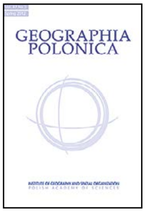

Geographia Polonica
2025, Volume 98, Issue 2, pp. 185-209
https://doi.org/10.7163/GPol.0299

INSTITUTE OF GEOGRAPHY AND SPATIAL ORGANIZATION
POLISH ACADEMY OF SCIENCES
www.igipz.pan.pl

www.geographiapolonica.pl

CHARACTERISTICS OF THE CHEMICAL COMPOSITION OF WATER IN RESERVOIRS UNDER THE INFLUENCE OF COAL MINE WASTE IN THE UPPER SILESIAN COAL BASIN (SOUTHERN POLAND)

Marek Sołtysiak • Jacek Różkowski

Institute of Earth Sciences
University of Silesia in Katowice
Będzińska 60, 41-200 Sosnowiec: Poland
e-mails: marek.soltysiak@us.edu.pl (corresponding author) • jacek.rozkowski@us.edu.pl

Abstract

This article presents research results on the water chemistry of 16 reservoirs adjacent to post-mining waste landfills in the Upper Silesian Coal Basin, sampled in 2022 and 2023. The waters of these reservoirs are anthropogenically modified; in terms of hydrochemical type, they are multi-ionic waters: Cl^-–SO_4^{2-}–Na^+, Cl^-–SO_4^-–HCO_3^-–Na^{2-}, and Cl^-–SO_4^{2-}–HCO_3^-–Na^+–Ca^{2+}. They are characterized by high electrical conductivity (EC; up to 21.5 mS/cm), high concentrations of Cl^- (up to 9.279 mg/L), SO_4^{2-} (up to 5.277 mg/L), and Na^+ (up to 4.783 mg/L). They are considered waters of poor quality (class V) due to their increased concentrations of Cl^- and SO_4^{2-} and high EC values. The Comprehensive Pollution Index (CPI) was also used to assess the degree of water pollution. Calculations indicated that the waters are either moderately ($0.47 < CPI < 1.92$) or heavily polluted ($CPI > 2$). Research has also shown that areas reclaimed with mining waste are informal post-mining waste dumps and should be treated as potential sources of groundwater pollution. In nearby reservoirs, there is a potential threat to shallow (0-10 m) groundwater of the first aquifer, which is especially important when the first aquifer is being used.

Keywords

mining waste dumps • water reservoirs • Upper Silesian Coal Basin • environmental hazards

Introduction

This article presents research results on the chemistry of water in reservoirs adjacent to post-mining waste landfills in the Upper Silesian Coal Basin (USCB), combined with hydrological and environmental mapping from 2022 and 2023. The interaction of post-mining waste landfills and the aquatic environment is an essential environmental problem in the USCB due to the scale of the phenomenon in one of the most industrialized and anthropogenically degraded regions of Europe. The research aimed to characterize the chemical composition and quality of surface waters from post-mining waste landfills in USCB and to analyze the factors causing the pollution of these waters.

In 1995, there were 65 active hard coal mines in the USCB, extracting 130 million Mg of coal. Mine-water inflows ranged from 0.9 to 73 $m^3 \cdot min^{-1}$. As much as 60% of the mine water was discharged into rivers (Różkowski et al. ed., 1997). In 1977-1989, the USCB had 83 mine water discharges from hard coal mines to the surface hydrographic network. In 2018, discharges in this area decreased to 64: 31 in the Odra basin and 33 in the Vistula basin. In 1967-2013, hard coal mines in the USCB discharged an average of 10.39 $m^3 \cdot s^{-1}$ of water into rivers, including 2.46 $m^3 \cdot s^{-1}$ into the Odra and 7.94 $m^3 \cdot s^{-1}$ into the Vistula. The volume of the discharged mine water reached its maximum in the years 1985-1988. The average volume of the discharged mine water at that time was 14.19 $m^3 \cdot s^{-1}$, 11.03 $m^3 \cdot s^{-1}$ of which was discharged into the Vistula basin and 3.16 $m^3 \cdot s^{-1}$ into the Odra basin. As a result of the mining restructuring that started in 1989, there was a systematic decrease in the volume of discharged mine water. Overall, the amount of discharged mine water decreased by 26% compared to 1977-1989 (Matysik, 2018). Currently, there are 56 active mining areas in the USCB (Mineral deposits, 2017).

Groundwater quality in the region is at risk due to the impact of coal mining waste. As of 1997, there were already about 300 mining waste dumps in the northeastern part of the USCB. The central dumping grounds, receiving waste from up to 20 mines, each covered an area of several hundred hectares (Różkowski et al., 1997). According to Gawor (2009), 750 million Mg of waste material was deposited in 136 mining waste dumps in the USCB area. The area occupied by landfills was 3,500 ha. The largest dumping ground was Smolnica, whose area is 255 ha. Currently, due to the energy transformation, the use of hard coal is decreasing, so less waste is generated. Waste recovery and processing are also carried out.

Hard coal mining waste consists of Carboniferous gangue rocks accompanying coal seams, originating from mining works (25-40% share) and produced in the process of coal enrichment (rinsing and post-flotation waste constitutes a 6-75% share) (Różkowski et al., 1997). The production of 1 Mg of hard coal generates 0.3-0.5 Mg waste (Rakwic, 2011). This includes shale, clay shale, mudstone, carbonaceous shale, sandstone, conglomerate, limestone, and coal. In 2007, in the extraction of 88.3 million Mg of hard coal (Statistics Poland, 2007), 34.4 million Mg of waste was produced, which gives a ratio of 1:0.39. The mining waste was dominated by rock material from gravity enrichment of coal (88.9%), waste from coal flotation (5.3%), waste from preparatory works (4.3%), and crushed rocks (1.4%) (Lutyński, 2010). According to data from the State Mining Office (Madej & Kujawski, 2023), in 2020 hard coal mining generated 30 million Mg of waste, of which 24.9 million Mg was generated in USCB and 5.1 million Mg in the Lublin Coal Basin (LCB). The ratio of coal exploitation to waste production was 55%.

The waste is partially managed. Some of it is used to fill excavations and voids in the rock mass, but most of it is utilized on the surface. 93.3% of the waste from hard coal mining remained on the surface in 2000, of which 43.3% was used for land leveling, 27.2% was used for engineering works, 12.9% was deposited in landfills, and 8.9% was used by other recipients. 0.5% of the waste was used to produce building materials (Krieger & Sroga, 2002).

As of 1992, 663 million Mg of waste had accumulated in the USCB. There has been a downward trend in hard coal mining for 30 years. Approximately 4.4 billion Mg of hard coal was mined in Poland in the years 1985-2023 (Fig. 1). Assuming the amount of waste generated and reaching the surface was 30%, it can be estimated that in the years 1985-2023, approximately 1.3 billion Mg of mining waste was generated in Polish coal basins. Taking into account the estimated amount of waste up to 1992 and its share of 30% of the extraction value, it can be estimated that 1.4 billion Mg of extracted Carboniferous rocks was deposited in landfills and used for engineering works on the surface in the USCB area.

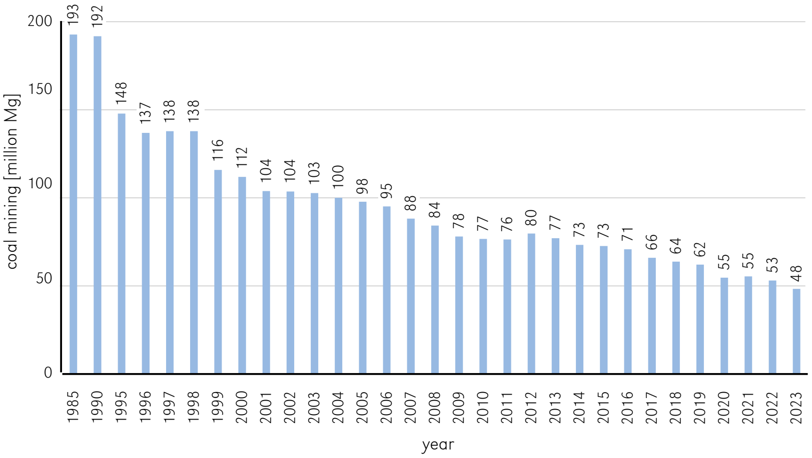

Figure 1. The volume of hard coal mining in Poland in the years 1985-2023

Source: Statistical Yearbooks of Industry (2007, 2011, 2015, 2020) and Hard coal (2022)

Waste from hard coal mines is a source of chlorides and sulfates and may cause acidification of the soil and water environment. Together with the mine water retained in mine reservoirs, it constitutes a significant environmental threat. In terms of mineral composition, hard coal waste contains illite (28-82%), kaolinite (9-65%), montmorillonite (0-5%), quartz (3-37%), chlorite (0-10%), pyrite (0-8%), and carbonaceous substances (15-30%). In terms of its chemical composition, waste from hard coal mines, expressed as oxides, is dominated by silica (SiO_2) and aluminum oxide (Al_2O_3). The most common oxides are Fe_2O_3, K_2O_2, CaO, and MgO (Tab. 1).

Degradation of the water environment in the area of post-mining waste dumps results from the leaching of easily soluble salts (chlorides, sulfates) from these wastes, which are introduced into surface and groundwater (Szczepańska, 1987; Twardowska et al., 1988). The origin of chlorides and sulfates in Carboniferous waste is different. Chlorides occur in the liquid phase in the pore solution in the rock. Research conducted by Bojarska and Bzowski (2012) and Rakwic (2011) does not indicate that waste from domestic coal mining is a source of heavy metal pollution. Waste and mine water may deliver excessive amounts of iron to the aquatic environment (Rakwic, 2011).

Table 1. Chemical composition of post-mining waste from hard coal mines (according to Rakwic, 2011)

No.	Component	Percentage
1.	SiO_2	35-60
2.	Al_2O_3	17-28
3.	Fe_2O_3	1.5-5.6
4.	K_2O_2	0.1-5.5
5.	CaO	0.3-1.8
6.	MgO	0.3-2.1
7.	Na_2O_3	0.01-0.07
8.	TiO_2	0.1-1.7
9.	P_2O_5	0.0-0.3
10.	SO_3	0.04-1.8
11.	Chlorites	0.02-0.06

After the deposition of coal waste, chlorides are easily leached from them, while sulfates are leached for several dozen years (Szczepańska, 1987). Therefore, post-mining waste dumps are a permanent source of hydrosphere pollution. The chloride salinity of the Carboniferous rocks of the USCB is in the range 0.001-1%. In turn, the sulfur content in coal seams is 0.01-10%. Sulfur in mining waste occurs in the form of organic and inorganic sulfur, mainly in pyrites. The oxidation process in the dump causes sulfide decomposition and water acidification and generates iron ions and sulfates. With 60 million Mg·year^{-1} of coal waste production, the amount of chlorides delivered to dumping sites with the waste was 40,000 Mg·year^{-1}, while sulfates amounted to 450,000 Mg·year^{-1} (Twardowska et al., 1988). According to Rakwic (2011), 0.2-0.6 kg of Cl^- is leached from 1 Mg of post-mining waste, corresponding to 20-60 Mg Cl^- per 100 thousand Mg of waste. Lysimetric research currently being conducted at the University of Silesia has shown that the concentration of chlorides in eluates from leaching from 2 Mg of post-mining waste from the eastern part of the USCB reached up to 36 g/l, and the total load of chlorides washed in the period August 2023-March 2024 was 5.4 kg (Sołtysiak, 2024).

The problem of transformation of the aquatic environment under the influence of post-mining waste landfills is reflected in the publications of researchers in Poland, such as Szczepańska (1987), Twardowska et al. (1988), and Stefaniak and Twardowska (2006), who dealt with chemical processes in deposited Carboniferous rocks. Rakwic (2011) examined the mineralogical composition of Carboniferous rocks. Fabiańska et al. (2024) dealt with changes in the weathering of mining waste (geochemistry, petrography, and mineralogy) in relation to selected USCB mines. Gołębiowski et al. (2010) and Zdechlik et al. (2011, 2012) used geophysical and hydrogeochemical methods to assess the migration of pollutants from coal waste landfills. Molenda and Chmura (2011), Chmura and Molenda (2012) and Molenda (2014 a,b) dealt with the phenomenon of meromixis in reservoirs that are recipients of mine waters in the USCB area with very high concentration of total dissolved solids and domination of chloride-sodium ions, the interaction between a thermally active coal landfill and the hydrobiological environment, and the presence of heavy metals in the leachate waters of hard coal mining waste landfills.

Voros et. al. (2021) characterized organic matter and investigated the mechanism of metal removal from mine sediments and metal transfer to the water. They studied the degree of environmental pollution in the part of the USCB within the borders of the Czech Republic. The utilitarian problem of the transformation of the aquatic environment under the influence of mining waste dumps is widely discussed around the world, as evidenced by the examples below. Gandy and Younger (2008) investigated the process of the physical flushing of pollutants from heaps in northern England. Mele et al. (1982) characterized leachate water from coal waste landfills in southwestern Illinois, paying attention to the long-term process of water contamination with sulfur and iron compounds. Marove et al. (2022) presented the degree of contamination of soil, sediments, and water around open-pit hard coal mines in Mozambique, while Dzhangi and Atangana (2024) observed changes in water quality under the influence of mining activity in neighboring South Africa. With respect to old mine dumps in Tasmania, the results of acid and metal generation in the drainage zone were presented by Movo et al. (2023). A review article on the scale of hard coal mining in China and the environmental impact of mining was presented by Tao et al. (2024). Research on microplastics in mine waters is very current (Brožová et al., 2023). Modern geoelectrical tests of waste rock samples using kinetic tests in columns for the assessment of the acidic drainage of mining waste dumps were proposed by Su et al. (2024).

Study area

The research area is located in the Province of the Polish Uplands, Subprovince of the Silesian-Kraków Upland (Kondracki, 1998).

In the study area, the average annual temperature is 8.1°C, ranging from -2.4°C (January) to 17.8°C (July) (Woś, 2010). In the period 1987-2021, annual rainfall ranged from 525 mm (1989) to 1,012 mm (2010), and the average annual rainfall was 735 mm.

The research area is located in the Vistula and Odra basins. The most important rivers in the detailed research area are, in the Odra basin, Kłodnica, Bierawka, and Szotkówka, and in the Vistula basin, Gostynka, Pszczynka, and Soła. The first-order Vistula-Odra watershed passes through the central part of the area (Fig. 2).

The USCB, covering an area of 5,500 km^2 in Poland, is located within the Upper Silesian massif. The productive Carboniferous formations consist of a complex of claystone-mudstone-sandstone rocks with numerous hard coal deposits with a maximum thickness of 8,200 m. In the north-eastern part of the Upper Carboniferous Zone, the Upper Carboniferous deposits are directly covered with Mesozoic or Quaternary deposits; in the southern and western parts, they are covered with Tertiary clay deposits (Różkowski et al., 1997; Różkowski, 2004).

Materials and methods

This study on water chemistry in reservoirs under the influence of coal mine waste in the USCB was based on hydrogeological investigations and hydrological and environmental mapping across an area of approximately 1,050 km^2.

Archive data

The analysis of changes in the natural environment under the influence of anthropogenic pressure in the area of the USCB was

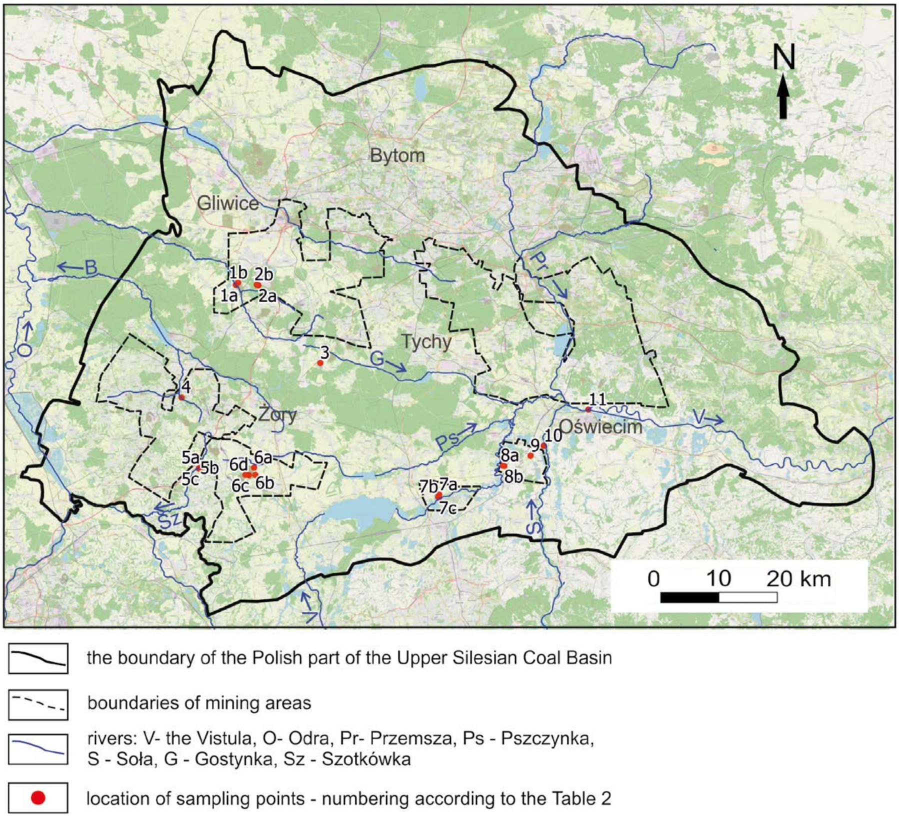

Figure 2. Map of the Upper Silesian Coal Basin with coal mining areas and location of sampling points

based on the published literature listed in the literature section, including topography maps, aerial photographs (www.geoportal.gov.pl; https://www.google.pl/maps/), field observations, and environmental reconnaissance. The maps used for spatial analyses included: the Detailed Map of Poland on a scale of 1:10,000, an orthophotomap, a digital terrain model, the Hydrographic Map of Poland, and the Open Street Map. The topographic maps were analyzed and interpreted using GIS methods. The QGIS application was used. Maps available in the Open Regional Spatial Information System (ORSIP) – Geoportal of the Silesian Province (https://www.orsip.pl/geoportal) were also analyzed.

Field sampling

In 2022 and 2023, hydrological and environmental mapping, physicochemical investigations, and water sampling were carried out in 12 selected USCB locations: Szczygłowice, Knurów, Gardawice, Rybnik Chwałowice, Połomia, Krzyżowice, Rydułtowice, Brzeszcze, Rajsko, and Oświęcim Dwory. The locations of the research objects and hydrochemical testing points are shown in Figures 2-4. The characteristics of selected mining waste dumps and reclaimed areas and their relationships to the groundwater are presented in Table 2. The characteristics of water reservoirs and watercourses in the area of post-mining waste storage and reclaimed areas are presented in Table 3.

The research objects selected were (numbering according to Tab. 2):

- reservoirs near open-pit mining excavations reclaimed with post-mining waste: gravel pit in Rajsko (p. 10), and Gardawice sand pit (p. 3);
- reservoirs at post-mining waste landfills: Szczygłowice (p. 1a), the Central Mining Waste Dump in Knurów (p. 2a), Kościelniok

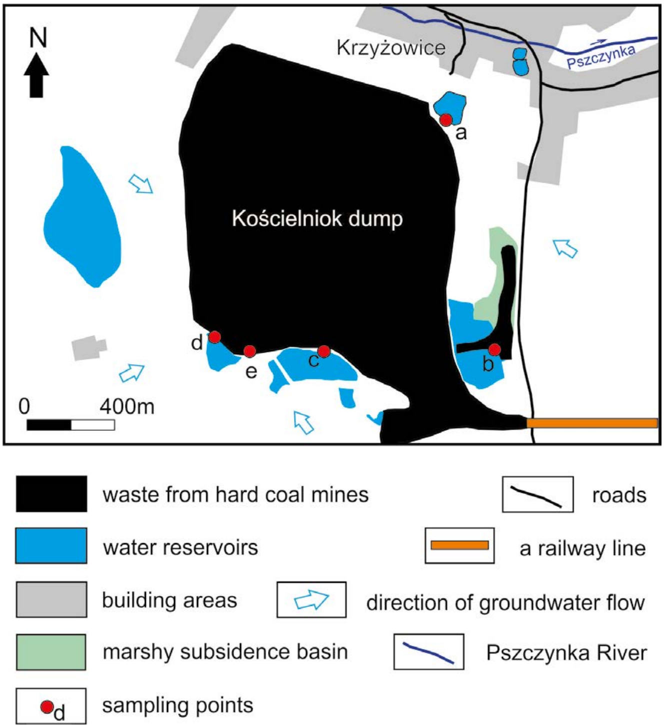

Figure 3. The area of the Kościelniok mining waste dump with the location of sampling point

in Krzyżanowice (p. 6a, 6c, 6d, 6e, Fig. 3), and Pochwacie in Połomia (p. 5a, 5b);

- reclaimed and flooded sinkholes: the Mośnik reservoir (p. 4), a reservoir in Brzeszcze (p. 8b), and the Kościelniok landfill area (p. 6b);
- mine water reservoirs: a sedimentation reservoir in Brzeszcze (p. 8a), and the decommissioned Rontok Wielki retention reservoir in Rydułtowice (p. 7b, Fig. 4);
- watercourses under the influence of stored mining waste: the Bierawka river (p. 1b), a ditch near the heap in Knurów (p. 2b), the Szotkówka river (p. 5c), and the Vistula (p. 11).

The area of post-mining waste landfills ranges from 8.0 to > 306.5 ha. Regarding morphology, landfills no. 1, 2, 4, 5, 6, 7, 8, and 10 are above-ground landfills, and landfills no. 3, 4, 7, 9, and 10 are places where the landfill is stored below ground level (Tab. 2). Activities within all facilities are guided by administrative decisions of the relevant mining authorities. The detailed research objects are surface waters occurring in the immediate vicinity of the stored mining waste described above. Most of them are water reservoirs with an area ranging from 0.05 ha (reservoir in the Gardawice sand pit) to 28.0 ha (Brzeszcze mine water settling pond), occurring at a distance of 0-10, locally up to 150 m from the landfills. The sampled water reservoirs are located at a distance of 50-1650 m from the nearest watercourses. In the case of the Mośnik Reservoir and the Połomski Reservoir, they are directly adjacent to surface watercourses.

Mining waste landfills and reclaimed areas are located where the first aquifer is associated with Quaternary sand and gravel

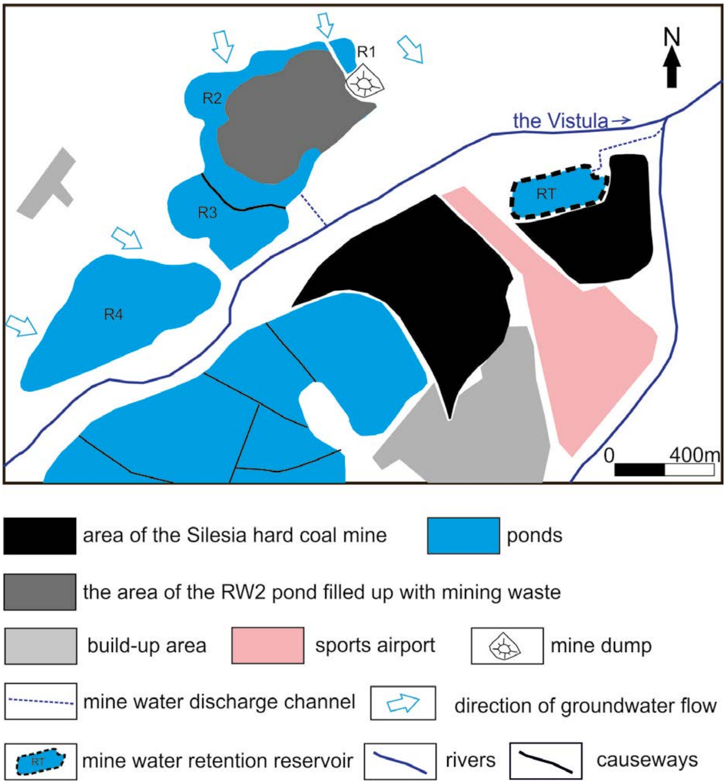

Figure 4. The Rontok mining waste landfill area with the location of sampling point

Table 2. Characteristics of the location of selected post-mining waste site and reclaimed areas in the Upper Silesian Coal Basin and their relationship to groundwater

* No.	Name/ locality	Geographic coordinates	Area [ha]*	Morphological form of deposition	Type of deposition	Depth to first aquifer [m]	Type of first aquifer / No. sheet of the HMP AOH	Groundwater vulnerability in the waste site area
1	Szczygłowice mine dump	50.198308, 18.636278	36.7	A	D	0-5	MI 941	VH
2	Central Mining Waste Dump in Knurów	50.200976, 18.678915	>306.5	A	D	unrecognized	MI 941	unrecognized
3	Gardawice sand mine / Gardawice	50.100062, 18.789725	66.0	U	R	5-10	MI 969	VH, H
4	Mośnik mine dump / Rybnik – Chwałowice	50.061588, 18.536920	>30.0	U, A	D, R	0-10	MI 968	VH, H, M
5	Pochwacie mine dump / Połomia	49.975736, 18.576033	>108.0	A	D, R	20-50	MI 991	H, VH
6	Kościelniok mine dump/ Krzyżowice	49.977407, 18.662032	153.3	A	D	2-5	MA 991	VH, H
7	Rydułtowice mine dump	49.947374, 19.005020	17.9	U, A	D, R	0-2	MI 993	VH
8	A dump in the Vistula valley / Brzeszcze	49.982508, 19.122901		A	D	0-2	MA 993	VH
9	Brzeszcze gravel pit / Brzeszcze	49.997691, 19.179182	15.4	U	R	0-2	MI 993	VH
10	Rajsko gravel pit / Rajsko	50.006451, 19.197865	8.0	U, A	R	0-1	MA 970	VH

* No. according to Figure 1; U – underground landfill; A – above-grade landfill; D – deposition of post-mining waste; R – reclamation with post-mining waste; MI – minor first aquifer; MA – main first aquifer; first aquifer vulnerability: VH – very high, H – high, M – medium, HMP AOH – Hydrogeological Map of Poland First Aquifer Occurrence Hydrodynamics 1:50,000

formations and does not serve as the main usable aquifer. Except for three locations, the first aquifer occurs in the study area at a depth of 0-2 to 5-10, locally 20-50 [m], and is usually characterized by very high or high vulnerability (Filar, 2006a, 2006b, 2007; Górnik, 2006a,b; Kempa & Bielewicz, 2006; Kempa & Pękała, 2006; Rubin & Rubin, 2010; Bielewicz & Suszka, 2013; Gruszewicz et al., 2013; Reczek & Biedroński, 2013; Rubin & Rubin, 2013; Tabs. 2, 3).

Laboratory analyses

In 2022 and 2023, physicochemical tests and water sampling were carried out at 22 points, made up of 1 to 5 sampling points in each of the selected research objects (Tab. 4). Samples were generally collected once. The exception to this was the Rajsko reservoir, where water samples were collected in 2016, 2018, and 2023 (Tab. 7). In the field, the water temperature and electrolytic conductivity (EC) were tested with a CC-401 meter and the pH was tested with a CP-315 meter, both by Elmetron. Samples for chemical analysis were collected in plastic containers. After transportation to the laboratory, the water samples were filtered using membrane filters with a pore diameter of 0.45 μm. The samples for cation analysis were acidified with HNO_3 2 mmol/l. The concentrations of anions in water were

Table 3. Characteristics of water reservoirs and watercourses in the area of post-mining waste site and reclaimed areas

No.*	Object/ locality	Geographic coordinates	Type of reservoir	Distance from the post-mining waste dump [m]	Distance from the watercourse [m]; name of the watercourse	Area [ha]
1	Bierawka River (a), a reservoir (b)/ Szczygłowice	a: 50.197422, 18.633317 b: 50.198673, 18.639075	NF. C. B	0	75 Bierawka	1.0
2	A reservoir (a), a ditch (b)/ Knurów	a: 50.195845, 18.675062 b: 50.196145, 18.672708	NF. C	10	600 Szczygłowicki Stream	8.8
3	A reservoir / Gardawice	50.103697, 18.791461	NF. P. B	0	1650 Gostynka	0.05
4	Mośnik Reservoir/ Chwałowice	50.061019, 18.535913	F. C. B	0	0	10.4
5	Połomski Reservoir (a, b), Szotkówka River (c) /Połomia	a, b: 49.981129, 18.573117 c: 49.978912, 18.568638	F. C	0	0 Szotkówka	16.3
6	Reservoirs (a-e) / Krzyżowice	a: 49.981078, 18.669667 b: 49.972849, 18.672253 c: 49.971736, 18.661735 d: 49.972477, 18.654234 e: 49.971773, 18.656728	NF. C	0-10	400 Pszczynka	1.5 (a) 7.6 (b) 3.9 (c) 1.6 (d) 0.3 (e)
7	Reservoirs: R1 (a), R2 (b), a channel R3 (c) / Rydułtowice	a: 49.949413, 19.008258 b: 49.946723, 19.006605 c: 49.944631, 19.005459	NF. C (a) I. B (b)	0 (a. b)	60-150 Wisła (water receiver)	1.0 (a) 26.5 (b)
8	Reservoirs (a, b) / Brzeszcze	a: 49.983525, 19.126203 b: 49.982958, 19.126935	I (a) NF. C. B (b)	do 150	90 Wisła (water receiver)	28.0 (a) 1.1 (b)
9	A reservoir / Brzeszcze	49.995148, 19.175242	NF. C	50	50	1.1
10	A reservoir /Rajsko	50.006857, 19.199154	NF. C	0	200 Soła River	0.7
11	The Vistula River/ Oświęcim – Dwory	50.056217, 19.293242	—	-	-	-

* Number consistent with Figure 2; Reservoir: F – flow-through, NF – non-flow, C – constant, P – periodic, B – buried, I – industrial

determined immediately after transportation to the laboratory. The tests were performed in the Laboratory of Environmental Analysis of the University of Silesia in Katowice using the ion chromatography method and the Metrohm 850 Professional IC with a sample feeder 858 Professional Sample Processor. The limits of quantification for the individual analyzed ions ranged from 0.01 to 0.03 mg/L (Tab. 4).

Data processing

After verifying the hydrochemical balance, the analysis results were subjected to basic statistical interpretation (Tab. 5). Hydrochemical types were defined and are shown in the Piper diagram. The Comprehensive Pollution Index (CPI) was also calculated. The CPI is the ratio of the concentration of each analyzed parameter to the assumed standards (Odipe et al., 2020). Using this indicator allows us to limit the number of marked parameters to one and thus simplify interpretation (Tanjung & Hamuna, 2019). The mathematical formula for the CPI is as follows:

$$\mathrm{CPI} = \frac{1}{n}\sum_{i=1}^{n} PI \tag{1}$$

where:

PI = Pollution Index of the individual parameter;
n = number of monitoring parameters;
PI = C_i/S_i;
C_i = observed value of i-th parameter;
S_i = RQO standard value of i-th parameter.

The limit values used were the limit values of parameters for groundwater quality class III (water of satisfactory quality), which correspond to good chemical status (according to the Regulation of the Minister of the Environment of February 11, 2004). The relevant parameters were EC (1.5 mS/cm) and the concentrations of Ca^{2+} (200 mg/L), Mg^{2+} (100 mg/L), NH_4^+ (2 mg/L), Cl^- (300 mg/L), SO_4^{2-} (250 mg/L), and NO_3^- (25.0 mg/L). Five classes of CPI values were used to evaluate the obtained results: 0 to 0.20 (clean); 0.21 to 0.40 (sub-clean); 0.41 to 1.00 (slightly polluted); 1.01-2.00 (medium polluted); > 2.00 (heavily polluted) (Liu et al., 1999; Matta et al., 2017; Son et al., 2020; Dzhangi & Atangana, 2024).

Results and discussion

The waters of reservoirs adjacent to the indicated industrial waste landfills are anthropogenically modified, with total dissolved solids reaching above 6.0 g/l. The pH of the waters is in the range 5.92-11.0, with 77% being weakly alkaline. These were multiionic waters of the Cl^-–SO_4^{2-}–Na^+, Cl^-–SO_4^{2-}–HCO_3^-–Na^+, and Cl^-–SO_4^{2-}–HCO_3^-–Na^+–Ca^{2+} types (Fig. 5), with high EC values of 1.05-21.5 (median 12.01) mS/cm, Cl^- values of 102-9,279 (median 803) mg/L, SO_4^{2-} values of 58-5,277 (median 652) mg/L, and Na^+ values of 143-4,783 (median 759) mg/L. The concentrations of the remaining elements in the waters were: Ca^{2+} 48-651 (median 102) mg/L, Mg^{2+} 15-486 (median 60) mg/L, K^+ 9-420 (median 34) mg/L, NH_4^+ 2.6-7.8 (median 4.5) mg/L, HCO_3^- 171-1,220 (median 331) mg/L, NO_3^- 1.7-23.5 (median 13.2) mg/L, F^- 0.24-8.19 mg/L, NO_2^- 0-3.15 mg/L, Br^- 0.96-38.95 mg/L, and PO_4^{3-} 0-3.59 mg/L (Tabs. 4, 5).

According to the Regulation of the Minister of Environment of 11 February 2004 on the classification for presenting the condition of surface and groundwaters, the method of conducting monitoring, and the method of interpreting the results and presenting the condition of these waters (Tab. 6), these are waters of quality class V, i.e. poor quality, which is usually characterized by increased concentrations of Cl^-, SO_4^{2-}, and EC, locally Mg^{2+}, NH_4^+, and PO_4^{3-} (Tab. 4). The authors used the above Regulation from 2004 because it allows for a wide range of interpretations of water quality (quality classes I to V). The Regulation of the Minister of Infrastructure of 25 June 2021 on the classification of ecological status, ecological potential and chemical status and the method of classifying the status of surface water bodies, as well as environmental quality standards for priority substances currently in force in Poland, define maximum values only for two

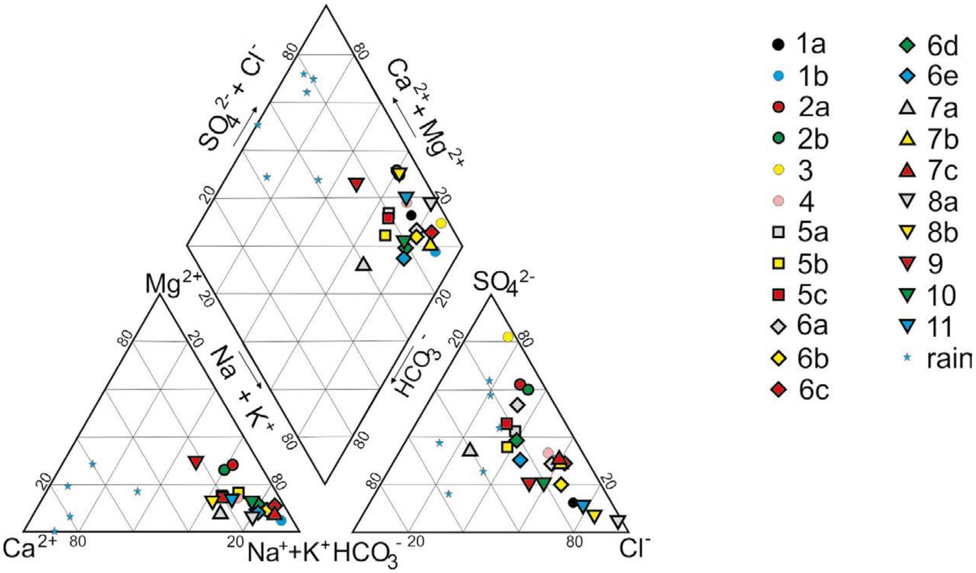

Figure 5. Reservoir water chemistry shown on the Piper diagram

quality classes: I and II. Quality classes III, IV, and V are defined as "above II", hence in the context of assessing the chemical status of waters, this classification is less detailed.

The significance of the problem of the threat to the aquatic environment from mining waste is reinforced by the Regulation of the Minister of the Maritime Economy and Inland Navigation of 12 July 2019 on substances particularly harmful to the aquatic environment and the conditions that must be met when introducing sewage into water or soil, as well as when discharging rainwater or meltwater into water or water facilities. A comparison of the permissible values specified in this regulation with the results of the tests indicates a very high level of contamination of the tested waters, especially at sites 1b, 2a, 2b, 3, 6a-6d, 7b-c, and 8a (Tab. 4). It is worth noting that site 3, i.e., the sand pit "Gardawice", is reclaimed with mining waste, while reservoir 6c is used as a fishing ground. The investigations also confirmed the poor quality of the Bierawka River waters in Szczygłowice (quality class V) (p. 1a).

The chemistry of surface waters in the areas of mining waste dumps and areas subject to reclamation using mining waste is influenced by specific spatial, technological, and temporal conditions.

Mining requires the drainage of workings and consequently leads to the discharge of mine waters into the environment. These waters are characterized by a diverse chemical composition, from fresh water to brines. An example of highly mineralized water is the water discharged into the retention reservoir in Brzeszcze (p. 8a), collecting mine waters of the Brzeszcze Coal Mine, which are then discharged, at high flow rates, into the Vistula as part of the hydrotechnical protection of the river. The chemical composition of the reservoir water is variable and depends on the amount and chemical composition of mine water flowing from the mine. During the tests carried out in 2023, the EC was 21.50 mS/cm, and the concentrations of the main components were: Na^+ 4,783 mg/L, Cl^- 9,279 mg/L, and SO_4^{2-} 244 mg/L (Tab. 4). Measurements carried out in April 2024 showed that the water flowing into the reservoir from the Brzeszcze mine was characterized by an EC of 49 mS/cm, and at the place of discharge of these waters into the Vistula, the EC was 34 mS/cm.

Table 4. Physicochemical properties and chemical composition of waters sampled in 2022 and 2023

Parameter	pH	EC	Ca^{2+}	Mg^{2+}	Na$^+$	K$^+$	NH$_4^+$	HCO$_3^-$	F$^-$
Unit of measure	[-]	mS/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
No. \DL	0.01	0.001	0.1	0.1	0.1	0.1	0.1	6.1	0.1
1a	5.92	5.65	123.64	86.58	1097.30	24.36	<0.1	414.90	0.96
1b	8.22	6.72	72.99	71.34	1746.60	10.83	<0.1	665.10	1.96
2a	6.64	7.68	249.98	267.78	1511.37	32.18	<0.1	469.90	1.64
2b	11.0	6.78	476.47	486.31	2233.87	54.11	<0.1	659.00	1.77
3	NM	9.99*	131.00	92.40	3050.00	420.00	NM	254.76	NM
4	7.22	2.60	84.84	46.85	418.21	9.42	<0.1	228.80	0.74
5a	7.96	1.93	84.86	37.46	322.61	8.62	<0.1	256.30	0.44
5b	7.69	3.67	138.51	63.95	702.20	12.96	5.18	604.10	0.81
5c	7.91	1.90	81.33	37.16	308.34	20.49	<0.1	274.59	0.43
6a	8.26	5.08	103.89	58.04	1044.43	30.40	<0.1	518.67	1.80
6b	8.38	5.59	113.72	48.93	1151.62	15.57	<0.1	604.10	1.95
6c	8.53	8.74	94.11	90.58	1972.00	40.86	<0.1	659.02	1.80
6d	7.32	7.18	182.14	94.18	1592.75	25.04	<0.1	1220.40	1.84
6e	7.88	3.19	47.75	45.70	646.71	14.26	<0.1	524.77	1.06
7a	7.48	1.05	55.44	15.07	142.92	24.66	7.79	280.70	0.24
7b	7.62	9.56	137	64	2258	40	< 0.1	906	3,33
7c	7.46	5.86	96.18	46.67	1386.47	18.99	<0.1	518.70	1.69
8a	8.26	21.50	650.85	294.57	4782.79	120.6	0.00	170.86	8.19
8b	7.46	2.53	126.20	42.57	353.56	19.64	2.58	183.06	0.73
9	6.94	1.47	76.00	21.08	251.06	9.45	<0.1	244.08	0.37
10	7.59	2.87	66.18	40.74	554.14	21.30	4.15	372.22	0.73
11	7.85	3.23	121.73	57.30	539.90	32.14	0.74	198.31	2.08
limits**	6.5-9				800	80	12.85		25

EC – electrolytic conductivity, * dry residue g/L , uncertain values are marked in gray font, DL – detection limit, NM- not marked, ** – limit value for water and sewage discharged into water and land – according to Regulation of the Minister of Maritime Economy and Inland Navigation of 12 July 2019 on substances particularly harmful to the aquatic environment and the conditions that must be met when introducing sewage into water or soil, as well as when discharging rainwater or meltwater into water or water facilities, *** – according to the Regulation of the Minister of Environment of 11 February 2004 on the classification for presenting the condition of surface and groundwaters, the method of conducting monitoring and the method of interpreting the results and presenting the condition of these waters

Water quality class***:	I	II	III	IV	V

Parameter	Cl^-	NO_2^-	Br^-	NO_3^-	PO_4^{3-}	SO_4^{2-}	Quality class	Parameters determining belonging to a quality class
Unit of measure	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L		
No. \DL	1.0	0.1	0.1	0.1	<0.4	1.0		
1a	1720.15	1.26	3.63	21.75	<0.4	400.47	V	SO_4^{2-}. Cl^-. EC
1b	1778.46	0.00	4.00	4.29	<0.4	1205.51	V	SO_4^{2-}. Cl^-. EC
2a	1141.31	1.99	2.91	4.62	<0.4	3082.21	V	SO_4^{2-}. Cl^-. EC. pH
2b	1995.37	0.00	4.50	4.61	<0.4	4646.46	V	SO_4^{2-}. Cl^-. EC
3	880.00	NM	NM	19.49	0.04	5277.00	V	SO_4^{2-}. Cl^-. EC
4	530.99	0.98	1.37	13.74	<0.4	415.60	V	SO_4^{2-}. Cl^-. EC
5a	283.85	0.48	1.03	5.04	<0.4	398.74	V	SO_4^{2-}
5b	561.81	0.83	2.12	6.54	<0.4	725.33	V	SO_4^{2-}. Cl^-. EC
5c	271.18	0.50	1.01	2.08	<0.4	382.36	V	SO_4^{2-}
6a	1132.45	0.00	4.47	6.80	<0.4	735.32	V	SO_4^{2-}. Cl^-. EC
6b	1398.65	2.09	5.70	4.99	<0.4	533.26	V	SO_4^{2-}. Cl^-. EC
6c	2173.28	0	8.23	5.81	<0.4	1265.71	V	SO_4^{2-}. Cl^-. EC
6d	1236.73	0	5.22	8.15	<0.4	1580.83	V	SO_4^{2-}. Cl^-. EC
6e	540.97	0.00	2.29	2.76	<0.4	511.95	V	SO_4^{2-}. Cl^-. EC
7a	102.18	0.44	0.33	1.65	3.59	170.32	V	NH_4^+ . PO_4^{3-}
7b	2365	4.65	11,64	12.64	<0.4	1488	V	SO_4^{2-}. Cl^-. EC
7c	1453.97	0.00	6.60	5.42	<0.4	872.95	V	SO_4^{2-}. Cl^-. EC
8a	9279.34	0.00	38.95	23.52	<0.4	243.97	V	Cl^-. EC. Ca^{2+}. Mg^{2+}
8b	789.03	0.83	3.21	4.65	<0.4	58.23	V	Cl^- . EC
9	292.27	0.28	0.96	1.66	<0.4	162.11	III	SO_4^{2-}. Cl^-. EC
10	626.31	0.00	1.79	3.55	<0.4	303.52	V	SO_4^{2-}. Cl^-. EC
11	965.44	3.15	4.74	30.51	<0.4	179.56	V	Cl^- . EC
limits**	1000	3.28		132.85	6.13	500		

Table 5. Variability of physicochemical parameters of the examined waters (without samples from the rivers: Vistula, Bierawka and Szotkówka)

Parameter	pH	EC	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	NH_4^{+}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	NO_3^{-}
Elements of statistics	-	mS/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Numbers	18	18	19	19	19	19	4	19	19	19	19
Minimum	6.64	1.05	48	15	143	9	2.6	171	102	58	1.7
Maximum	8.53	21.50	651	486	4,783	420	7.8	1,220	9,279	5,277	23.5
Mean	7.65	6.01	157	101	1,375	49	4.9	492	1,503	1,246	7.4
Median	8.09	12.01	102	60	759	34	4.5	331	803	652	13.2
Statistical deviation	0.55	4.85	154	119	1,159	93	2.2	270	1,995	1,493	5.9
Upper quartile	7.29	2.58	76	43	418	13	2.9	255	541	304	4.3
Lower quartile	8.23	7.95	139	92	1,972	40	7.1	659	1,779	1,488	8.2

Table 6. Selected parameters classifying the quality of surface water based on the Regulation of the Minister of Environment of 11 February 2004 on the classification for presenting the condition of surface and groundwaters, the method of conducting monitoring and the method of interpreting the results and presenting the condition of these waters (Journal of Laws No. 32, item 284, 2004)

Parameter	Unit of measure	Limit values of water quality classes				
		I	II	III	IV	V
pH	[-]	6.5-8.5	6.0-8.5	6.0-9.0	5.5-9.0	<5.5 or >9.0
EC	mS/cm	0.5	1.0	1.5	2.0	>2.0
Ca^{2+}	mg/L	50	100	200	400	>400
Mg^{2+}	mg/L	25	50	100	200	>200
NH_4^{+}	mg/L	0.5	1.0	2.0	4.0	>4.0
Total alkalinity	mg $CaCO_3$/L	>200	100	20	10	<10
Cl^{-}	mg/L	100	200	300	400	>400
NO_2^{-}	mg/L	>0.03	0.1	0.5	1.0	>1.0
NO_3^{-}	mg/L	5	15	25	50	>50
PO_4^{3-}	mg/L	0.2	0.4	0.7	1.0	>1.0
SO_4^{2-}	mg/L	100	150	250	300	>300

EC – electrolytic conductivity

The impact of the discharge on the quality of the waters of the Vistula is documented by a comparison of the EC above and below the discharge, which was 0.7 and 2.1 mS/cm, respectively. The waters of the Brzeszcze reservoir probably infiltrate through a 15 m wide dam into the neighbouring reservoir 8b, which was formed as a result of land subsidence, as indicated by the Cl^{-} concentration in the water of 789 mg/L. Even before the discharge of water from the Brzeszcze Coal Mine settling tank, the waters of the Vistula River are under the influence of subsidence basins filled with mining waste over a length of about 500 m.

Despite the operation of the Vistula hydrotechnical protection system, the water quality in the Oświęcim – Dwory profile is poor

(EC: 3.2 mS/cm; Cl^-: 965 mg/L, and SO_4^{2-}: 179 mg/L), which is the result of the cumulative effect of mine water discharges from the reservoirs of the Silesia and Brzeszcze Coal Mines and waters discharged into the Vistula tributaries: the Pszczynka, the Gostynia, and the Przemsza (Fig. 2, Tab. 4).

An example of the spatial conditions influencing the chemical composition of reservoirs adjacent to the waste dump is the Kościelniok landfill in Krzyżanowice. In the area of the dump there are eight permanent, non-flowing water reservoirs with an area of 0.3-7.6 ha (Fig. 3). As part of the study, five of them were sampled, and a diverse chemical composition was found (Tab. 4). The diversification of water chemistry is probably influenced by the distance from the dump, the volume of the reservoirs, and the direction of continuous waste deposition. The highest concentrations of the determined components were found in the largest fishing pond (p. 5c, Tab. 4) and in the flooded area at the dump slope (p. 5e): Na^+ 1,593-1,972 mg/L, Cl^- 1,237-2,173 mg/L, SO_4^{2-} 1,266-1,581 mg/L, and EC 7.18-8.74 mS/cm. In the smaller fishing pond (p. 5d) the concentrations of the analysed components in water are 2-3 times lower: Na^+ 647 mg/L, Cl^- 541 mg/L, SO_4^{2-} 512 mg/L, and EC 3.19 mS/cm. This can be related, among other things, to the supply of the reservoir with groundwater flowing in from the south-west (Kempa & Bielewicz, 2006; Fig. 3).

In the area of the Kościelniok landfill, Prymnesium Parvum was found in reservoirs no. 5a and 5b (Fig. 6; Jasser, 2023; Weber et al., 2024). Analysis of the spatial and technical conditions indicates a lack of contact between these reservoirs and flowing waters. The presence of this halophyte in reservoirs of standing water in the vicinity of waste landfills from a coal mine, reaching 200 million cells/l (Jasser, 2023), is a new and significant biological threat to surface waters. The studied reservoirs may be a place where this organism multiplies. Research by Jasser (2023) revealed the presence of Prymnesium Parwum in the Vistula in Oświęcim – Dwory (p. 11, Tab. 4) in the amount of 253,000 cells/l, constituting 0.6% of the phytoplankton biomass.

Figure 6. Water reservoir at the Kościelniok mining (p.6) waste dump with an information board about the occurrence of Prymnesium parvum. Water from the reservoir is returned to the coal mine

A spatially diversified chemical composition of water in neighbouring reservoirs was also found in Rydułtowice (Fig. 4). The following reservoirs are used as retention reservoirs for groundwater from the Silesia coal mine: the R2 pond (Rontok Wielki), with an area of 32 ha, and the R3 pond (Rontok Mały), with an area of 9.5 ha. The waters retained in the reservoirs in the past (2001-2006) were characterised by high concentration of total dissolved solids (EC up to 74 mS/cm) and high Cl^- concentrations (up to 38 g/L; Molenda 2018). In 2003, the reservoirs were decommissioned, which resulted in a decrease in water salinity – the average Cl^- concentration in the years 2004-2010 was 0.2-0.4 g/L (Fig. 7). The typical SO_4^{2-} concentration in the waters of the Rontok Wielki reservoir

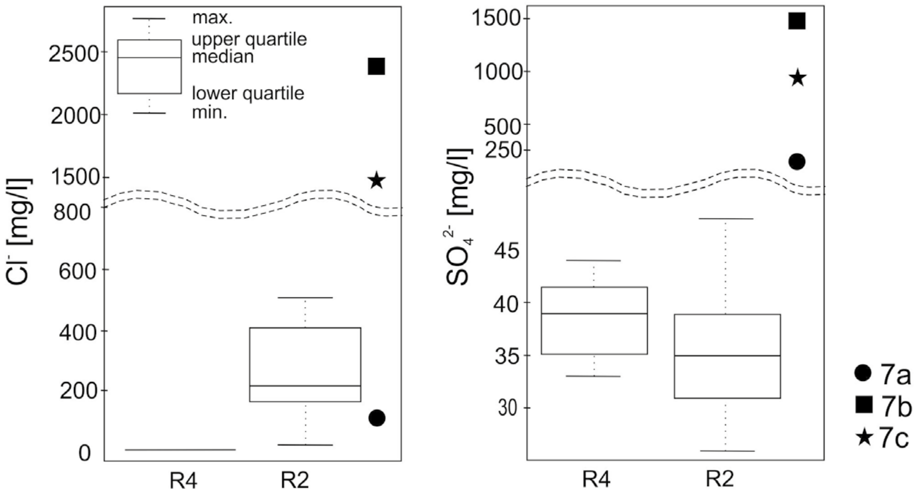

Figure 7. Box diagram of the chemical composition of water from the Rontok Wielki ponds (R2) and the Rontok ponds (R4) according to Molenda 2018 with an update as of December 2023. Points 7a, 7b, and 7c reflect the results of our own research – numbering is in accordance with Tables 3 and 4

at that time was 30-40 mg/L, and this was even lower than in the neighboring Rontok reservoir (R4), which had no contact with mine waters (Fig. 7). In 2010, the conductivity of the water in the R2 reservoir dropped to 0.5 mS/cm (Molenda, 2018). After 2015, the R2 reservoir began to be filled with mining waste, and a 1.35 ha heap was built nearby. In 2023, the area of the R2 reservoir filled with mining waste was 22 ha. On the other hand, the waters of the R1 reservoir located at the heap (p. 7a) were characterized by lower concentration of total dissolved solids (EC 1.05 mS/cm, Cl^- concentration 102 mg/L, SO_4^{2-} concentration 170 mg/L), with relatively high concentrations of NH_4^+ (7.79 mg/L) and PO_4^{3-} (3.59 mg/L), probably of agricultural origin. The low concentration of total dissolved solids of the waters of this reservoir and the presence of pollution indicators characteristic of agriculture result from the inflow of groundwater from outside the storage area, i.e. from the north towards the Vistula River, and the location of the heap on the ground. At the same time, in the R2 reservoir, in the foreland of the dumped waste, waters with a conductivity of 9.5 mS/cm, Cl^- concentrations of 2.4 g/L, and SO_4^{2-} concentrations of 1.5 g/L were found. The chemical composition of the waters in the R2 reservoir is likely associated with the deposition of mining waste and the leaching of pollutants from it. The chemical composition of water from point 7c, which is a periodic outflow from reservoir R2, is the result of the mixing of waters of different concentration of total dissolved solids.

In the Rajsko area (p. 10, Fig. 8), where intensive washing out of components by atmospheric precipitation from waste rock continues, there was a clear reduction in the concentrations of most of the analyzed components in the period 2016-2023. Specifically, Ca^{2+} was reduced from 181 to 66 mg/L, Mg^{2+} from 166 to 41 mg/L, Na^+ from 3,090 to 554 mg/L, K^+ from 59 to 21 mg/L, Cl^- from 4,667 to 626 mg/L, Br^- from 15.45 to 1.8 mg/L, F^- from 6.46 to 0.7 mg/L, NO_3^- from 27.1 to 3.6, NO_2^- from 4.13 to 2.65 mg/L, and EC from 13.77 to 2.87 mS/cm (Tab. 7). The exception is the persistently high SO_4^{2-} concentration (309-304 mg/L), which is due to the long-term oxidation of pyrite in waste rock (Tab. 7) (Szczepańska, 1987; Twardowska et al., 1988). The decrease in the concentration

Table 7. Results of physicochemical analyzes from a reservoir Rajsko in 2016, 2018 and 2023 according to Sołtysiak et al. (2018a) with an update as of November 2023

Parameter	Detection limit	Year		
		2016	2018	2023
pH	0.01	8.30	7.54	7.59
EC [mS/cm]	0.001	13.77	6.50	2.87
Ca^{2+} [mg/L]	0.1	180.9	123.9	66.0
Mg^{2+} [mg/L]	0.1	166.0	69.0	41.0
Na^{+} [mg/L]	0.1	3090.0	1319.0	554.0
K^{+} [mg/L]	0.1	590.1	33.0	21.0
Cl^{-} [mg/L]	1.0	4667.0	2132.0	626.0
SO_4^{2-} [mg/L]	1.0	309.1	322.6	304.0
Br^{-} [mg/L]	0.1	15.6	7.4	1.8
F^{-} [mg/L]	0.1	6.5	2.9	0.7
NO_3^{-} [mg/L]	0.1	27.1	23.3	3.6
NO_2^{-} [mg/L]	0.1	4.131	2.648	<0.1

Figure 8. Water reservoir in the foreground of the mining waste dump at the site of the gravel pit in Rajsko (p. 10)

of total dissolved solids of the waters of this reservoir is the result of their outflow into the Soła River, which further dilutes the leached compounds.

The depth of water sampling for chemical analyses is of great importance due to the stratification of water chemistry in reservoirs. The water sample collected at a depth of 4 m in the Połomski Reservoir near the Pochwacie landfill (Fig. 9) was characterized by significantly higher concentrations of components in the water than the sample collected at the surface (respectively: Na^+ 702 and 323 mg/L, HCO_3^- 604 and 256 mg/L, Cl^- 562 and 284 mg/L, SO_4^{2-} 725 and 399 mg/L, and EC 3.67 and 1.93 mS/m). In groundwater, as part of the monitoring of the Pochwacie landfill in 2016, concentrations of Cl^- up to 1,770 mg/L and of SO_4^{2-} up to 2,982 mg/L were found (Łaganowska, 2019). The chemical composition of water from the Szotkówka River below the Pochwacie landfill site (p. 5c) indicates the mixing of waters from the surface and deep zones of the floodplain (Tab. 4). The theoretical mass of pollutant loads from the landfill has been estimated by Sołtysiak et al. (2018b). According to these calculations, 660 mg Cl^-, 1100 mg SO_4^{2-}, 199 Na^+, and 36 mg K^+, can be potentially leached from one kilogram of dry mass of mining waste.

The lowest concentration of total dissolved solids was found in waters collected in the Brzeszcze Gravel Pit (p. 9, Tab. 4). In relation to the location of areas reclaimed with waste, the sampling site is located beside the groundwater inflow (Kempa & Pękała, 2006), hence it cannot be ruled out that in the locations of the remaining four reservoirs, a more pronounced influence of mining waste is apparent. Nevertheless, the Cl^- concentration in this location is close to the maximum value for water quality class III.

The chemistry of the Vistula River waters in Oświęcim reflects the influence of mine waters discharged into the streams in the Vistula River basin from the Upper Silesian Coal Basin (USCB). The high flow rate in the river (about 40 $m^3 \cdot s^{-1}$) determines the relative dilution of salt loads discharged by the USCB mines, which is reflected by the concentrations of the main components in the Vistula waters: Na^+ 534 mg/L, Cl^- 965 mg/L, SO_4^{2-} 180 mg/L, and an EC value of 3.23 mS/cm (p. 11, Tab. 4). Although these values are lower than those of mine waters, in terms of chemical status they reduce the water quality. The pollutant load in Oświęcim Dwory is influenced by the size of the load carried by rivers from the USCB area, while these loads are simultaneously diluted by the waters of the

Figure 9. Submerged subsidence basin and the Szotkówka River (p.5) flowing through it in the vicinity of the Pochwacie mining waste dump (in the foreground)

Soła River, flowing out of the Beskid Mountains. Matysik (2018) documented here the lowest share of mine waters among the USCB rivers, averaging no more than 10% of the lowest annual river flows in a multi-year period, including in the Vistula River (Jawiszowice and Nowy Bieruń cross-sections). The impact of mining anthropopression on the surface water environment is documented by data from the period of increased mining activity in the 1980s and 1990s. The average concentration of total dissolved solids of mine waters pumped into the rivers in 1984 was 10.9 g/L and the total load of Cl^- and SO_4^{2-} discharged into the rivers of the Vistula River Basin was 5,100 Mg/24h (Różkowski et al. ed., 1997).

The influence of mining waste dumps can also be observed in the Odra River basin. One of the most polluted rivers in the region is the Bierawka (Nádudvari & Fabiańska, 2015). Indeed, Cl^- concentrations in the Bierawka (p 1a) are comparable to those in the reservoir waters at the nearby mining waste dump (p. 1b). However, the waters from the reservoir have SO_4^{2-} concentrations (1.2 g/L) that are three times higher than those of the waters of the Bierawka. In addition to the dumps located near the river, the chemical composition of the Bierawka waters is influenced by mine water discharges, hence the EC changes observed by the authors, which were in the range of 5.65-20 mS/cm.

In the Odra River Basin, very high sulphate loads in reservoirs in the vicinity of landfills are visible in Knurów (p. 2a, 2b) and Gardawice (p. 3). In the foreland of landfills with areas of > 306 ha and > 66 ha, respectively, sulphate concentrations were 3.1 g/L and 5.3 g/L. The sulphate concentration in water collected from the ditch at the base of the dump in Knurów was equally high, amounting to 4.6 g/L. Mining waste was stored on this dump even before 1996 (https://geoportal.orsip.pl/). With a target capacity of 136 million Mg, the waste collected there is and will be a long-term source of pollution with respect to both sulfates and chlorides.

The sand pit in Gardawice (Fig. 10) also deserves attention. Despite its status as a reclaimed area, it has a negative impact on the aquatic environment. As part of the reclamation process, approximately 10 million Mg of waste was deposited here, and this is an area with high and very high groundwater vulnerability to pollution (Tab. 2), as is confirmed by the chemical composition of water collected from a seasonal reservoir located in the foreland of the landfill (p. 3, Tab. 4). The amount of dissolved substances exceeded 10 g/L, with a dominant share of sulphate concentrations.

Figure 10. The area of the Gardawice sandpit (p. 3) reclaimed with mining waste. The excavation currently visible in front of the waste mass has been filled

The relationships between the analyzed mining waste dumps and surface waters are twofold. In the case of the analyzed reservoirs, we observe direct degradation of reservoir water quality to quality class V by pollutants washed out from the dumps. In the case of flow-through reservoirs, such as the Mośnik reservoir and the Połomski reservoir, direct contamination of streams (the Chwałowicki stream, the Szotkówka river, and the Bierawka river) occurs and the potential for self-purification is conditioned by the flow rate in the streams. In the case of non-flow-through reservoirs, one can theoretically consider deep infiltration of water into the groundwater table and outflow towards the drainage base (locations no. 1b, 2a, 6c, 6d, 6e, 8b, 9). However, the bottoms of the analyzed reservoirs are often clogged, and along the potential flow path, the water self purification process would occur within the pore environment.

The obtained CPI calculation results indicate that there are no clean waters among the tested samples. The CPI values range from 0.47 to 7.63 (Fig. 11). The values obtained by Dzhangi & Atangana (2024) for the Boesmanspruit coal mining area are comparable, ranging from 0.44 to 4.81. The least polluted water is that collected in the Brzeszcze Gravel Pit (CPI 0.47). In the Polish classification system, this is the only water sample classified as class III, i.e. water of satisfactory quality. Six water samples, taken from reservoirs located on the side of the groundwater inflow relative to the landfill (9, 7a, 6e) or flow-through reservoirs, belong to the slightly polluted category. Eight samples are medium polluted and eight are heavily polluted. The heavily polluted waters (CPI > 2) were collected from standing waters in contact with large volumes of waste rocks (dumps in the Bierawka valley, Kościelniok, Rontok, and the Central Mining Waste Dump in Knurów). In the case of the dump in Knurów, the CPI value of 5.72 was calculated for a water sample taken from a ditch surrounding the dump. The maximum CPI value (7.63) was calculated for mine waters from the retention reservoir of the Brzeszcze Coal Mine (Fig. 11).

The relationships between the analyzed mining waste dumps and the accompanying water reservoirs and groundwater indicate a potential threat to shallow groundwater, most often in the depth range of 0-5 m, with

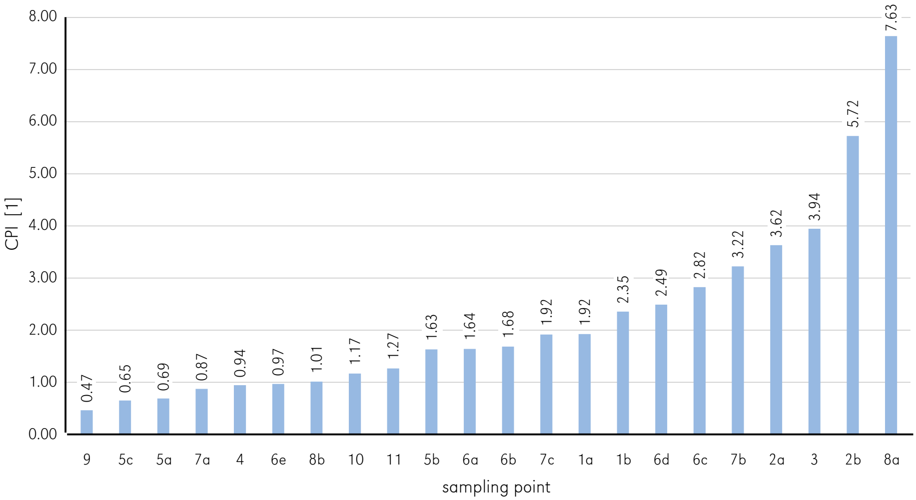

Figure 11. CPI values calculated for water samples collected in 2023 from the coal mine waste storage areas in the USCB

high and very high groundwater vulnerability. This is particularly important when the groundwater aquifer is also the Main Utility Aquifer, as in the areas of the Kościelniok and Rajsko dumps, or in the Vistula valley in Brzeszcze (Tab. 2).

Conclusion

This article has presented research results on the water chemistry of 10 reservoirs adjacent to post-mining waste landfills in the Upper Silesian Coal Basin in 2023. Mining activities have transformed these waters into $Cl^-–SO_4^{2-}–Na^+$, $Cl^-–SO_4^{2-}–HCO_3^-–Na^+$, and $Cl^-–SO_4^{2-}–HCO_3^-–Na^+–Ca^{2+}$ types. They are characterized by high total dissolved solids and high Cl^-, SO_4^{2-}, and Na^+ concentrations. These are waters of quality class V, i.e., of poor quality.

The chemistry of surface waters in the areas of post-mining waste dumps and those subject to reclamation depends on the functions performed by the reservoirs, their volume, the mineralogical and chemical composition of the waste, the duration of waste exposure, the intensity of pollutant leaching, and the distance of the reservoirs from the post-mining waste landfills. At the same time, contact of the waste or the connection of a reservoir with flowing water facilitates the discharge of pollutant loads and thus prevents their accumulation in the reservoir.

The changes in the concentrations of the tested components in the reservoir water over time result from their intensive leaching by infiltration water from waste rock. At the same time, a constant concentration of sulfates in the water was found due to the long-term oxidation of pyrite in the deposited mining waste.

The results of the Comprehensive Pollution Index (CPI) calculations indicate that the waters are moderately or heavily polluted. The heavily polluted waters (CPI > 2) were collected from standing waters in contact with large volumes of waste rock and from the water of the retention reservoir in Brzeszcze functioning as part of the hydrotechnical protection of the Mała Wisła River.

Areas reclaimed with mining waste are informal waste dumps and should be treated as potential sources of groundwater pollution. In their immediate vicinity, and in nearby water reservoirs, there is a potential threat to shallow (0-10 m) groundwater of the first aquifer, which is especially important when the first aquifer is being tapped as a water resource.

Acknowledgments

The research was financed by the funds of the Society for Earth in Oświęcim as part of the Europe Beyond Coal grant in 2023, as well as from the reserve of the Director of the Institute of Earth Sciences at the University of Silesia.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

References

Bielewicz, R., & Suszka, G. (2013). GIS Database of the Hydrogeological Map of Poland, First aquifer. Vulnerability to pollution, sheet 969 – Tychy. Warsaw: The Polish Geological Institute – National Research Institute

Bojarska, K., & Bzowski, Z. (2012). Wyniki badań wyciągów wodnych odpadów wydobywczych z kopalń węgla Górnośląskiego Zagłębia Węglowego w aspekcie wpływu na środowisko. *Górnictwo i Geologia*, *7*(12), 101-113.

Brožová, K., Halfar, J., Čabanová, K., Motyka, O., Drabinová, S., Hanus, P., & Heviánková, S. (2023). The first evidence of microplastic occurrence in mine water: The largest black coal mining area in the Czech Republic. *Water Research*, *244*(1). https://doi.org/10.1016/j.watres.2023.120538

Chmura, D., & Molenda, T. (2012). Influence of thermally polluted water on the growth of helophytes in the vicinity of a colliery waste tip. *Water, Air, & Soil Pollution*, *223*(9), 5877-5884. https://doi.org/10.1007/s11270-012-1323-1

Dzhangi, T. R., & Atangana, E. (2024). Evaluation of the impact of coal mining on surface water in the Boesmanspruit, Mpumalanga. South Africa. *Environmental Earth Sciences*, *83*(6), 159. https://doi.org/10.1007/s12665-024-11431-6

Fabiańska, M. J., Ciesielczuk, J., Szczerba, M., Nisz-Kennan, M., Więcław, D., Szram, E., Nadudvari, A., & Ciesielska, Z. (2024). Weathering alterations of coal mining wastes geochemistry, petrography, and mineralogy, a case study from the Janina and Marcel Coal Mines, Upper Silesian Coal Basin (Poland). *International Journal of Coal Geology, 281*. https://doi.org/10.1016/j.coal.2023.104407

Filar, S. (2006a). GIS Database of the Hydrogeological Map of Poland, First aquifer. Occurrence and hydrodynamics, sheet 941 – Gliwice. Warsaw: The Polish Geological Institute – National Research Institute.

Filar, S. (2006b). GIS Database of the Hydrogeological Map of Poland, First aquifer. Occurrence and hydrodynamics, sheet 968 – Rybnik. Warsaw: The Polish Geological Institute – National Research Institute.

Filar, S. (2007). GIS Database of the Hydrogeological Map of Poland, First aquifer. Vulnerability to pollution, sheet 941 – Gliwice. Warsaw: The Polish Geological Institute – National Research Institute

Gandy, C. J., & Younger, P. L. (2018). Predicting long-term contamination potential of perched groundwater in a mine-waste heap using a random-walk method. *Hydrogeology Journal*, *16*(3), 447-459. https://doi.org/10.1007/s10040-007-0243-4

Gawor, Ł. (2009). Uregulowania prawne w Polsce i Niemczech. Gospodarka odpadami górniczymi. *Odpady i Środowisko 1*(10), 32-36.

Geoportal. https://www.geoportal.gov.pl/

Gołębiowski, T., Marcak, H., Tomecka-Suchoń, S., Zdechlik, R., Zuberek, W., & Żogała, B. (2010). Use of geophysical methods for the assessment of migration of contaminants from the coal-mining waste dumps. In A. Zuber, J. Kania, E. Kmiecik (Eds.), *Abstract book*, Vol. 2, XXXVIII IAH Congress: Groundwater quality sustainability. Katowice: University of Silesia Press.

Google.Maps. https://www.google.pl/maps/

Górnik, M. (2006a). GIS Database of the Hydrogeological Map of Poland, First aquifer. Occurrence and hydrodynamics, sheet 969 – Tychy. Warsaw: The Polish Geological Institute – National Research Institute.

Górnik, M. (2006b). GIS Database of the Hydrogeological Map of Poland, First aquifer. Occurrence and hydrodynamics, sheet 970 – Oświęcim. Warsaw: The Polish Geological Institute – National Research Institute.

Gruszewicz, P., Gąsior, Ł., & Miś, D. (2013). GIS Database of the Hydrogeological Map of Poland, First aquifer. Vulnerability to pollution, sheet 970 – Oświęcim. Warsaw: The Polish Geological Institute – National Research Institute.

Hard coal. (2022). Polish Geological Institute – National Research Institute. https://www.pgi.gov.pl/surowce/energetyczne/wegiel-kamienny.html#2022

Jasser, I. (2023). *Raport z badań fitoplanktonu Wisły w kierunku zidentyfikowania obecności Prymnesium parvum*. (Typescript). Uniwersytet Warszawski.

Kempa, J., & Bielewicz, R. (2006). GIS Database of the Hydrogeological Map of Poland, First aquifer. Occurrence and hydrodynamics, sheet 991 – Zebrzydowice. Warsaw: The Polish Geological Institute – National Research Institute

Kempa, J., & Pękała, Z. (2006). GIS Database of the Hydrogeological Map of Poland, First aquifer. Occurrence and hydrodynamics, sheet 993 – Kęty. Warsaw: The Polish Geological Institute – National Research Institute

Kondracki, J. (Ed.), (1998). *Geografia regionalna Polski*. Warszawa: PWN

Krieger, W., Sroga, C. (2002). Odpady z górnictwa i przeróbki kopalin w Krajowym Planie Gospodarki Odpadami. *Przegląd Geologiczny*, *50*(12), 1189-1194.

Lutyński, A. (2010). Foresight w zakresie priorytetowych i innowacyjnych technologii zagospodarowania odpadów pochodzących z górnictwa węgla kamiennego. *Górnictwo i Geoinżynieria*, *34*(4/1), 145-153.

Łaganowska, N. (2019). Wpływ składowiska odpadów górniczych „Pochwacie" na środowisko gruntowo-wodne na podstawie badań monitoringowych. *Acta Geographica Silesiana*, *13/2*(34), 75-94.

Liu, S., Zhu, J. P., & Jiang, H. H. (1999). Comparison of several methods of environment quality evaluation using complex indices. *Environmental Monitoring in China*, *15*(5), 33-37.

Madej, B., & Kujawski, P. (2023). Gospodarowanie odpadami wydobywczymi oraz masami ziemnymi lub skalnymi przemieszczanymi w związku z wydobywaniem kopalin ze złóż. *Bezpieczeństwo Pracy i Ochrona Środowiska w Górnictwie, 1*, 2-7.

Marove, C. A., Sotozono, R., Tangviroon, P., Tabelin, C. B., & Igarashi, T. (2022). Assessment of soil, sediment and water contaminations around open-pit coal mines in Moatize, Tete province, Mozambique. *Environmental Advances*, *8*. https://doi.org/10.1016/j.envadv.2022.100215

Matta, G., Kumar, A., Uniyal, D. P., Singh, P., Kumar, A., Dhingra, G. K,. Ajendra, K., ... & Shrivastva, N. G. (2017). Temporal assessment using WQI of River Henwal, a tributary of River Ganga in Himalayan Region. *International Journal for Environmental Rehabilitation and Conservation*, *8*(1), 187-204.

Matysik, M. (2018). *Wpływ zrzutów wód kopalnianych na odpływ rzek Górnośląskiego Zagłębia Węglowego*. Wydawnictwo Uniwersytetu Śląskiego.

Mele, L. M., Prodan, P. F., & Schubert, J. P. (1982). Characterization of runoff water from coal-waste disposal sites in southwestern Illinois. *Mine water and the Environment*, *1*, 1-14. https://doi.org/10.1007/BF02506201

Mineral deposits. (2017). Polish Geological Institute – National Research Institute. Retrieved from https://geoportal.pgi.gov.pl/midas-web/pages/index.jsf?conversationContext=2

Molenda, T., & Chmura, D. (2011). Seasonal changes in selected physicochemical parameters of saline water bodies. *Ecological Chemistry and Engineering. A*, *18*(2), 225-233.

Molenda, T. (2014a). Analysis of concentrations heavy metals (Zn, Pb, Cu, Cd) in spoil tip leachate from coal mining. In *International Multidisciplinary Scientific Geoconferences SGEM, Albena (Bulgaria). Conference Proceedings, Vol. 1 – Hydrology and Water Resources* (pp. 35-42).

Molenda, T. (2014b). Impact of saline mine water: Development of a Meromictic Reservoir in Poland. *Mine Water and the Environment*, *33*, 327-334. https://doi.org/10.1007/s10230-014-0262-z

Molenda, T. (2018). Impact of a saline mine water discharge on the development of a Meromictic Pond, the Rontok Wielki Reservoir, Poland. *Mine Water and the Environment*, *37*(4), 807-814. https://doi.org/10.1007/s10230-018-0544-y

Movo, A., Parbhakar-Fox, A., Meffre, S., Cooke, D. (2023). Geoenvironmental characterisation of legacy mine wastes from Tasmania – Environmental risks and opportunities for remediation and value recovery. *Journal of Hazardous Materials*, *454*. https://doi.org/10.1016/j.jhazmat.2023.131521

Nádudvari, A., & Fabiańska, M. J. (2015). Coal-related sources of organic contamination in sediments and water from the Bierawka River (Poland). *International Journal of Coal Geology*, *152*, Part B, 94-109. https://doi.org/10.1016/j.coal.2015.11.006

Odipe, O. E., Adewoye, S. O., & Sawyerr, H. O. (2020). Statistical and Pollution index assessment of water quality parameters in Ilorin metropolis, Nigeria. *IOSR Journal of Environmental Science, Toxicology and Food Technology*, *14*(6), 01-06. https://doi.org/10.9790/2402-1406030106

ORSIP. https://geoportal.orsip.pl/

Rakwic, B. (2011). *Modelowanie hydrochemiczne jako element oceny przydatności odpadów z górnictwa podziemnego w budownictwie drogowym*. Gliwice: Wydawnictwo Instytutu Techniki Górniczej KOMAG.

Reczek, D., Biedroński, G. (2013). GIS Database of the Hydrogeological Map of Poland, First aquifer. Vulnerability to pollution, sheet 993 – Kęty. Warsaw: The Polish Geological Institute – National Research Institute.

Regulation of the Minister of Environment of 11 February 2004 on the classification for presenting the condition of surface and groundwaters, the method of conducting monitoring and the method of interpreting the results and presenting the condition of these waters. Journal of Laws No. 32 of 2004, item 284.

Regulation of the Minister of Infrastructure of 25 June 2021 on the classification of ecological status, ecological potential and chemical status and the method of classifying the status of surface water bodies, as well as environmental quality standards for priority substances. Journal of Laws of 2021, item 1475.

Regulation of the Minister of Maritime Economy and Inland Navigation of 12 July 2019 on substances particularly harmful to the aquatic environment and the conditions that must be met when introducing sewage into water or soil, as well as when discharging rainwater or meltwater into water or water facilities. Journal of Laws of 2019, item 1311.

Różkowski, A., Chmura, A., & Siemiński, A. (Eds.), (1997). *Użytkowe wody podziemne Górnośląskiego Zagłębia Węglowego i jego obrzeżenia*. Prace Państwowego Instytutu Geologicznego.

Różkowski, A. (2004). *Środowisko hydrogeochemiczne karbonu produktywnego Górnośląskiego Zagłębia Węglowego*. Katowice: Wydawnictwo Uniwersytetu Śląskiego.

Rubin, K., Rubin, H. (2010). GIS Database of the Hydrogeological Map of Poland, First aquifer. Vulnerability to pollution, sheet 968 – Rybnik. Warsaw: The Polish Geological Institute – National Research Institute.

Rubin, K., Rubin, H. (2013). GIS Database of the Hydrogeological Map of Poland, First aquifer. Vulnerability to pollution, sheet 991 – Zebrzydowice. Warsaw: The Polish Geological Institute – National Research Institute.

Sołtysiak, M., Dąbrowska, D, Krzykawski, T. (2018a). Environmental effects of using mining waste for reclamation gravel pit in Rajsko (Sola valley, southern Poland). In *8th International Multidisciplinary Scientific Geoconference SGEM, Albena (Bulgaria). Conference Proceedings, Vol. 18, Ecology, Economics, Education and Legislation, Issue 5.2* (pp. 347-354). https://doi.org/10.5593/sgem2018/5.2/S20.047

Sołtysiak, M., Dąbrowska, D., & Slosarczyk, K. (2018b). Natural and formal-legal aspect of the environmental impact assessment of the planned reclamation of mining damage in the Szotkowka valley (Southern Poland). In 1*8th International Multidisciplinary Scientific Geoconference SGEM, Albena (Bulgaria). Conference Proceedings, Vol. 18, Ecology, Economics, Education and Legislation, Issue 5.4* (pp. 501-508). https://doi.org/10.5593/sgem2018/5.4/S23.064

Sołtysiak, M. (2024). Assessment of leachability of pollutants from commercial aggregate using a lysimeter; report on research carried out for the Society for the Earth. Katowice: SPINUS, University of Silesia (Unpublished report).

Son, C. T., Giang, N. T. H., Thao, T. P., Nui, N. H., Lam, N. T., Cong, V. H. (2020). Assessment of Cau River water quality assessment using a combination of water quality and pollution indices. *Journal of Water Supply: Research and Technology – AQUA*, *69*(2), 160-172. https://doi.org/10.2166/aqua.2020.122

Statistical Yearbook of Industry – Poland. (2007). Warsaw: Statistics Poland

Statistical Yearbook of Industry – Poland. (2011). Warsaw: Statistics Poland

Statistical Yearbook of Industry – Poland. (2015). Warsaw: Statistics Poland

Statistical Yearbook of Industry – Poland. (2020). Warsaw: Statistics Poland

Statistical Yearbook of Industry – Poland. (2022). Warsaw: Statistics Poland

Su, D., Almpanis, A., & Power, C. (2024). Complex electrical measurements of waste rock during acid mine drainage generation and release: Kinetic column tests. *Journal of Environmental Management*, *351*. https://doi.org/10.1016/j.jenvman.2023.119996

Stefaniak, S., & Twardowska, I. (2006). Przemiany chemiczne w odpadach górniczych na przykładzie zwałowiska w Czerwionce – Leszczynach. *Górnictwo i Geologia*, *1*(3), 89-100

Szczepańska, J. (1987). *Zwałowiska odpadów górnictwa węgla kamiennego jako ogniska zanieczyszczeń środowiska wodnego*. Kraków: Akademia Górniczo-Hutnicza im. Stanisława Staszica.

Tanjung, R. H., & Hamuna, B. (2019). Assessment of water quality and pollution index in coastal waters of Mimika, Indonesia. *Journal of Ecological Engineering*, *20*(2), 87-94. https://doi.org/10.12911/22998993/95266

Tao, M., Daoming, Lu D., Shi, Y., Liu, K., Yan, D., & Memon, M. B. (2024). Life cycle assessment of coal mines of diverse scales over time in China. *Science of The Total Environment*, *912*. https://doi.org/10.1016/j.scitotenv.2023.169236

Twardowska, I., Szczepańska, J., & Witczak, S. (1988). *Wpływ odpadów górnictwa węgla kamiennego na środowisko wodne: Ocena zagrożenia, prognozowanie, zapobieganie*. Wrocław: Ossolineum.

Voros, D., Rimacova, D., Medvecka, L., Gerślova, E., & Diaz-Somoano, M. (2021). The impact of saline mine water on fate of mineral elements and organic matter: The case study of the Upper Silesian Coal Basin. *Chemosphere*, *284*. https://doi.org/10.1016/j.chemosphere.2021.131397

Weber, Ł., Krawczyk, Ł, Kuś, P., Mazur-Marzec, H., Pasztaleniec, A., & Cimoch, M. (2024). *Wpływ amoniaku na rozwój Prymnesium parvum. Analiza danych środowiskowych z kanału gliwickiego testy laboratoryjne i terenowe*. Warszawa: Instytut Ochrony Środowiska – Państwowy Instytut Badawczy

Woś, A. (2010). Klimat Polski w drugiej połowie XX wieku. Poznań: Wydawnictwo Naukowe Uniwersytetu A. Mickiewicza

Zdechlik, R., Gołębiowski, T., Tomecka-Suchoń, S., Żogała, B. (2011). Wykorzystanie metod hydrogeochemicznych i geofizycznych do oceny wpływu składowisk odpadów górniczych na środowisko wodne. *Biuletyn Państwowego Instytutu Geologicznego*, *445*(445-2), 725-736.

Zdechlik, R., Kmiecik, E., Haładus, A. (2012). Ocena wpływu składowiska odpadów wydobywczych kopalni węgla kamiennego „Dębieńsko” na jakość wód podziemnych. In P. Bukowski (Ed.), *Wybrane problemy badań geologicznych i hydrogeologicznych dla górnictwa i energetyki*. Katowice: Główny Instytut Górnictwa – Państwowy Instytut Badawczy.

Article first received • 30 July 2024
Article accepted • 7 February 2025