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TECHNICAL COMMUNICATION

Main Key Heritage Adit (Sztolnia Dziedziczna) in Zabrze, Upper Silesian Coal Basin, Poland

Kajetan d'Obyrn[1] **· Adam Postawa**[1]

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Abstract
The Main Key Heritage Adit in Zabrze was used during from 1799 to 1953 to drain a series of underground coal mines and is the longest such facility in Europe. It discharges water of variable quality to the Bytomka River. At times, the adit water has greatly exceeded allowable discharge water quality limits. The refurbishment of the adit at the beginning of the twenty-first century allowed tourists to access 2.5 km of the original 14.25 km of tunnels. It also enabled the monitoring of groundwater in this part of Zabrze. Three series of water samples from leaks at the adit and the "Carnall" shaft (34 samples in total) were collected from 2017 to 2018. The total dissolved solids content of the samples ranged from 640 to 2670 mg/L with pH ranging from 6.7 to 8.5. Waters belong to various chemical types, from Ca-HCO_3-SO_4 and Ca-HCO_3-Cl to Ca-Na-Mg-Cl-HCO_3-SO_4. High concentrations of metals (e.g. Fe up to 64.4 mg/L) and anthropogenic pollutants such as NO_3 (up to 151.4 mg/L) were observed. The pollution is caused both by natural processes (weathering of sulfides) and anthropogenic factors (long-term mining activities, intensive land use, and past and present leaks of city sewerage). The hydrogeological role of the adit and the possibilities of its multifunctional use may serve as an example of good practices that can be used during the rehabilitation of closed mines elsewhere in the world.

Keywords Coal mine · Leaks · Water pollution

Introduction

The city of Zabrze is situated in the northern part of the Upper Silesian Coal Basin. The land morphology has been strongly transformed due to long-term intensive human activities such as coal extraction, industrial development, and municipal infrastructure. Many spoil and slag heaps can be found in the city area, with embankments and other anthropogenic structures.

The Main Key Heritage Adit (GKSD) in Zabrze is unique in the Upper Silesian Coal Basin. It constituted a model for a novel approach to adit design, transportation, and water drainage in this part of Europe. The transportation function resulted from the need to deliver increasing quantities of coal to the industrial facilities of the Upper Silesia, which was difficult due to the shortage of paved roads. The drainage function of the adit was known for centuries as the best method of collecting waters from the mine workings until pumps powered by steam engines were invented.

The adit is of key importance for draining shallow circulation waters (from several meters to ≈ 40 m under the ground surface), as it collects waters originating from local Quaternary and Carboniferous aquifers. The chemical composition of the infiltrating waters results from both natural geochemical processes and the migration of anthropogenic pollutants from the land surface. The waters that flow out of the adit are fed to the Bytomka River, affecting the river water quality. For that reason, it is essential to determine the chemical composition of the adit water and the scope of changes in its main parameters.

Adit construction commenced in 1799 and lasted for 64 years. When the project was completed in 1863, the adit became the longest hydrotechnical facility operated in coal mines in Europe. The adit started in the "Król" coal mine in Chorzów and ended at its outlet in the Bytomka River in Zabrze (Fig. 1), one of the lowest places in the Upper Silesian Coal Basin, at a terrain elevation of 234.1 m above sea level. The adit was 14.25 km long, and the difference in the

✉ Adam Postawa
postawa@agh.edu.pl

[1] Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology, 30 Mickiewicza Ave, 30-059 Krakow, Poland

levels between the inlet and the outlet was 12.3 m, with a gradient of 0.86 ‰. Water was drained from the "Król" coal mine in Chorzów and other local coal mines located along the course of the adit to the Bytomka River, at a rate of ≈ 3 L/s; however, the flow rate in the Bytomka River ranged from 2 to 3 m^3/s in 2010–2018 outside the flood periods, e.g. in May 2010 when the flow rate increased to more than 18 m^3/s.

Initially, 22 blind shafts were drilled along the course of the adit, and horizontal corridors were cut out between them later. The work was primarily carried out manually. Blasting was conducted only where the hardest sandstone occurred. The corridors were supported by either cut stones or bricks. Certain adit sections, in compact sandstone, were left without any support system. The adit was cut at various rates, depending on the local geological structure. Aside from this, several hundred meters of the adit branches were cut out each year, allowing for the drainage of several local coal mines.

In 1806, the adit reached the Einsiedel Level (Level 501), where a coal loading station was provided. About 1810, the adit was completed at the "Carnall" shaft level, at the end of the adit. Growing demand for coal led to the coal seams subjected to drainage by the adit being quickly extracted, and the miners started to access the saddle layer deposits of Level 500, located below the adit. By the time the adit reached its target length, all of the coal seams above the adit had been long extracted. The transportation function concluded in 1842, after construction of a railway line and completion of road paving in Silesia. In subsequent years, water was pumped through the "Dechen," "Oyenhausen," and "Carnall" shafts (Fig. 2). Mining operations conducted at lower levels adversely affected the adit support structures, primarily due to uneven land subsidence. After the occurrence of a local sinkhole in 1953, the adit was removed from the register of mine workings, and the adit's small shafts and outlet were buried (Priedl 2006; Wiśniewski 2009).

Renovation of the adit commenced in 1999. Ten years later, the "Carnall" and "Wilhelmina" shafts were uncovered and cleared. Clearance of the Main Key Heritage Adit was a very slow process because the silt sediment was up to 3 m thick. It is estimated that ca. 19,000 Mg of silt was removed from the adit. The workers even found sewers dumping municipal wastewater into the adit. The section that was cleared in Zabrze is nearly 2.5 km long. Midway between the outlet and the "Carnall" shaft, the adit splits into north and south branches (western forking). Both branches run parallel to the "Carnall" shaft, at a distance from several meters to about a dozen meters. The former coal loading station was reconstructed for exhibition purposes, together with a corridor at Level 510. Boat trips constitute an additional attraction onsite. The 1.1 km tourist route leads from the old coal loading station to the adit outlet (Bugaj and Glosz 2012).

The adit contains Quaternary and Carboniferous sediments. The Quaternary sediments lie directly on the roof of the Carboniferous sediments strata and contain fine- and medium-grained sands, clays, silts, aggregates, and gravel. The formation thickness varies along the 2.5 km of the cleared adit, reaching 40 m in the northwestern section. A typical Quaternary formation sequence starts with sands and gravel, interbedded with clay and silt layers of various thicknesses. Clay layers can be found at the bottom of the series. Where these layers are thinner, sand and gravel sediments lie directly on the Carboniferous formation, while elsewhere, that sequence can contain several layers separated by clay sediments (Fig. 2).

The paralic series (the Lower Namur) is the best-documented stratigraphic series in the Zabrze area. The series was deposited in cycles. From bottom to roof: coal, claystone, mudstone, sandstone (mostly with fine-, medium- and coarse-grained sandstones), mudstone, and a subsequent coal layer. We find limnic sedimentation in the Upper Namur. The whole Upper Silesian sandstone series is dominated by gray, fine- or medium-grained sandstones. Coarse-grained sandstones and conglomerates occur less often. Interlays of mudstone and claystone are encountered there, with their thicknesses reaching several meters each. The coal seams in the Ruda layers are up to 15 m thick over all of Upper Silesia. The adit rock mass is cut through by a considerable number of faults and is folded as well. Two tectonic units are distinguished there: the Concordia Overlap and the Zabrze Dome (Kędzior 2008).

The hydrodynamic and hydrochemical conditions of the Upper Silesian Coal Basin and coal mining's influence on the hydrogeological conditions of the basin were presented by Rogoż and Posyłek (2000) and Wilk (2003), as well as a number of thematic papers (e.g. Duży et al. 2017; Pluta 2005; Rogoż 1996; Różkowski 1997). The two aquifers in the Quaternary and Carboniferous units are close to the adit. The Quaternary aquifer has several sublayers due to the presence of clay or silt interbeds in many areas and has two components. The upper part includes only fine sands, with hydraulic conductivities (k) from 0.25×10^{-6} m/s to 3×10^{-6} m/s; water occurs locally, usually as perched water, over thin layers of clays or loams. The lower part consists of sands and gravels and its thickness varies significantly. In some areas (e.g., in the northwestern part of the adit), the thickness of this lower part is reduced practically to zero. In such areas, sediments representing the upper part of the Quaternary aquifer are in direct hydraulic contact with the Carboniferous aquifer. Piezometric data show that the aquifers in the Carboniferous rocks have been almost completely drained by the mine workings (Cempiel et al. 2014). The only groundwater detected in the Carboniferous formations occurred in the contact zones with the overlying Quaternary aquifer. Water from precipitation infiltrates and flows

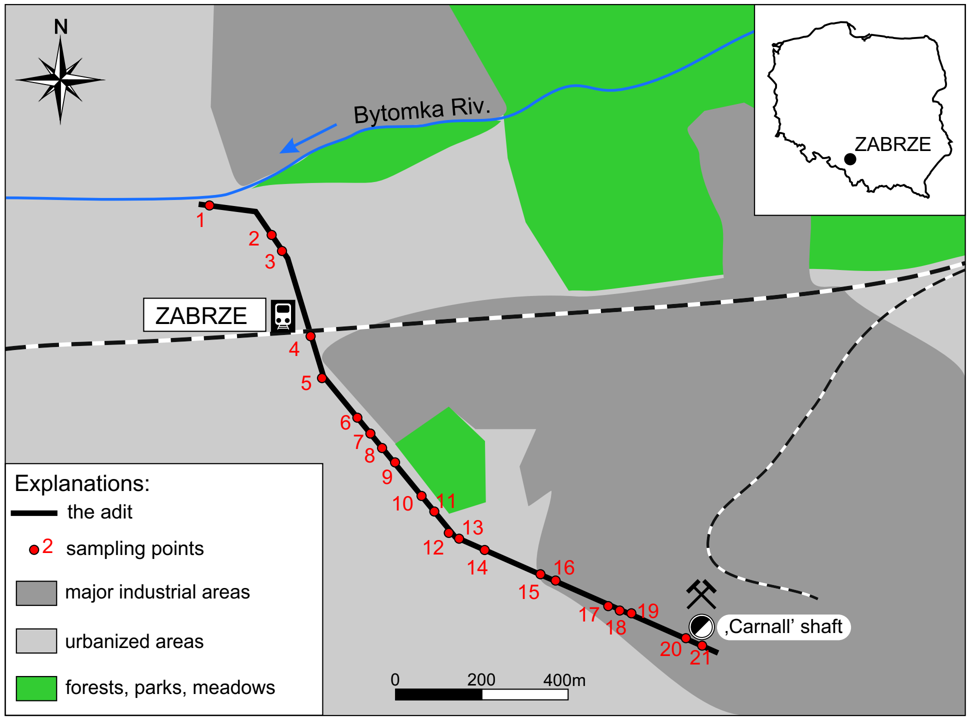


Fig. 1 Location of the rehabilitated Adit section on the map of Zabrze

through a network of fractures and cracks down to unused workings and down to the drainage system of the operating "Bielszowice" coal mine, whose workings are located several hundred meters below the adit. The water is interpreted as flowing in the southwestern direction, i.e., along the dip of the bedding.

Methods of Investigation and Interpretation

Interpretation of the water quantities flowing to the adit is a complex issue, due to the nature of the inflows, which occur as rather scattered dripping or seepage (humidity effects). On some of the adit walls, the humidity and dripping zone extends over distances of several dozen meters and increases or decreases spatially. The inflow rate varies, presumably reflecting the intensity of precipitation infiltration and variable vertical hydraulic conductivity but affected by the adit ventilation system and air-drying systems, which are designed to dry the adit walls and roof since the adit is a heritage structure, and it is necessary to limit the humidity of wooden support systems in some of the workings. Consequently, water infiltrating through the wooden supports into the adit evaporates and affects the quality of the inflow measurements.

The rate of groundwater inflow depends on the precipitation and water flow paths. By contrast, the ventilation effects are rather immediate and depend only on the number of persons underground at the time. As part of the present study, water flow measurements were conducted in large leak locations (points 8, 11, 13 on Fig. 2). The discharges measurements were done by collecting water from a leak directly to a bucket with a known volume and measuring the elapsed time. Measurements of total discharge from an adit to Bytomka River were conducted with a sharp-crested weir installed in a ditch at the outlet of the adit. The results of physical and chemical analyses of the groundwater flowing into the adit were obtained in 2013–2018. The analyses were conducted at four measurement points: the "Carnall" shaft, Sienkiewicza Street, the western adit branch, and the adit outlet. In addition, 34 water samples were collected to test leaks within three testing series in 2017–2018. Leak 12 was sampled only once, as it disappeared later. The samples were collected directly from the leaks and stored in 500 cm^3 containers made of polyethylene, without filtration.

Chemical analyses of the water samples collected in the adit were conducted in the accredited Hydrogeochemical Laboratory of the Dept. of Hydrogeology and Engineering Geology of AGH University of Science and Technology in Krakow. Both pH and electrical conductivity were measured using a WTW Multi 3430 m. Several methods were used to test the element concentrations in the water samples. The first was inductively coupled plasma mass spectrometry (ICP-MS)—ELAN 6100 (Perkin Elmer). The equipment used in the laboratory allowed for element concentrations ranging from 0.01 µg/L to 100 g/L. Another method was the inductively coupled plasma—optical emission spectrometry method (ICP-OES)—Plasma 40 (Perkin Elmer).

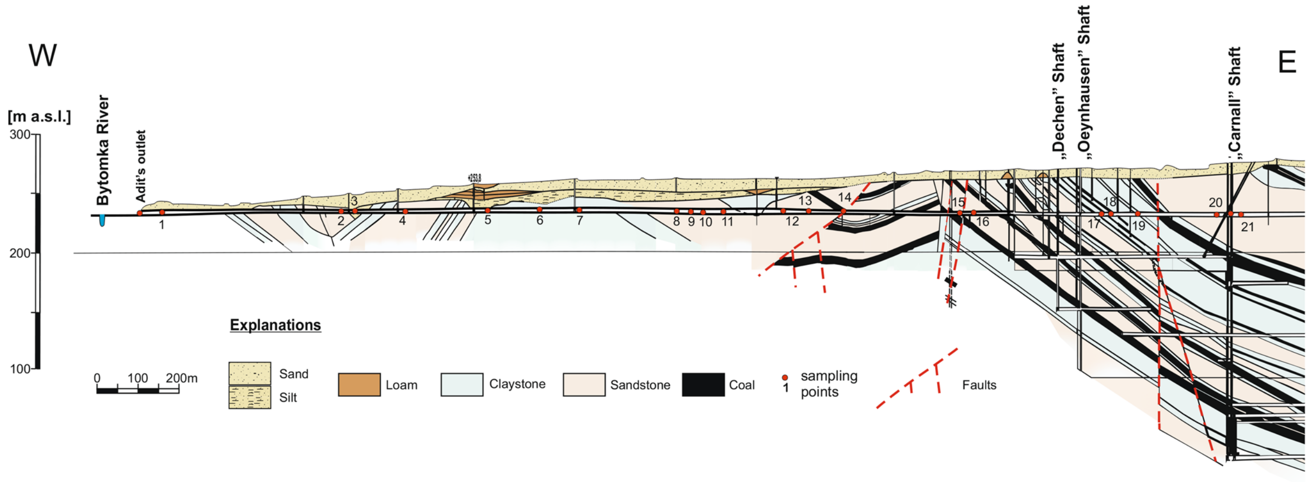


Fig. 2 Geological cross-section of the adit area, with the sample collection sites (sketched after a mid-nineteenth century cross-section by an unknown author)

The spectrophotometer possessed by the laboratory allows for the determination of metals and metalloids ranging from 1 µg/L to 1,000 g/L. The chloride concentrations and alkalinity were determined using the titration method, with the suspensions determined by weight.

Results of Inflow Rate Measurements

The adit water outflows were not measured regularly, although the results clearly indicated outflow reductions from July 2013 to April 2018. In July 2013, the inflow to the adit was estimated at ca. 500 m^3/day, and, according to recent measurements, it has decreased to 170–250 m^3/day, with a minimum inflow at the adit outlet of less than 120 m^3/day (Fig. 3). The inflow rate measurements, conducted in various seasons during 2017, did not vary by more than 15% (Table 1). However, this is a limited data set.

The inflow rate at leak number 19, situated about 190 m west of the "Carnall" shaft, was measured about a dozen times, although irregularly, from 2010 to 2014. The rate ranged from 0.6 to 10 L/min, with an average value of 2.6 L/min (according to data stored in the Coal Mining Museum Archives in Zabrze). Unfortunately, more detailed data are not available.

The calcium ion dominated among cations in almost all of the water samples, except for three in which sodium prevailed. The bicarbonate ion dominated among anions, although chloride and sulfate prevailed in five samples (Fig. 4).

Water collected from leaks at the adit had pHs ranging from 6.7 to 8.5, with an arithmetic mean of 7.5. Electrical conductivity values belonged to a broad range, from 786 to 3,630 µS/cm, with an average value of 1,678 µS/cm. The total dissolved solid content ranged from 640 to 2,670 mg/L. Using the hydro-chemical parameters obtained from all of the tests, four-, five-, and six-ion waters were classified, according to Altowski-Szwiec classification, as follows:

- Ca-HCO_3-SO_4, Ca-HCO_3-Cl, Ca-Mg-HCO_3-SO_4, Ca-Mg-Cl-HCO_3, Ca-HCO_3-Cl-SO_4, Ca-HCO_3-SO_4-Cl,
- Ca-Na-HCO_3-Cl, HCO_3-Cl-Ca-Na, Na-Ca-SO_4-Cl
- Ca-HCO_3-Cl-Na-SO_4, Ca-Mg-HCO_3-Cl-SO_4, Na-Ca-Cl-SO_4-HCO_3, Na-Ca-Cl-HCO_3-SO_4
- Ca-Na-Mg-Cl-HCO_3-SO_4

In one series of samples collected at the adit outlet in 2008 (i.e. before the proper refurbishment works started), there was 690 mg/L of suspended matter, exceeding the legally allowed values (35 mg/L) many times over. High concentrations were also determined in the cases of hydrogen sulfide, sulfides, zinc, and lead, as well as ammonium nitrogen and phosphorus. Since the samples were collected before the adit refurbishment and only at the adit outlet, the results were not included in the figures or Table 2. These results present qualitative information.

Figures 5, 6, and 7 present the changes in the nitrate-nitrogen, chloride, and sulfate concentrations, respectively. Nitrate concentrations in the water may be due the migration of land-surface pollution, similar to changes in the chloride content, which also resulted from anthropogenic activities. However, the process of metal sulfides, particularly pyrite, weathering, may still be active with sulfate washing out of the Carboniferous sediments after about 200 years since the respective section of the adit was excavated. Sulfates and iron, as well as other metal ions in the inflow waters, may originate either from pollution migrating from the land surface or oxidation of metal sulfides dispersed in the Carboniferous sediments, as well as from corrosion of the support systems used in the adit, e.g., anchors.

The Carboniferous sediments, which were cut through by the adit, contain metal sulfides and, in particular, iron sulfides. With that in mind, special attention was paid to the microelements that could be associated with the Carboniferous formations. It was found that the concentrations of certain microelements were relatively high (Table 2). The concentrations had broad ranges, from those typical for groundwater to highly irregular ones, displaying high changeability over time.

Discussion

The average annual precipitation in Zabrze amounted to 641 mm in recent years. The highest values were recorded in July: 93 mm on average, with February being the driest month of the year: 31 mm (https://pl.climate-data.org/location/739/). In recent years, the highest precipitation was recorded in 2010, with the value of 840 mm/year. Figure 8 presents the total monthly precipitation in Zabrze.

During high precipitation periods, the quantity of water infiltrating into the adit should be increasing, but in fact the total inflow into the adit was reduced by more than half in recent years, mainly due to the protection and preservation work completed in the adit. Other reasons for decreasing inflows in recent years was relatively low precipitation, and the replacement and separation of rainwater sewers in Zabrze. Even early in the twenty-first century, water leaking from unsealed sewers flowed into the adit and was channeled to the Bytomka River in an uncontrolled manner.

Table 1 Yields of selected leaks

Location No	Date of measurement	Inflow rate [L/min]
8	03.07.2017	9.0
	11.12.2017	8.1
11	19.06.2017	2.3
	10.11.2017	2.2
13	03.07.2017	3.5
	10.11.2017	2.8

The measurements of ammonium nitrogen and phosphorus in 2008 reflected the effects of the raw sewage. However, inflow from sewers into the adit have been considerably reduced, due to upgrades of the city's sewage systems, although sporadic excess values indicate that some sewage contribute still occur, suggesting possible inflow from rainwater or municipal sewers into the adit. During the renovation works conducted in the adit, the stonework and masonry support sections were reconstructed by replacing lost pieces and improving sealing conditions. Glue and binder injections were applied to the ceiling, along with anchored lining, and that stopped much of the inflow paths into the adit. The presence of many workings and voids around the adit allowed the water to find new flow courses, migrating deeper into the lower workings of the "Bielszowice" coal mine.

After 2013, the effects of the renovation work conducted in the adit were clearly reflected in the measured parameters. Removal of tons of dirt (deposited in the adit as silt and dust materials, as well as coal dust, along with water from behind the leaky support systems) caused a considerable drop in the suspended material. However, although the

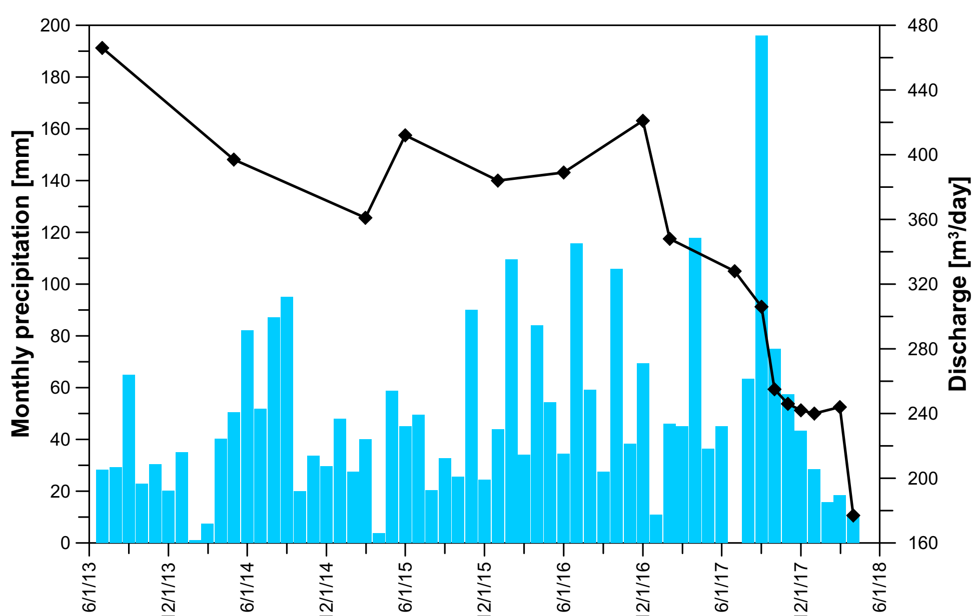


Fig. 3 Changes in volume of the water pumped at the Adit's outlet, and precipitation in the area over time

concentrations of zinc and lead dropped below the allowed values, and concentrations of phosphorus and nitrogen were much lower than those measured five years earlier, total suspended values still exceeded the allowed values. The sample tests of 2014 indicated a further drop in such anthropogenic pollution, such that the allowed values were exceeded only in two out of four samples.

The chemical composition of the adit water from the Quaternary and Carboniferous formations is influenced by both natural and anthropogenic factors. The primary natural factors are the mineral composition of the strata and the water's residence time in the rock mass. The anthropogenic factors were divided by Motyka and Witkowski (2002) into internal and external ones. The internal factors are associated with natural geochemical processes initiated by human activities, which includes the natural chemical weathering of metal sulfides initiated by mine drainage, and related changes in the redox conditions in the rock mass. The external factors include the influence of various anthropogenic pollution sites on the land surface.

Internal pollution sites develop due to dewatering of the rock mass and changes of the original redox conditions, from close to reducing to oxidizing ones. That process is primarily associated with deep and long-term dehydration conducted in mining operations and metal sulfide weathering (acid mine drainage). With the participation of bacteria, bivalent iron is oxidized to trivalent iron, thereby catalyzing increased pyrite oxidation. In the presence of sulfate ion (SO_4^{2-}), calcium sulfate (gypsum or anhydrite) can precipitate, though its solubility is much greater than that of calcium carbonates, causing an increase in dissolved calcium and sulfate concentrations. The relevant reaction is:

$$CaCO_3 + H^+ + SO_4^{2-} \rightarrow CaSO_4 + HCO_3^- \quad (1)$$

Industrial and infrastructural facilities situated above the adit are external pollution sites. A heat and power plant, with its ash and slag heaps, is located next to the "Carnall" shaft. Temporary coal and ash storage yards do not have paved substrates to prevent the penetration of washed pollutants into the ground. In addition, one of the main streets of Zabrze runs above the adit and along that street, a number of businesses are located, e.g. a metalworking plant, a brewery, local boiler houses, four petrol stations, dozens of car parks, a railway and coach station, and many service outlets. However, the development of that area after the economic transformation of Poland in the 1990s changed considerably. Some of these potential anthropogenic pollution sources do not exist today. Others changed their production or service profiles, and new businesses either replaced old ones or were built on undeveloped or green lands.

When interpreting the results of chemical analyses based on Figs. 7, 8, and 9, and Table 2, one notices a lack of regularity in the changes of NO_3, Cl, and SO_4 values over

Fig. 4 Piper diagram for samples collected from leaks in the Adit

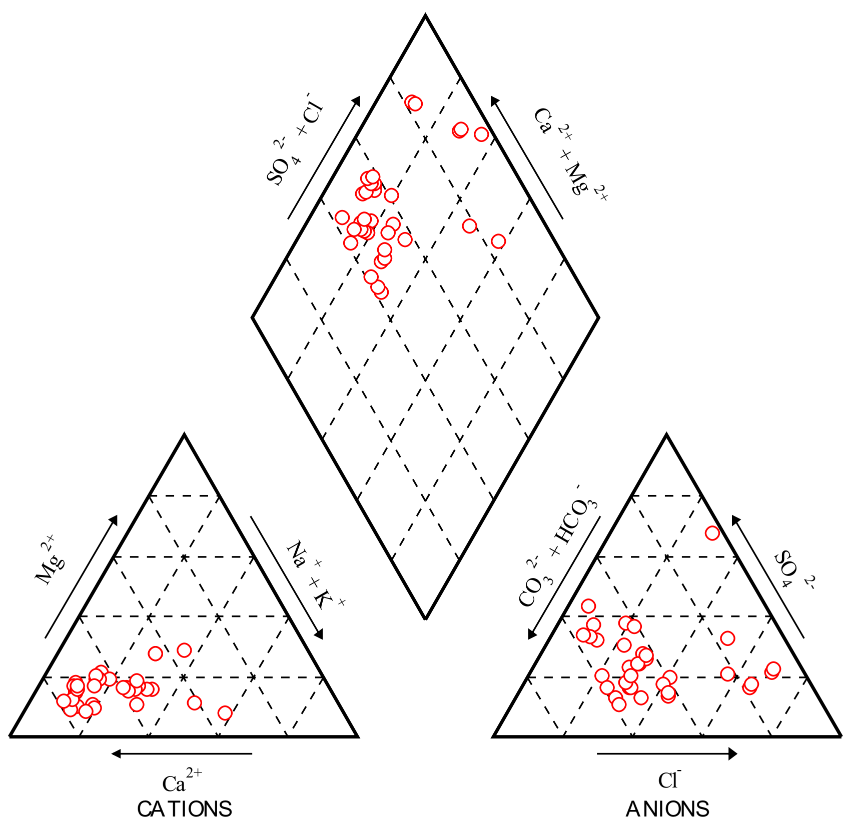


Table 2 Summary chemical compositions of water from leaks in the Adit Concentrations in [mg/L]

Parameter	Min	Max	Average	Median	Parameter	Min	Max	Average	Median
TDS	640	2670	1315	1136	Mn	0.0006	2.57	0.565	0.239
Ca	14.0	468	188	186	Mo	< 0.01	0.017	0.0048	0.0021
Mg	0.78	114	35	26.5	Ni	< 0.05	0.180	0.022	0.006
Na	20.5	276	83.2	63.6	Li	0.0019	0.097	0.027	0.024
K	0.36	69.6	11.8	6.7	Pb	< 0.0001	0.494	0.0219	0.0002
HCO_3	3.07	625	406	429	Rb	0.0004	0.258	0.0173	0.0062
SO_4	20	1103	314	215	Sb	< 0.0001	0.0137	0.0015	0.0002
Cl	2.5	898	185	162	Se	< 0.001	0.797	0.169	0.0054
Ag	< 0.01	0.033	0.0066	0.0027	Sn	< 0.001	0.0722	0.028	0.0303
Al	< 0.001	3.09	0.17	0.005	Sr	0.133	0.712	0.357	0.339
As	< 0.001	0.039	0.007	0.002	Te	< 0.0001	0.0369	0.0081	0.0003
B	< 0.001	0.731	0.113	0.084	Ti	< 0.001	0.0413	0.0113	0.0088
Ba	< 0.001	0.105	0.042	0.036	Tl	< 0.0001	0.02	0.0016	0.0002
Bi	< 0.001	0.39	0.029	0.0012	U	< 0.0001	0.0068	0.008	0.0028
Br	< 0.01	0.89	0.106	0.076	V	0.0007	0.062	0.0248	0.0204
Cd	< 0.01	0.0045	0.0004	0.0001	W	< 0.0001	0.0255	0.0039	0.0008
Co	< 0.0001	0.067	0.0029	0.0005	Zn	0.005	2.5	0.215	0.0674
Cr	< 0.01	0.0657	0.0095	0.004	SiO_2	5.69	26.9	13.4	12.8
Cs	< 0.0001	0.181	0.019	0.0004	NO_3	0.60	151	20.6	11.1
Cu	< 0.001	0.233	0.016	0.0016	NH_4	0.06	6.30	0.84	0.29
Fe	< 0.01	64.4	4.34	0.16	NO_2	0.01	1.2	0.19	0.08
Ga	0.0002	0.02	0.0034	0.0009	PO_4	0.006	3.91	0.344	0.157
Hg	< 0.0001	0.1	0.004	0.00004					

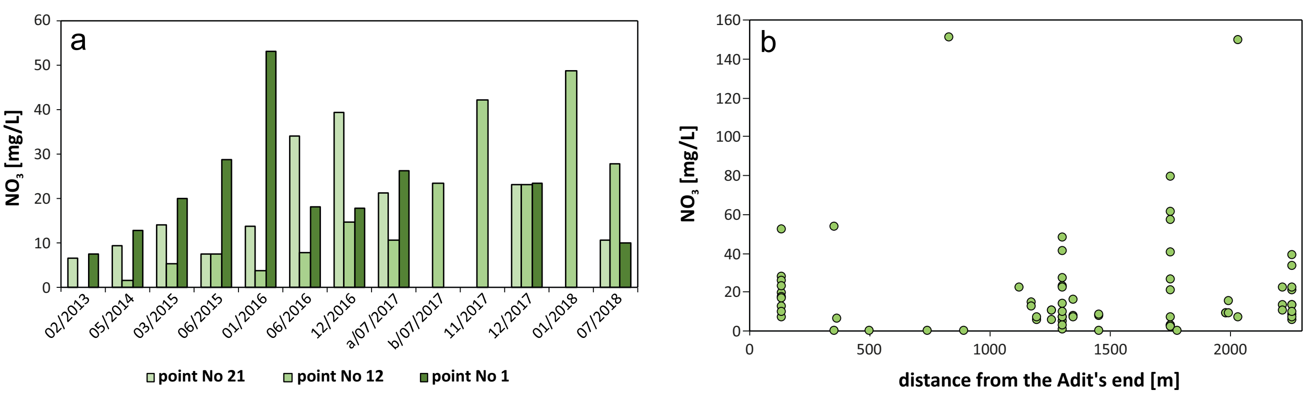


Fig. 5 Changes in the nitrate nitrogen contents **a** In time, at three measurement points in the Adit. **b** at all the measurement points, depending on the distance from the Adit's outlet.

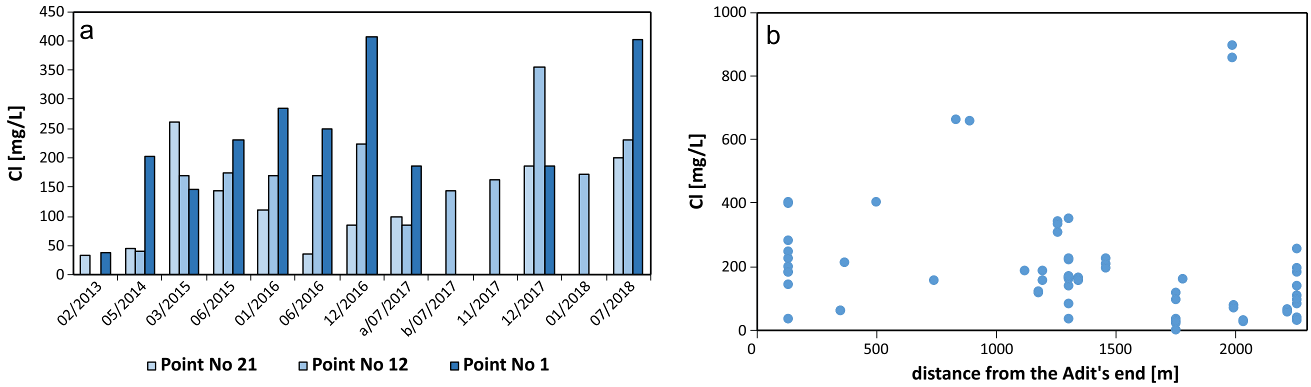


Fig. 6 Changes in the chloride contents. **a** In time, at three measurement points in the Adit. **b** At all the measurement points, depending on the distance from the Adit's outlet.

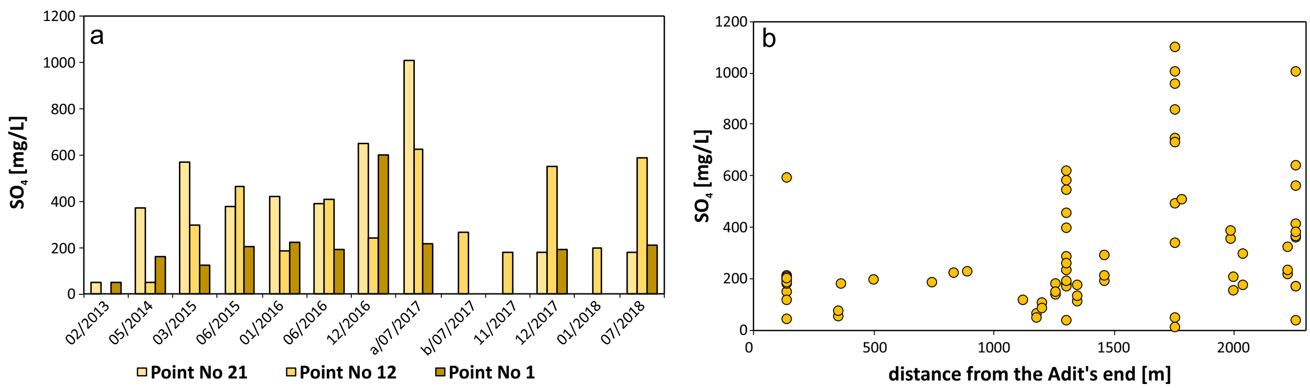
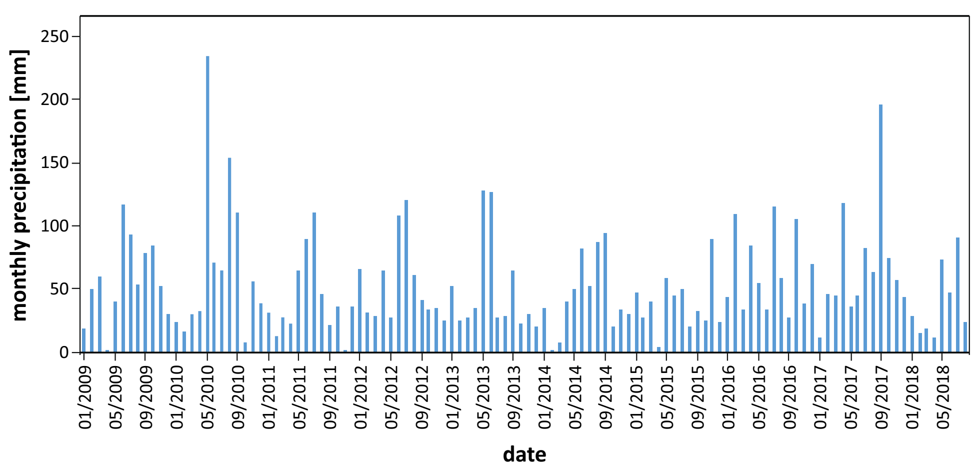


Fig. 7 Changes in the sulphate contents. **a** In time, at three measurement points in the Adit. **b** At all the measurement points, depending on the distance from the Adit's outlet.

Fig. 8 Total monthly precipitation in Zabrze



time and with respect to the distance from the adit outlet. One can only identify the increasing trend of chloride ion concentration close to the "Carnall" shaft since mid-2016 and the same about the sulfate content at the western adit branching until mid-2017. As to the remaining major ions and microelements, no correlations were found. Such test results do not allow a clear answer to the question of whether the relevant increased concentrations correspond to natural or anthropogenic pollution. For example, the increased sulfate concentrations found near the "Carnall" shaft may be associated either with sulfide weathering that has continued in coal seams and surrounding rocks for 200 years or with the migration of contaminants from coal and ash heaps located at the heat and power plant.

The anthropogenic nature of the increased Na and Cl contents is indicated by the hydrogeochemical coefficients presented in Figs. 9 and 10. The changing chloride contents is likely associated with winter road and car park maintenance and various times of water inflows from the land surface to the adit, and it is not possible to exclude other contamination sites, such as metal works, railway tracks, or service outlets. Increased chloride and sodium ion concentrations may also originate from leaky sewers.

The increased values of nitrogen and phosphorus compounds concentrations can be due to either leaky rainwater and wastewater sewers or regular leaching by infiltrating precipitation of compounds that accumulated in the soil from before the construction of the sewage systems. Also, one cannot exclude that the increased nitrogen and phosphorus compounds concentrations originate from not-yet-upgraded sewage system sections or sewer failures that occur in areas with a risk of subsidence from earlier and/or still active mining.

The complexity of geogenic and anthropogenic factors causes the diverse chemical composition of waters in the adit. It is very difficult to establish the proportions of such factors due to the fluctuations of the hydrodynamic field and the high diversity of the geochemical field in the aeration zone above the adit. The instability of the hydrodynamic field is associated with the changing intensity of the infiltration of meteoric waters, depending on precipitation and its intensity over time. Water flow direction follows the dip of the beds; however, the infiltration water flow direction may locally depend on the hydraulic network configuration (cracks and interbed joints) and the hydrogeological properties of beds.

Conclusions

The water originating from precipitation infiltrating the adit is the main source of inflow to the Main Key Heritage Adit. The adit serves as a local water drainage basin in that area, and the rock mass above the adit is situated in the aeration zone. As to the other types of waters, the active "Bielszowice" coal mine workings constitute the drainage basins. Precipitation infiltrates the adit workings through Quaternary and Carboniferous sediments. Boreholes and old small, buried shafts have become primary paths for infiltrating waters. Land management and development affect inflow to the adit, as does land surface permeability (infiltration coefficient) and the geological and hydrogeological conditions. The last includes the influence of the workings situated above the adit, post-mining cracks and fractures in the rock mass, and discontinuous tectonic formations, as well as the Quaternary lenses of poorly permeable sediments. There is also the possibility of additional, accidental inflow coming from leaking water mains and/or sewers.

It is not possible to clearly determine the cause of the increased macro- and microelement concentrations in the adit leaks with respect to natural and anthropogenic sources of water pollution. Although some pollution is clearly associated with land use and land development, that does not explain all the pollution, which may be due to previous land use.

The hydrogeological role of the adit presented in this article and the possibilities of its multifunctional use may

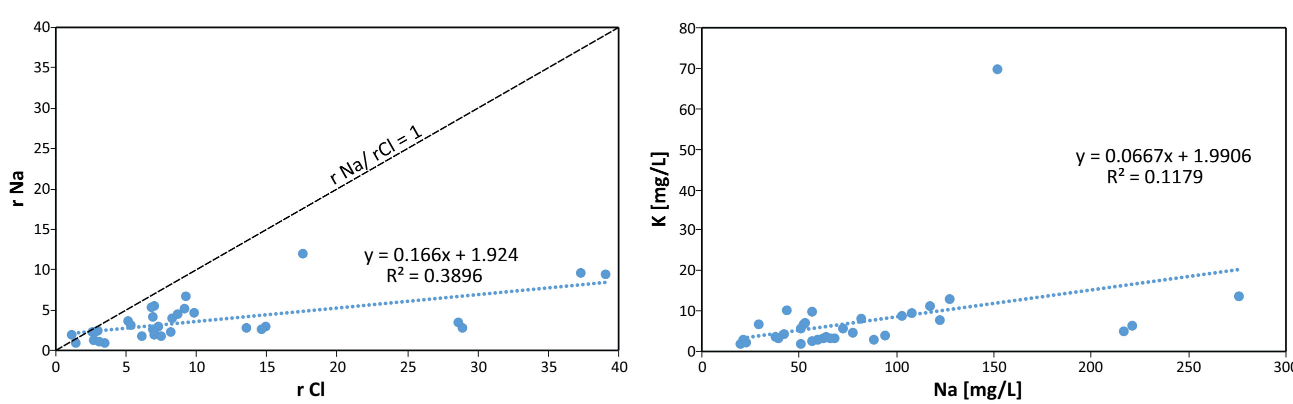


Fig. 9 Hydrogeochemical coefficients rNa/rCl and K/Na

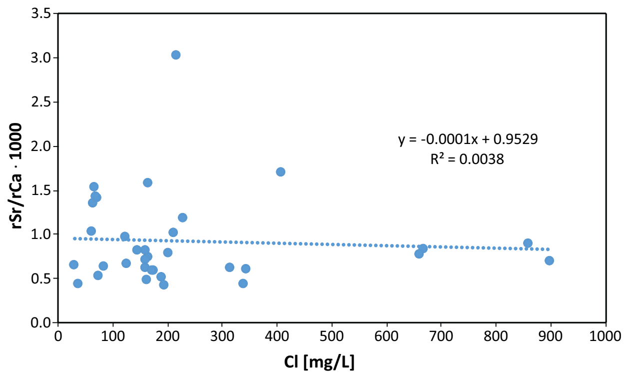


Fig. 10 Relation of rSr/rCa × 1,000 coefficient to chloride content

constitute an example of good practices that can be used during mine closures elsewhere in the world.

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References

Bugaj T, Glosz M (2012) Main Key Heritage Adit as a European centre of technical culture and industrial tourism in Zabrze. Min Tunn Constr 1:50–62 **[in Polish]**

Cempiel E, Czajkowska A, Nowińska K, Pozzi M (2014) Symptoms of anthropopression in the catchment area of the Bytomka River. P.A. NOVA, Gliwice, Poland **[in Polish]**

Duży S, Dyduch G, Preidl W, Stacha G (2017) Drainage adits in upper Silesia—industrial technology heritage and important elements of the hydrotechnical infrastructure. Stud Geotech Mech 39(4):25–34. https://doi.org/10.1515/sgem-2017-0034

Kedzior A (2008) Depositional architecture of the Zabrze Beds (Namurian B) within the main anticline of the Upper Silesia Coal Basin, Poland. Stud Geol Pol 129: 131–156. http://sgp.ing.pan.pl/129_pdf/SGP129_131-156.pdf

Motyka J, Witkowski AJ (2002) Groundwater contamination in the area of Zn-Pb ore mines situated in the southern part of the Olkusz-Zawiercie Triassic aquifer (Poland). In: Merkel BJ, Planer-Friedrich B, Wolkersdorfer C (eds) Uranium in the aquatic environment. Springer, Berlin, pp 1029–1036. https://doi.org/10.1007/978-3-642-55668-5_121

Pluta I (2005) Waters of Mines in the Upper Silesian Coal Basin - Genesis, Pollution and Treatment Methods. Scientific works of the Central Mining Institute 865 **[in Polish]**

Preidl W (2006) Assessment of the technical condition of the support of the Main Key Hereditary Adit in the Zabrze section. Min Geoeng 4:97–102 **[in Polish]**

Rogoż M (1996) The influence of flooding up of coal mines upon water environment. Arch Min Sci 41:105–130 **[in Polish]**

Rogoż M, Posyłek E (2000) Hydrogeological problems in Polish hard coal mines. Central Mining Institute, Katowice, Poland **[in Polish]**

Różkowski A (1997) Impact of coal mining on quality and quantity of fresh groundwater in the Upper Silesian Coal Basin (Poland). In: Proceeding of 6th IMWA Congress, vol 1, pp 98–103

https://pl.climate-data.org/location/739/. Accessed 23 Mar 2020

Wilk Z (2003) Hydrogeology of polish mineral deposits and water problems in mining, vol 1. AGH Univ of Science and Technology Publications, Kraków **[in Polish]**

Wiśniewski L (2009) The Main Key Heritage Adit as a technical monument, included in the European cultural heritage. In: Zagożdżon PP, Madziarz M (eds) The history of mining—a part of European cultural heritage, vol 2, pp 311–325 **[in Polish]**