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Quality of mine waters discharging to the surface in a hard coal post-mining area

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ABSTRACT

The quality of mine waters discharging to the surface in the area of the inactive and reclaimed Jan Šverma hard coal mine, located in the Žacléř mining district in the Czech Republic, was investigated. The mine waters discharge to the surface primarily through abandoned adits. The study focused on discharges from the Prokopi, Antoni, and Egidi adits. These outflows form and feed a watercourse known as the Lampertický Potok. Both mine waters and stream waters were subjected to chemical analyses. The following parameters were determined: pH, conductivity, dissolved solids, suspended matter, BOD_5, COD_{Cr}, chlorides, sulphates, Ca, Mg, Fe, Mn, and As. The mine waters contained high concentrations of dissolved substances, exceeding the regulatory standards for wastewater discharged into the environment. Among the dissolved substances, sulphates, calcium, and magnesium were dominant, though significant amounts of iron, manganese, and chlorides were also detected. Water contamination was selective and spatially variable. The stream waters were contaminated, particularly with sulphates, magnesium, and manganese. Neither the mine waters nor the stream waters were found to contain organic compounds. The research demonstrated that reclaimed post-mining areas can adversely affect the environment, in the presented case, in a selective manner resulting from the geochemical parameters of the rocks, reclamation methods, and targeted protective measures.

Keywords: mining area, hard coal mine reclamation, mine water discharge, water contamination

INTRODUCTION

Underground mining activity, especially hard coal extraction, is associated with adverse environmental changes, not only within the rock mass but also on the land surface (Li et al., 2024). Geological, hydrogeological, hydrological, soil, and habitat parameters are subject to transformation (Zhang and Zhang, 2021). A serious problem for human economic activity, including infrastructure safety, is the occurrence of fractures and fault displacements in rock strata, as well as land subsidence (Xie et al., 2022). Mine dewatering and the pumping of mine waters to the surface also exert a significant impact on the environment (Bednar et al., 2024; Mitko et al., 2024).

Many environmental and socio-economic hazards associated with hard coal mining persist long after mine closure (Price and Wright, 2016; Rocha-Nicoleite et al., 2017). Abandoned mine workings are most frequently closed using traditional caving methods or backfilled with waste rock material. Such measures do not prevent rock mass deformation and land subsidence. Moreover, the cessation of dewatering leads to groundwater rebound within the abandoned mine workings. Rising water levels in these mines often result in uncontrolled discharges to the surface (Merritt and Power, 2022). Analogously to active operations, these discharges are referred to as mine waters.

This paper addressed the issue of mine water discharge into the environment. Such discharge may be intentional, arising from the necessity to dewater mine workings, or, as previously mentioned, these waters may escape in an uncontrolled manner to the ground surface. The primary concern lies in the quality of the mine waters and the resulting environmental hazards. Opitz and Timms (2016) highlighted the necessity of correct water quality classification. While acidic and metalliferous mine waters are typically identified on the basis of geochemical parameters, these authors argue that water quality assessment should be more comprehensive, irrespective of the mine type or the extracted commodity.

Mine water quality is typically investigated on a local or regional scale. While some studies demonstrate low concentrations of problematic substances (e.g., Mahato et al., 2017; Kolev et al., 2018), the majority of reports reveal contamination. For instance, Miclean et al. (2025) characterised mine water quality in the Maramureș region of Romania, identifying high concentrations of sulphates and toxic elements (Mn, Fe, Zn). These authors also assessed a high carcinogenic risk associated with the presence of cadmium, arsenic, and chromium. Younger (2001) demonstrated that in Scotland, mine waters represent the second largest source of surface water pollution after wastewater, highlighting widespread iron pollution in particular. Furthermore, Wang et al. (2022) identified a sodium-chloride hydrochemical water type during investigations in the Tangjiahui region of China, which resulted from the dissolution of halite deposits and caused, among other things, elevated TDS and EC values. Given the numerous challenges faced by mining enterprises arising from mine water quality, Meuzelaar et al. (2025) proposed the utilisation of modern methods to analyse mine water databases.

It is beneficial that the discharge of mine waters into the environment takes place in a controlled manner. Periodic retention of these waters in sedimentation ponds is frequently applied to achieve a purification effect through the sedimentation of suspended solids and chemical precipitation of substances (Jabłońska, 2006; Rudakov et al., 2024). Harat et al. (2015) present a system for discharging mine waters from various mines into the Oder River (Poland) via a special collecting channel, wherein the water flow is automatically regulated depending on the current quantitative and qualitative water resources of the river. Intentional treatment of mine waters using electrocoagulation and other processes is also applied (Mamelkina et al., 2019; Atallah et al., 2024; Tumialan et al., 2024). Due to such measures, mine waters can be discharged into the environment with lower risk.

The recipients of mine waters are most frequently surface waters (watercourses, water bodies). Due to their quality parameters, mine waters can pose a significant threat to aquatic ecosystems. For instance, Olenici et al. (2025) found a negative impact of mine waters on biodiversity in surface waters (the Abrud River catchment, Romania) based on investigations of indicator organisms—diatoms. There have also been cases of almost complete degradation of riverine biota, as demonstrated by the study of Sadiku et al. (2021) concerning the Marec River (Kosovo). Additionally, the pollution caused by mine waters can limit the possibilities of human utilisation of water resources. For example, Bouzekri et al. (2020) investigated water quality in the Moulouya River (Morocco), which is locally fed by mine waters. They identified high concentrations of heavy metals (As, Cd, Pb, Zn, Cu) that precluded the use of the water for municipal purposes; furthermore, due to the high cadmium content, the water was also unsuitable for irrigation.

The aim of this study was to assess the quality of mine waters discharging in an uncontrolled manner to the surface within the former Žacléř mining area in the Czech Republic. The quality parameters of the stream fed by mine waters were also investigated.

RESEARCH OBJECT

The research focused on the Lower Silesian Coal Basin, where hard coal deposits were exploited from the 15th century until the end of the 20th century. This is a cross-border area between Poland and the Czech Republic located in the Sudetes Mountains, extending approximately between the towns of Kudowa-Zdrój (PL), Nowa Ruda (PL), Wałbrzych (PL), Kamienna Góra (PL), Žacléř (Czech Republic), and Hronov (Czech Republic). Coal extraction in the Lower Silesian Coal Basin, both on the Polish and Czech sides, ended in the 1990s. The mines were closed and subjected to reclamation.

The study area was the former Žacléř mining district located in the Czech Republic (Figure 1). The geographical coordinates of the central part of this area are 50°40'N, 15°56'E. Large-scale hard coal mining was carried out there from the second half of the 19th century in numerous underground workings reaching depths of nearly 1,000 m. As a result of their consolidation in 1950, the Jan Šverma mine was established, producing 200,000–250,000 tons of coal annually. Over time, mining became unprofitable, and the mine was closed in

1992. A decision was made to reclaim the mine using an innovative approach, as the traditional closure methods applied in Czech mines within the Lower Silesian Coal Basin (e.g., the Odolov mine or the Katerina mine) had caused negative environmental impacts (Rapantová and Grmela, 2002). The reclamation of the Jan Šverma mine involved filling all underground workings (from the lowest to the highest levels) with special liquid mixtures of ash and industrial waste (Harat and Grmela, 2013). The mixtures included, among others, power plant ash, flotation waste, surface-cleaning waste (e.g., from sandblasting), flue gas desulphurisation products, and products from neutralisation processes (e.g., gypsum sludge). After testing in the laboratories of VSB – Technical University of Ostrava, the mixtures obtained certificates authorising their use in the mine. During the filling operations, no empty spaces were left, and the applied material, characterised by self-hardening properties, began to function as a foundation, effectively stabilising the rock mass.

The filling of the underground workings was carried out between 1993 and 2007. In total, 44.2 km of mine workings were filled using 618,250 tons of mixtures (Harat and Grmela, 2013; Harat et al., 2017). By the end of 2005, the decommissioning of the mine's first level had been completed, followed by the closure of the mine voids between the first level and the ground surface. Mining operations in exposed workings, the reconstruction of tunnels for a planned mining museum, and the exploitation of the Žacléř quarries (I, IIB, and IIA) were carried out simultaneously. Over time, the mine waste dumps and quarries were reclaimed, contributing to an improvement in the landscape (Figure 2). The reclamation of the entire area was finally completed in 2025.

It was not possible to prevent the uncontrolled discharge of mine waters derived from precipitation infiltration, particularly through abandoned adits, such as Wilhelmina, Prokopi, Antoni, Egidi, Josefi, Cisarska, Karel, and Barbora. These waters feed nearby streams: the Lampertický Potok, the Černý Potok, and the Lesní Potok. In terms of discharge capacity, the outflows from the Prokopi adit (approximately 400–900 L/min), the Antoni adit (approximately 40–50 L/min), and the Egidi adit (approximately 100–200 L/min) are particularly significant (Grmela, 2016). The discharge points of these adits were bricked up, and the waters flow through open channels – partially reinforced with riprap – to form the Lampertický Potok stream. It should be noted that the natural water resources of the Lampertický Potok upstream of the mine water inflows, i.e. within the headwater zone, are highly limited, with no-flow conditions most frequently observed (Grmela and Ličbinská, 2020).

METHOD

The environment in the Žacléř mining area is monitored by GEMEC – UNION a.s., Důl Jan Šverma, Žacléř. The monitoring tasks include the control of the quality of mine waters and the waters of the Lampertický Potok. In recent years, the quality of waters from the Prokopi and Antoni adits (waters mixed after prior connection of channels and flow through a settling pond), from the Egidi adit, and from the Lampertický Potok downstream of the mine water inflows has been monitored (Figure 3).

In this study, the parameters of the investigated waters – the Prokopi+Antoni (P+A), Egidi (Eg), and the Lampertický Potok (LP) — from the years 2020–2025 were analysed. Samples were collected four times each year, resulting in 24 measurement series (n = 24). Laboratory analyses were performed in an accredited laboratory by the state-owned enterprise Povodí Labe (Elbe

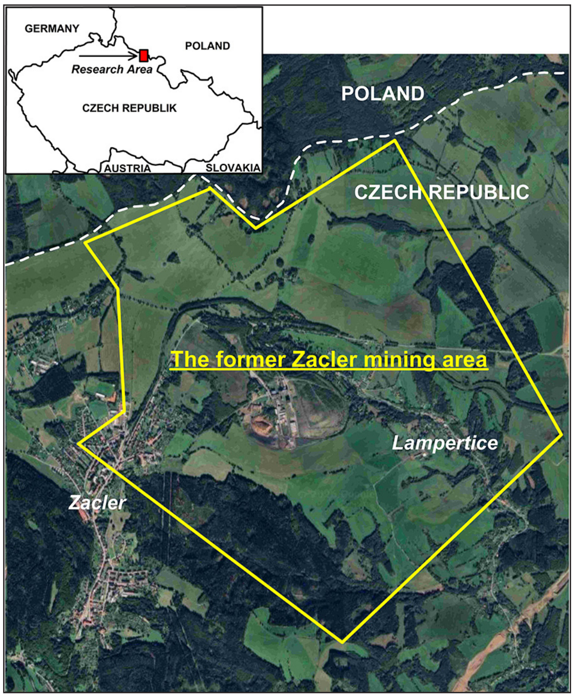

Figure 1. Location of the former Zacler mining area (based on Grmela, 2016 and Google Maps)

Figure 2. Reclamation of the central mine waste dump (photo by A. Grmela)

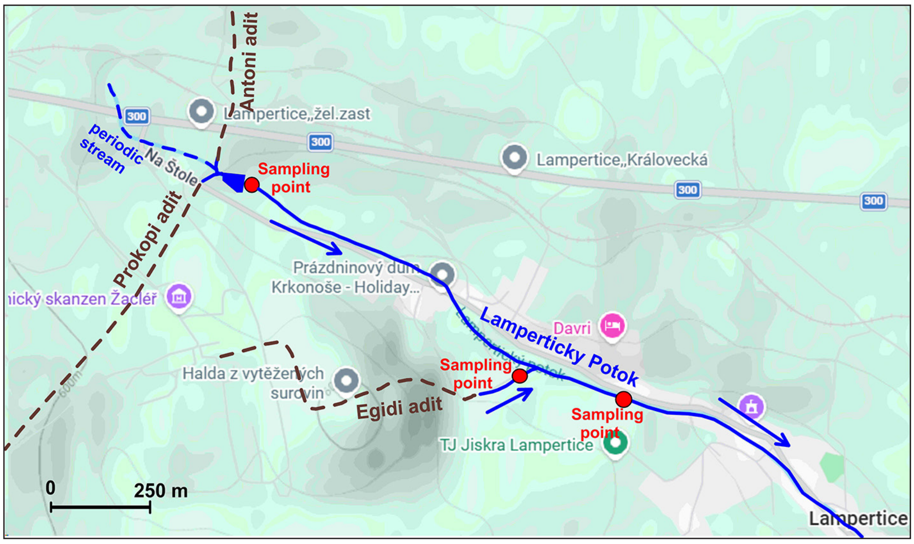

Figure 3. Water sampling points for laboratory analysis (based on Google Maps)

River Basin). Numerous physicochemical parameters were determined, the following of which have been presented due to data completeness: pH, conductivity (C), total dissolved solids (TDS), suspended matter (SM), BOD_5, COD_{Cr}, chlorides, sulphates, Ca, Mg, Fe, Mn, and As. The numerical data were provided by GEMEC – UNION as part of a long-term cooperation agreement. The numerical analyses were based on parameter values from individual measurement series. The results were single measurements (no replicates were performed); therefore, basic statistical characteristics for the data series were presented – minimum and maximum values, arithmetic mean, standard deviation, and coefficient of variation. The trends in parameter changes were also analysed using linear regression based on the least squares method. In order to identify relationships between the quality of mine waters and stream waters, Pearson correlation analysis was performed.

The parameter values of both the mine waters and the stream waters were compared against environmental quality standards. These standards are defined in Government Decree of the Czech Republic No. 401/2015 on indicators and permissible values of surface water and wastewater pollution, requirements for permits to discharge wastewater into surface waters and sewerage systems, and on sensitive areas. The mine waters were analysed with respect to the requirements for wastewater discharged into the environment, whereas the stream waters were evaluated against the permissible contamination thresholds for surface waters.

RESULTS

The values of the investigated water parameters varied among individual measurement points during the study period (Table 1). In some cases, the range of values was considerable – for example, suspended matter content in the waters from the Prokopi+Antoni adits varied from 2 to 50 mg/L, chloride concentration in waters from the Egidi adit ranged from 32 to 185 mg/L, and the recorded concentration of magnesium in the stream waters was within the range of 61–600 mg/L. However, variability is better illustrated by the standard deviation (SD). In conjunction with the arithmetic mean, it indicates the stability or variability of a parameter. For example, the pH of the studied waters was practically constant. With mean values of approximately 8, SD was approximately 0.3, which corresponds to a coefficient of variation (CV) of 3.5–4.0%. Low variability was, among others, observed for water conductivity, dissolved solids content, and calcium concentration. On the other hand, high variability was recorded particularly for total suspended matter, as well as for organic pollution indicators (BOD_5, COD_{Cr}), chloride, iron, and manganese contents (Table 1).

Variations in parameter values were observed among the studied sampling points (Table 1). For instance, magnesium levels in the waters from the Egidi adit were distinctly higher than in the other studied waters, while waters from the Prokopi+Antoni adit showed distinctly higher iron concentrations. The waters of the Lampertický Potok were characterised by the lowest total dissolved solids (TDS) content and, consequently, the lowest electrical conductivity. However, this does not imply that they contained the lowest amounts of all investigated substances; for example, they had higher chloride and manganese concentrations than the waters from the Egidi adit. The highest TDS content and electrical conductivity were recorded in the waters from the Egidi adit. The data indicate that this was primarily a consequence of exceptionally high sulphate and magnesium concentrations.

In the analysis of temporal changes in the values of individual parameters (during the 2020–2025 study period), no clear regularities were identified. First, comparative analysis showed no influence of seasonality on parameter levels. Second, linear regression analysis did not reveal any significant trends in parameter changes over time. The coefficients of determination (R^2) were often close to zero and occasionally reached values of 0.2–0.3. Only in three cases did the R^2 values exceed 0.5, indicating the possible development of a trend, which in all cases was decreasing:

- conductivity of water from the Prokopi+Antoni adits ($y = -36.913x + 3588.1$; $R^2 = 0.5645$),
- concentration of manganese in water from the Prokopi+Antoni adits ($y = -0.1193x + 3.8751$; $R^2 = 0.534$),
- concentration of chlorides in the Lampertický Potok waters ($y = -8.131x + 229.93$; $R^2 = 0.5513$).

It should be noted that the previously presented variation in values may be related to the hydrometeorological conditions prevailing prior to and during sample collection. The amount and intensity of precipitation, which affect water discharge levels, most often determine suspended matter content (Huynh et al., 2023), but may also influence the values of other parameters (Levei et al., 2011). Due to the lack of available hydro-meteorological data, such an analysis could not be performed in this study.

DISCUSSION

Assessment of mine water quality

As Grmela (2016) noted, the degree of connection between all underground mine workings in the studied area is not known. Therefore, it is difficult to precisely identify the hydraulic pathways through which mine waters discharge to the surface. The analysis of correlations between parameter values of the waters from the Prokopi+Antoni and Egidi adits has demonstrated that water outflows from these adits do not appear

Table 1. Water quality parameters in the Žacléř mining area for 2020–2025 – minimum (min) and maximum (max) values, arithmetic mean (av), standard deviation (SD), coefficient of variation (CV)

Parameter	Value type	Prokopi+Antoni adits	Egidi adit	Lampertický Potok
pH	min–max	6.8–8.0	7.1–8.2	6.9–8.3
	av	7.7	7.8	8.1
	SD / CV	0.27 / 3.5%	0.27 / 3.5%	0.32 / 4.0%
Conductivity (C) (μS/cm)	min–max	2780–4380	1950–4390	2130–4040
	av	3127	3468	2607
	SD / CV	347 / 11.1%	621 / 17.9%	386 / 14.8%
Total dissolved solids (TDS) (mg/L)	min–max	2280–3420	1670–4620	1750–4120
	av	2707	3464	2318
	SD / CV	258 / 9.5%	818 / 23.6%	465 / 20.1%
Suspended matter (SM) (mg/L)	min–max	2.0–50.0	2.0–26.0	2.0–18.0
	av	11.2	8.7	6.3
	SD / CV	9.3 / 83.0%	7.4 / 85.1%	5.1 / 81.0%
BOD_5 (mgO_2/L)	min–max	0.5–6.3	0.7–5.0	0.7–3.4
	av	1.7	1.8	1.8
	SD / CV	1.4 / 82.4%	1.2 / 66.7%	0.8 / 44.4%
COD_{Cr} (mgO_2/L)	min–max	5.0–33.0	5.0–11.0	5.0–16.0
	av	8.3	6.6	7.3
	SD / CV	5.6 / 67.5%	2.0 / 30.3%	2.8 / 38.4%
Chlorides ($mgCl^-/L$)	min–max	136–723	32–185	90–287
	av	224	75	161
	SD / CV	128 / 57.1%	32 / 42.7%	52 / 32.3%
Sulphates ($mgSO_4^{2-}/L$)	min–max	760–1360	677–2300	559–2070
	av	1066	1733	991
	SD / CV	148 / 13.9%	444 / 25.6%	292 / 29.5%
Ca (mg/L)	min–max	197–263	93–233	144–213
	av	224	179	174
	SD / CV	20 / 8.9%	33 / 18.4%	18 / 10.3%
Mg (mg/L)	min–max	78–320	217–584	61–600
	av	259	441	246
	SD / CV	60 / 23.2%	109 / 24.7%	89 / 36.2%
Fe (mg/L)	min–max	0.1–2.5	<0.05–0.28	<0.05–0.38
	av	1.17	<0.06	<0.12
	SD / CV	0.75 / 64.1%	–	–
Mn (mg/L)	min–max	0.8–4.6	<0.02–0.26	0.02–1.50
	av	2.71	<0.03	0.38
	SD / CV	0.95 / 35.1%	–	0.45 / 118.4%
As (μg/L)	min–max	<1–3.7	<1	<1
	av	<1.1	<1	<1
	SD / CV	–	–	–

to be hydraulically connected. The Pearson correlation coefficients (r) were as follows:
- r = 0.65 for pH,
- r = -0.24 for conductivity,
- r = -0.22 for dissolved solids,
- r = -0.05 for suspended solids,
- r = 0.07 for BOD_5,
- r = 0.23 for COD_{Cr},
- r = -0.20 for chlorides,
- r = 0.59 for sulphates,
- r = -0.05 for calcium,
- r = 0.19 for magnesium.

A statistically significant correlation (p = 0.05; n - 2 = 22) was found only for pH, which was highly similar in both cases and exhibited very low variability, and for sulphates, elevated levels of which are generally characteristic of mine waters (Mamelkina et al., 2019).

Mine waters discharging to the surface are classified as wastewater. The parameter values of the studied waters (Prokopi+Antoni—P+A; Egidi—Eg) were compared against legal standards for wastewater discharge into the environment. For certain parameters, compliance was maintained, or exceedances were recorded only sporadically; however, several parameters exhibited values above the permissible limits (Table 2). When analysing the quality of mine waters in the study area, it should be noted that no mining operations have been conducted here since the underground workings were backfilled. This absence of active mining may have reduced the leaching intensity of the rock material and, consequently, minimised the contamination of migrating waters.

Mine waters may be strongly acidic, mainly due to the oxidative dissolution of pyrite (Nordstrom, 2011), but they can also exhibit neutral or alkaline reactions (Singh et al., 2011). The investigated mine waters were most often slightly alkaline, with pH values between 7.5 and 8. In the case of the Žacléř mining area, this may be partly attributed to the use of calcium-containing materials (e.g., ash and gypsum waste) for mine backfilling. The observed pH values showed low variability and did not exceed the quality standards for wastewater discharged into the environment.

Table 2. Quality standards for mine water discharged into the environment and the number of samples (out of 24 tested) in which these standards were exceeded

Parameter	Limit	Number of exceedances	
		P+A	Eg
pH	6–10	0	0
C (µS/cm)	–	–	–
TDS (mg/L)	2400	22	21
SM (mg/L)	100	0	0
BOD_5 (mgO_2/L)	6	1	0
COD (mgO_2/L)	35	0	0
Cl^- (mg/L)	300	4	0
SO_4^{2-} (mg/L)	900	20	21
Ca (mg/L)	250	4	0
Mg (mg/L)	400	0	16
Fe (mg/L)	2	4	0
Mn (mg/L)	1	21	0
As (µg/L)	20	0	0

Conductivity (C) indicates the presence of electricity-conducting ions that originate from dissolved salts and inorganic compounds. In the investigated mine waters, it averaged over 3000 µS/cm (no standard value for conductivity has been defined). Slightly higher values and slightly greater variability were recorded for waters from the Egidi adit. For example, Hubert and Wolkersdorfer (2015) reported an average conductivity value of 2601 µS/cm in mine waters from a coal mine in South Africa. Based on conductivity measurements, these authors estimated the content of dissolved substances in mine waters.

Laboratory analyses demonstrated that the total dissolved solids (TDS) content in the waters from the Egidi adit was generally higher (mean 3464 mg/L) than in those from the Prokopi+Antoni adit (mean 2707 mg/L) and exhibited greater variability. Regardless of the adit, the TDS content in the studied waters exceeded the regulatory standards for wastewater in almost all measurement series. The recorded TDS levels of approximately 3 g/L should be considered high, although greater contents have been reported in the literature (e.g., Gavrishin, 2018). High TDS values can pose a significant challenge for the potential utilisation of mine waters (Singh et al., 2011).

Suspended matter in the investigated mine waters occurred in small amounts, typically at levels of a few to several mg/L. The quality standard was not exceeded. It is worth noting that the observed variability in suspended solids content may be influenced by hydro-meteorological conditions, i.e., the intensity of precipitation infiltration. In the studied discharges (P+A, Eg), maximum suspended solid concentrations were not recorded in the same measurement series, which suggests limited or absent hydraulic connectivity. In contrast to the obtained results, literature reports indicate high suspended solids content in mine waters, sometimes requiring the use of sedimentation tanks prior to their discharge into the environment (Policht-Latawiec and Kapica, 2013).

Analyses of BOD_5 and COD_{Cr} generally did not indicate organic contamination of the investigated mine waters. BOD_5 values were most often in the range of 1–2 mg O_2/L, while the values of COD ranged from 5–10 mg O_2/L There was only a single instance of non-compliance with the

BOD_5 standard. However, contamination of mine waters with organic matter is possible, as demonstrated by Zhang and Zhang (2021) in a study of an area with intensive mining activity in China.

Excess chloride concentrations (>300 mg/L) were only detected in waters discharging from the Prokopi+Antoni adits, during the first four measurement series. In subsequent series, chloride concentrations generally did not exceed 200 mg/L. In waters flowing from the Egidi adit, values were typically in the order of several tens of mg/L. The situation was different in the case of sulphates. First, in almost all measurement series at both sampling sites, the regulatory limit (900 mg/L) was exceeded. Second, significantly higher sulphate concentrations were observed in waters from the Egidi adit. Unfortunately, salinization of mine waters, in particular contamination with sulphates, is a common problem (Shvets et al., 2025).

In the conducted study, calcium was present at higher concentrations in the waters from the Prokopi+Antoni adits (mean above 220 mg/L). The regulatory limit was exceeded in four measurement series. No exceedances were recorded in waters from the Egidi adit. The situation was the opposite in the case of magnesium: contamination was identified in the waters from the Egidi adit (exceedances of the standard in most measurement series), while no exceedances were observed in waters from the Prokopi+Antoni adits. The source of calcium and magnesium in mine waters is mainly natural geochemical processes. Therefore, the content of these macronutrients may vary regionally, as confirmed, for example, by the results presented by Ciosmak et al. (2017).

Regarding iron, its elevated concentrations were detected only in the waters from the Prokopi+Antoni adits. In four measurement series, the regulatory limit was exceeded. Field observations indicate that significant amounts of iron are discharged with water from the Prokopi adit. The discharge zone is covered with ochre-coloured deposits (Figure 4), indicating oxidation of iron compounds and their precipitation from the solution. Since the downstream water was also coloured, a sedimentation pond was constructed along its flow path (after mixing with water from the Antoni adit) in order to capture iron compounds.

The waters from the Prokopi+Antoni adits were also characterised by high manganese content. In almost all measurement series, the regulatory limit for wastewater discharged into the environment was exceeded. In waters from the Egidi adit, manganese was most often undetected. The issue of environmental protection against the manganese present in mine waters in the United Kingdom was highlighted by Moorhouse-Parry and Satterley (2023). They demonstrated the need to design treatment systems for removing manganese from mine waters, which until recently had focused primarily on iron removal.

The content of arsenic in the investigated mine waters generally did not exceed 1 μg/L (the detection limit). On several occasions, slightly elevated values above 1 μg/L were recorded in waters from the Egidi adit. No exceedance of the regulatory limit was observed. These results are considered favourable in light of the studies reporting contamination with this element associated with coal mining activities (Bhardwaj et al., 2020).

Assessment of the stream water quality

The Lampertický Potok belongs to the Elbe River basin. It is approximately 4.5 km long and flows into the Ličná Potok downstream of the village of Lampertice. The mine waters discharging from the Prokopi and Antoni adits effectively constitute the headwaters of the Lampertický

Figure 4. Mine water discharge from the Prokopi adit (photo by K. Novotný)

Potok; upstream of this confluence, the stream is an ephemeral watercourse. Approximately 1 km downstream of the Prokopi and Antoni confluence, the stream is joined by the waters from the Egidi adit. The water samples from the Lampertický Potok were collected for analysis at a distance of 250 m downstream of the Egidi adit inflow (Figure 3).

Given the hydrological situation, it can be assumed that the mine waters exert a significant impact on the stream water quality due to the low dilution capacity for pollutants. The correlation analysis revealed a relationship between their values in the mine waters and the stream waters for several parameters (Table 3). A connection between the quality of water in the Prokopi+Antoni adits and the stream waters was found for pH, BOD_5, COD_{Cr}, chloride, sulphate, and manganese. For the waters from the Egidi adit and the stream, a statistically significant correlation was observed for pH, BOD_5, COD_{Cr}, and calcium. Excessively low concentrations of iron and arsenic (frequently below the detection limit) precluded verification of any relationship.

Table 3. Pearson's correlation between the parameters of mine water and the water of the Lampertický Potok (statistically significant values for $p = 0.05$, $n - 2 = 22$ are in bold)

Parameter	Correlation coefficient r	
	P+A – LP	Eg – LP
pH	**0.84**	**0.84**
C	0.25	0.12
TDS	0.30	0.00
SM	0.05	0.33
BZT_5	**0.55**	**0.61**
$ChZT_{Cr}$	**0.66**	**0.66**
Cl^-	**0.83**	-0.34
SO_4^{2-}	**0.46**	0.05
Ca	0.36	**0.59**
Mg	0.36	0.05
Fe	–	–
Mn	**0.63**	–
As	–	–

The water quality of the Lampertický Potok is undoubtedly influenced not only by mine waters but also by spatial runoff from the catchment area. The upper catchment consists of post-mining areas with reclaimed waste rock dumps. Under these conditions, the research demonstrated the expected contamination of the stream waters. The values of the stream water parameters were compared against legal standards for surface water quality, with the established limits being exceeded for certain parameters (Table 4).

The stream waters typically exhibited a pH slightly exceeding 8 units, indicating a weakly alkaline character. These pH values complied with regulatory standards and cannot be interpreted as an ecological hazard.

The situation was different for electrical conductivity, although this parameter is not subject to regulatory limits. Values usually ranged between 2500 and 3000 μS/cm, whereas in most surface

Table 4. Surface water quality standards and exceedances in the Lampertický Potok from 2020 to 2025

Parameter	Standard (annual average)	Exceeding the standard					
		2020	2021	2022	2023	2024	2025
pH	5–9	no	no	no	no	no	no
C (μS/cm)	–	–	–	–	–	–	–
TDS (mg/L)	750	yes	yes	yes	yes	yes	yes
SM (mg/L)	20	no	no	no	no	no	no
BOD_5 (mgO_2/L)	3,8	no	no	no	no	no	no
COD (mgO_2/L)	26	no	no	no	no	no	no
Cl^- (mg/L)	150	yes	no	no	no	no	no
SO_4^{2-} (mg/L)	200	yes	yes	yes	yes	yes	yes
Ca (mg/L)	190	no	no	no	no	no	no
Mg (mg/L)	120	yes	yes	yes	yes	yes	yes
Fe (mg/L)	1	no	no	no	no	no	no
Mn (mg/L)	0.3	yes	yes	yes	yes	yes	no
As (μg/L)	5	no	no	no	no	no	no

waters they reach only several hundred μS/cm (Kovacova, 2024). This indicates anthropogenic impacts on the stream water quality, which is further confirmed by the total dissolved solids (TDS) content in the stream water, exceeding the surface water quality standards by a factor of two, three, or even four. Such concentrations can degrade aquatic ecosystems in various ways and adversely affect technical infrastructure.

In contrast to total dissolved solids, suspended solids were present at low levels (typically a few mg/L) and did not exceed regulatory limits. Neither the mine waters nor the catchment areas contributed suspended solids to the stream. The upper catchment of the Lampertický Potok is forested and managed as grassland, which undoubtedly restricts the migration of soil and rock material. This land-use structure, coupled with the absence of residential areas generating wastewater, also resulted in a low organic matter content in the stream waters. Consequently, the BOD_5 and COD_{Cr} indicators were low, remaining below the established thresholds.

During the first year of the study, the concentration of chlorides was more than 200 mg/L, i.e., above the regulatory limit. In subsequent years, the mean concentration reached approximately 140 mg/L. In view of the literature reports, these values cannot be considered high. For instance, in post-mining areas in southern Poland, concentrations of chloride in surface waters ranging from ca 650 to 1300 mg/L have been reported (Czajkowska and Gawor, 2021). However, mining-related anthropogenic pressure on the Lampertický Potok waters was clearly evident in the case of sulphate concentrations, which ranged from approximately 600 to 2000 mg/L, significantly exceeding regulatory limits. Such levels indicate corrosive properties of the water and its low suitability for practical use.

Calcium concentrations ranged from approximately 150 to 200 mg/L. There was no exceedance of the regulatory standard, which is set at an annual average of 190 mg/L. The calcium concentration remained relatively stable throughout the entire study period, indicating that it is geochemically controlled by the mine-water inflow and catchment denudation. Magnesium concentrations in the stream waters were more variable and exceeded the surface water quality standard in every year of the study. The elevated magnesium levels in the stream are undoubtedly influenced by the inflow from the Egidi adit, which is characterised by high concentrations of this element.

Iron is a common contaminant of surface waters in coal mining areas and can pose a threat to living organisms (Cadmus et al., 2018). No contamination with this element was found in the studied stream waters, despite its occurrence in higher amounts within the discharge from the Prokopi adit. It appears that the retention of iron in the sedimentation pond provided effective protection against its migration. Conversely, a disadvantageous situation was observed regarding the presence of manganese in the stream waters. Its concentrations were highly variable and most frequently exceeded the regulatory limits, with the annual average standard not being exceeded only in the final year of the study. The origin of manganese in the waters of the Lampertický Potok is certainly determined by mining anthropogenic pressure, as this element entered in large quantities with the waters from the Prokopi+Antoni adits.

Arsenic occurred in the studied stream waters in amounts undetectable by the laboratory methodology, i.e., below 1 μg/L. Consequently, the surface water quality standard (annual average of 5 μg/L) was not exceeded. It is worth noting that arsenic concentrations in the mine waters also did not pose an environmental concern.

CONCLUSIONS

Hard coal mining areas, even after the cessation of mining activities, may remain sources of environmental pollution. This has been demonstrated by studies on the quality of the aquatic environment in the former Žacléř mining area.

The mine waters discharged to the surface in an uncontrolled manner contained substantial amounts of total dissolved solids, exceeding the regulatory standards for wastewater discharged into the environment. The contamination of the mine waters was selective and spatially variable. For instance, high magnesium concentrations were recorded concurrently with low calcium concentrations within the same discharge point. Furthermore, elevated manganese concentrations were detected in one outflow, whereas this element occurred in trace amounts within another. Such variations may stem from the geochemical heterogeneity of the rocks, as well as from the application of specific reclamation materials.

Mining anthropogenic pressure resulted in an adverse impact on the surface waters. The waters of the Lampertický Potok, fed by both mine waters and spatial runoff from the reclaimed areas, were contaminated particularly with sulphates, magnesium, and manganese. To conduct a toxicological assessment, it would be necessary to expand the scope of the research.

Neither mine waters nor catchment areas contributed to organic contamination of the stream waters. Iron migration was effectively limited through targeted mitigation measures (a sedimentation pond).

Continued monitoring of both mine and surface waters is imperative to evaluate pollution trends, particularly given that the Žacléř mining site was reclaimed using novel reclamation techniques.

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