, A.; Seweryński, J. The Use of Membrane Techniques in Treatment and Desalination of Coal Mine Waters. *Przegląd Górniczy* **1999**, *55*, 18–23. (In Polish)
35. Razowska-Jaworek, L.; Pluta, I.; Chmura, A. Mine Waters and Their Usage in the Upper Silesia in Poland. Examples from Selected Regions. In Proceedings of the 10th International-Mine-Water-Association Congress, Karlsbad, Czech Republic, 2–5 June 2008; pp. 113–116.
36. Statistics Poland Reporting—Mine Dewatering. Available online: https://www.pgi.gov.pl/psh/materialy-informacyjne-psh/sprawozdawczosc-gus-odwodnienia-gornicze-1.html (accessed on 23 January 2024). (In Polish)
37. Kotas, A. Structural Evolution of the Upper Silesian Coal Basin (Poland). In Proceedings of the 10th International Congress of Carboniferous Stratigraphy and Geology, Madrid, Spain, 12–17 September 1983; Volume 3, pp. 459–469.
38. Bukowy, S. Geotectonic Position of the Upper Silesian Coal Basin. In *Tectonics of the Upper Silesian Coal Basin*; Trzepierczyński, J., Ed.; University of Silesia: Katowice, Poland, 1985. (In Polish)
39. Buła, Z.; Żaba, J.; Habryn, R. Tectonic Subdivision of Poland: Southern Poland (Upper Silesian Block and Małopolska Block). *Przegląd Geol.* **2008**, *56*, 912–920. (In Polish)
40. Wilk, Z.; Kulma, R. *Hydrogeology of Polish Mineral Deposits and Mining Water Issues*; Uczelniane Wydawnictwa Naukowo-Dydaktyczne AGH: Cracow, Poland, 2004; ISBN 8389388065. (In Polish)
41. Jureczka, J.; Dopita, M.; Gałka, M.; Krieger, W.; Kwarciński, J.; Martinec, P. *Geological Atlas of Coal Deposits of the Polish and Czech Parts of the Upper Silesian Coal Basin*; Polish Geological Institute—National Research Institute: Warsaw, Poland, 2005. (In Polish)
42. Kotas, K. (Ed.) Coal-Bed Methane Potential of the Upper Silesian Coal Basin, Poland. *Prace Państwowego Instytutu Geologicznego* **1994**, *142*, 5–81. (In Polish)
43. Porzycki, J. Mudstone Series of the Lower Westphalian in the Upper Silesian Coal Basin. In *Carboniferous of the Upper Silesian Coal Basin*; Wydawnictwa Geologiczne: Warsaw, Poland, 1972. (In Polish)
44. Buła, Z.; Kotarba, M.; Smolarski, L. Assessment of the Size of the Basic Lithological Types Forming the Upper Carboniferous Formations of the Upper Silesian Coal Basin. In *Development of Models and Balance of Gas Generation and Accumulation in the Coal-Bearing Series of the Upper Silesian Coal Basin*; PPGSMiE PAS Center: Cracow, Poland, 1995. (In Polish)
45. Kotas, A. Major Features of the Geological Structure of the USCB At the Background of the Tectonic Position and Structure of the Deep Bed of Productive Formations. In *Problems of Geodynamics and Rock Bursts*; Committee of Mining of the Polish Academy of Sciences: Cracow, Poland, 1972; pp. 5–55. (In Polish)
46. Rozkowski, A.; Chmura, A.; Gajowiec, B.; Wagner, J. Impact of Mining on the Groundwater Chemistry in the Upper Silesian Coal Basin (Poland). *Mine Water Environ.* **1993**, *12*, 95–105. [CrossRef]
47. Różkowski, A. Hydrogeological Characteristic of the Upper Silesian Coal Basin. *Przegląd Geol.* **1964**, *12*, 75–79. (In Polish)
48. Chmura, A. Hydrogeological Characteristics of the Utility Aquifers. Quaternary Aquifers. In *Utility Groundwater of the Upper Silesian Coal Basin and Its Borders*; The Polish Geological Institute—National Research Institute: Warsaw, Poland, 1997; pp. 51–53. (In Polish)
49. Tokarz, M.; Mucha, W. Use of Geothermal Energy from Mines Water in Spółka Restrukturyzacji Kopalń S.A. Centralny Zakład Odwadniania Kopalń. *Technika Poszukiwań Geologicznych Geotermia Zrównoważony Rozwój* **2013**, *1*, 103–113. (In Polish)
50. Konsek, S.; Czapnik, A. Target Dewatering Model Liquidated Coal Mines in the Upper Silesian Coal Basin. *Systemy Wspomagania Inżynierii Produkcji* **2020**, *9*, 99–110. (In Polish)

51. Postawa, J.; Szczepański, A.; Tomys, A. Dewatering of Closed Mines with Deep-Well Pump Units. *Górnictwo Geoinżynieria* **2004**, *28*, 189–204. (In Polish)
52. Frolik, A.; Muniak, A. Program of Water Drainage System Simplification for Hard Coal Mines under Liquidation Which Are Supervised by the Regional Board of Mining in Katowice. *Bezpieczeństwo Pracy Ochrona Środowiska Górnictwie* **2006**, *3*, 32–37. (In Polish)
53. Rogoż, M.; Frolik, A. The Concept of Dewatering Abandoned Mines in the Northern Part of the Upper Silesian Coal Basin. In Proceedings of the Konferencja SITG w Katowicach. Doświadczenia z likwidacji zakładów górniczych, Mysłowice, Poland, 4–6 April 2001. (In Polish).
54. Regulation on the Quality of Water Intended for Human Consumption. Available online: https://leap.unep.org/en/countries/pl/national-legislation/regulation-quality-water-intended-human-consumption (accessed on 19 February 2024).
55. Marchacz, W.; Rogoż, M. Performing Underground Drilling in Water Hazard Conditions. *Wiadomości Górnicze* **1967**, *2*, 37–42. (In Polish)
56. Pluta, I.; Szczepańska, J. Waters of Upper Silesian Coal Basin Mines in the Light of New Regulations: Terminology, Reserves, Utilization. *Przegląd Górniczy* **2004**, *60*, 25–32.
57. Pluta, I.; Mertas, J.; Dziendziel, F.; Węglorz, M. Hydrogeochemical Zoning and Origin of Waters in the Region of the Kazimierz-Juliusz and the Ziemowit Mining Areas. *Biuletyn Państwowego Instytutu Geologicznego* **2009**, *436*, 367–371. (In Polish)
58. Karpiński, M.; Batko, R.; Kmiecik, E.; Tomaszewska, B.; Zdechlik, R. The Temporal Variability of the Water Inflow to the Underground Sobieski Coal Mine. *Technika Poszukiwań Geologicznych Geotermia, Zrównoważony Rozwój* **2017**, *56*, 49–60. (In Polish)
59. Czapnik, A.; Janson, E.; Jasińska, A. Selected Problems with Monitoring in Abandoned Hard Coal Mines in the Upper Silesian Coal Basin. *Biuletyn Państwowego Instytutu Geologicznego* **2009**, *436*, 55–60. (In Polish)
60. Lach, R. Water and Wastewater Management of Mines in the Aspect of Environmental Protection. In Proceedings of the Ekologiczne Aspekty Podziemnej Eksploatacji Złoż Kopalin Użytecznych Conference, Szczyrk, Poland, 23–25 November 1993. (In Polish).
61. d'Obyrn, K.; Rajchel, L. Balneological Values of the Wieliczka Salt Mine. *Acta Balneol.* **2014**, *4*, 220–223. (In Polish)
62. Rajchel, L. Balneological Resources of the Carpathian Province. *Acta Balneol.* **2016**, *4*, 275–278. (In Polish)