The Colourful Lakes in Wieściszowice, Sudetes Mountains, Poland – An example of Chemical Variation in Abandoned Pyrite Mine Pit Lakes

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Extended Abstract

Abandoned flooded mines, especially pit lakes, are places where various geochemical processes affecting water quality and the environment can be studied (Chudy *et al.* 2021). Understanding the water chemistry and processes in post-mining lakes is crucial, especially for those that became popular tourist and recreational attractions. Details about the complexity of post-mining lakes have been given by various researchers in four comprehensive monographs over the last two decades, providing an overview of former metal, lignite and hard coal open-cast mines affected by acid mine drainage. Abandoned open pit mines, which eventually form pit lakes, are common wherever easily accessible, shallow mineral deposits are found. The best-explored open pit lakes are in Germany, Australia, Spain, Portugal, the USA, Canada, and Poland. Yet, the Colourful Lakes (Fig. 1), one of the most popular touristic sites in southwest Poland, are a stimulating site for hydrogeological and isotopic investigations because of their differences from the Iberian pyrite belt pit lakes. While the former are relatively small with acid to circumneutral pH-values, the latter are much larger with commonly low pH-values and a high acidity. This study aims to understand temporal and spatial changes in the chemistry (major and trace elements) and stable isotope composition of shallow pit lakes, exemplified by the Wieściszowice Colourful Lakes. None of the previous studies on the Colourful Lakes have investigated the possible lake stratification and the chemical mechanisms occurring in different seasons. Therefore, this study fills the knowledge gap of long abandoned (almost 100 years) shallow and unremediated metal mining lakes.

The Colourful Lakes near the village of Wieściszowice, Poland, refer to four abandoned mining lakes, commonly called Yellow, Purple, Blue, and Green Lakes, created after mining and sulfuric acid production ceased in 1925. This area was shaped by historic surface and underground mining of mineral resources from the late 18th to the early 20th century. Nowadays, the higher parts of the Wielka Kopa hill (Blue Lake location) are covered with pine-spruce forests, while deciduous trees dominate the lower parts (Purple and Yellow Lakes locations) with a high proportion of birch. Only after intense rainfall the Green Lake appears, and as it was dry at the time of sampling, it was not investigated during this study. The Blue Lake

***Figure 1** Images showing three of the Colourful lakes near Wieściszowice, Poland. From left to right: Blue, Purple, and Yellow Lakes (from Chudy* et al. *2021).*

is 150 m long, 30–50 m wide, and 7–8 m deep, while the Purple Lake has dimensions of about 430 × 110 m, a very variable shoreline, and depth mainly dependent on rainfall. About 20 years ago, the Yellow Lake formed between the mined dumps, disappearing in dry years with low rainfall. Geological research has been carried out in Wieściszowice, with the first scientific activities mainly related to mineral exploitation dating back to the 18th century, when pyrite deposits were discovered. Subsequent geological research was related to the attempt to resume sulfide mining after the World Wars, but exploitation was eventually abandoned.

Blue Lake, Purple Lake, and Yellow Lake are located around mine tailings and are characterised by different chemical compositions, pH values and electrical conductivities (Table 1, Fig. 2). In addition to chemical analysis, the lake's water chemistry results were analysed using hierarchical cluster and principal component analysis. As shown, each lake falls into its own cluster, indicating that the individual chemistry of the three lakes was statistically significantly different and could be discussed individually. Of all the lakes, the Blue Lake was found to have the highest pH, the lowest TDS and the lowest concentration of trace elements. Purple and Yellow Lakes were found to be in the Fe-buffer range and had higher electrical conductivities attributed to the influence of pyrite weathering and efflorescent minerals from the waste rock. Finally, the results highlight that, in addition to rainfall, the Blue Lake is fed by the intermittent Rdzawy Potok stream. In contrast, the Purple and Yellow Lakes are predominantly fed by groundwater.

The isotopic composition of the lakes was investigated to determine the sulfate source in the water. Results from the Blue Lake show seasonal variations in sulfate concentrations and $\delta^{34}S(SO_4^{2-})$ and $\delta^{18}O(SO_4^{2-})$, with the

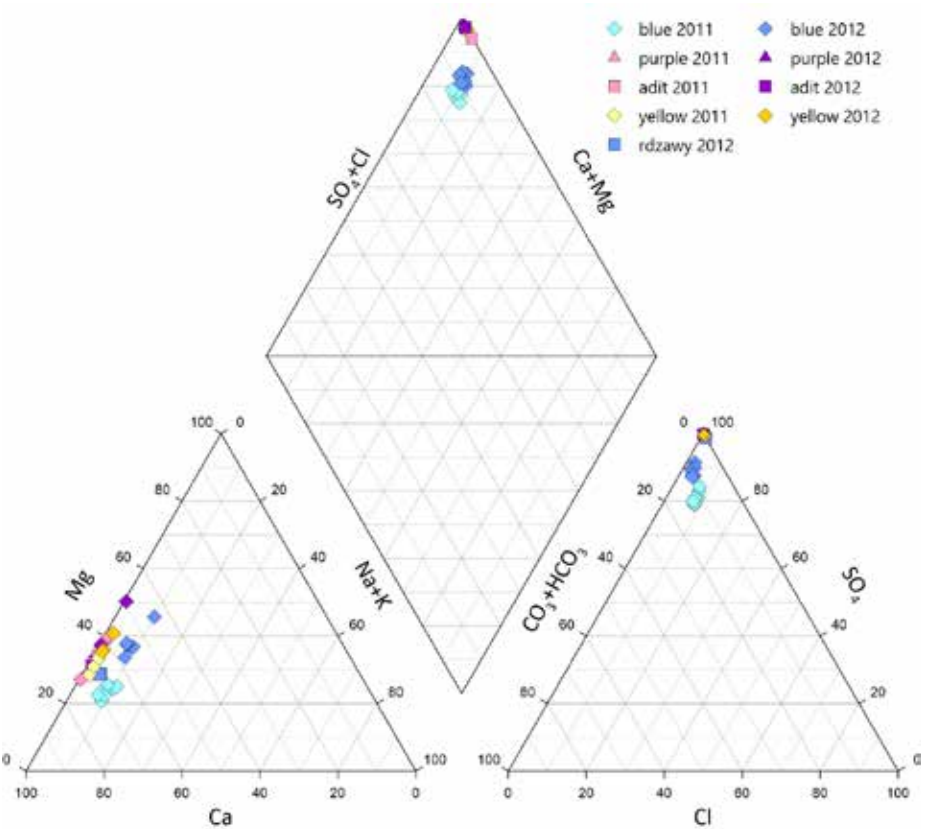

__Figure 2__ Piper diagram of the Wieściszowice Colorful Lakes water samples (from Chudy et al. *2021).*

***Table 1** Summarized results of the chemical and physicochemical parameters of the two sampling campaigns in the Colourful Lakes. TDS: total dissolved solids, EC: electrical conductivity, b.d.l.: below detection limit, –: not analyzed, IB error: PHREEQC ion balance error (from Chudy* et al. *2021).*

	Blue Lake, *n* = 15				Purple Lake, *n* = 6				Yellow Lake, *n* = 6			
	min.	max.	$\bar{x}$	σ	min.	max.	$\bar{x}$	σ	min.	max.	$\bar{x}$	σ
T, °C	11.2	20.4	16.7	2.7	15.7	22.3	18.3	2.7	13.7	19.4	16.4	2.5
pH, –	4.85	5.74	5.14	0.24	2.37	2.88	2.62	0.26	2.25	2.90	2.61	0.31
Eh, mV	479	532	503	20	659	785	717	47	732	792	759	23
pE, –	8.48	9.42	8.91	0.37	11.65	13.88	12.68	0.84	12.94	14.02	13.45	0.41
EC, µS/cm	160	188	180	7	2470	3950	3130	648	1540	1956	1678	161
TDS, mg/L	80	144	114	22	2500	4776	3313	839	1236	1624	1360	141
Cl-, mg/L	1.54	5.13	3.51	1.55	0.64	2.57	1.43	0.79	1.35	4.54	2.64	1.28
HCO3-, mg/L	7.93	14.03	10.82	2.02	–	–	–	–	–	–	–	–
SO42-, mg/L	62.9	88.8	74.1	6.9	1268	3108	1930	650.1	618.8	837.6	716.1	86.1
NO3-, mg/L	0.05	4.21	1.10	1.19	7.68	20.79	13.68	4.46	4.14	8.97	5.90	2.05
PO43-, mg/L	b.d.l.	0.30	0.08	0.10	0.01	0.45	0.13	0.17	0.01	0.11	0.06	0.05
NH4+, mg/L	b.d.l.	0.41	0.13	0.15	0.08	1.09	0.54	0.42	b.d.l.	1.31	0.57	0.59
Na+, mg/L	2.29	3.61	2.98	0.41	2.73	4.77	3.53	0.81	3.24	4.14	3.60	0.37
K+, mg/L	0.07	0.25	0.14	0.06	0.04	0.16	0.11	0.05	0.15	0.40	0.26	0.11
Mg2+, mg/L	4.18	6.98	5.66	1.10	67.9	138.2	103.5	29.7	32.62	38.50	35.24	2.12
Ca2+, mg/L	11.32	25.99	19.80	4.11	179.9	619.5	303.7	161.7	86.25	137.74	112.28	19.88
Mn2+, mg/L	0.12	0.21	0.17	0.03	1.62	3.31	2.43	0.71	0.39	0.68	0.48	0.11
Fetot, mg/L	0.06	0.21	0.13	0.06	25.38	109.34	68.82	38.19	12.16	71.74	39.76	29.12
SiO2, mg/L	31.92	36.41	34.82	1.46	86.38	154.73	119.89	26.62	33.27	73.12	54.04	14.59
Al, mg/L	0.40	5.49	2.15	1.73	34.66	84.28	57.42	20.98	10.17	22.80	15.07	4.88
Ag, µg/L	0.01	2.80	0.69	1.09	0.04	2.19	0.55	0.85	0.06	4.60	1.76	2.08
As, µg/L	b.d.l.	2.13	1.10	0.73	37.03	84.83	68.76	20.52	1.61	11.50	7.86	3.81
Ba, µg/L	2.70	10.53	7.15	2.81	6.05	8.77	7.37	1.11	b.d.l.	7.77	4.02	3.28
Cd, µg/L	0.02	0.26	0.14	0.10	0.39	3.81	2.12	1.52	0.13	1.52	0.84	0.46
Co, µg/L	26.17	39.05	33.68	3.48	115.2	1072.0	518.9	384.0	345.7	420.8	370.7	27.4
Cr, µg/L	b.d.l.	0.67	0.20	0.23	49.33	125.04	89.44	32.49	19.80	27.77	23.47	2.79
Cu, µg/L	2.26	3.72	2.96	0.42	24.45	471.35	202.40	194.01	6.97	49.04	27.43	21.15
Mo, µg/L	b.d.l.	2.70	0.68	0.96	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	5.13	1.49	2.46
Ni, µg/L	1.82	35.25	11.39	11.25	47.27	327.11	182.60	116.75	26.54	159.37	65.84	53.31
Pb, µg/L	b.d.l.	13.08	4.99	4.79	b.d.l.	4.81	2.09	2.07	b.d.l.	7.89	3.40	3.58
Sn, µg/L	b.d.l.	0.03	0.01	0.01	b.d.l.	0.04	0.02	0.02	b.d.l.	0.06	0.02	0.03
Sr, µg/L	2.56	3.82	3.13	0.47	30.09	44.03	37.45	5.41	16.98	21.99	19.94	1.77
Ti, µg/L	b.d.l.	12.83	4.00	4.81	b.d.l.	19.34	9.50	9.67	11.70	20.82	17.20	4.84
Zn, µg/L	7.47	29.10	11.99	7.13	80.84	839.10	356.19	290.38	22.70	159.80	65.46	52.41
IB error, %	-13.01	3.05	-2.59	4.08	-17.04	7.24	-5.47	10.5	-15.06	25.05	4.79	18.18

main source of sulfate being surface runoff containing sulfate and oxidised organic sulfur (Fig. 3). There was no evidence of sulfate from direct oxidation of pyrite, which would have negative $\delta^{34}S(SO_4^{2-})$ values ranging from about –4.5‰ to about –3.5‰. Consequently, the sulfate in the lake is thought to be derived from leaching of efflorescent salts in the adjacent tailings surrounding this water body. In contrast, the Purple Lake has high sulfate concentrations, with both sulfate concentrations and $\delta^{34}S(SO_4^{2-})$ and $\delta^{18}O(SO_4^{2-})$ showing seasonal variations. As the correlations between sulfate concentrations, $\delta^{34}S(SO_4^{2-})$ and $\delta^{18}O(SO_4^{2-})$, are statistically significant, a common source can be expected. Furthermore, the study found that the sulfate source is related to anthropogenic activities, such as the mining and ore processing. The isotopic composition of oxygen and hydrogen results in the lakes show small variations in September 2011. Greater variations were found in June 2012, but there was no relationship between depth and $\delta^2H(H_2O)$ or $\delta^{18}O(H_2O)$, indicating good mixing processes.

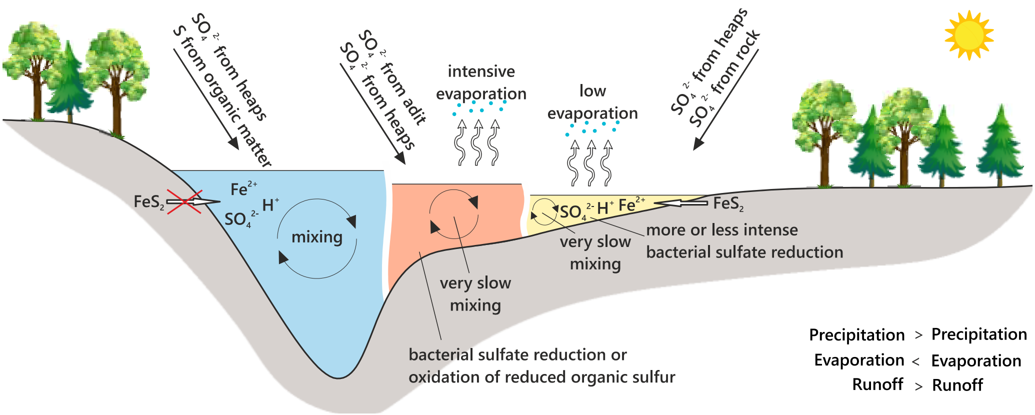

***Figure 3** Graphical abstract that shows the processes that take place around the Colourful Lakes (from Chudy* et al. *2021).*

Based on the PHREEQC results, the dominant phases controlling the chemistry of the in Blue Lake were identified as $Al(OH)_3(a)$, barite and $Fe(OH)_3(a)$, while in the Purple and Yellow Lakes the dominant phases were anhydrite, gypsum and chalcedony (though rather amorphous SiO_2 would be expected). Distinctively, the distribution of species and saturation indices in the three lakes showed a pattern that differentiated them. While the Blue Lake showed a slight stratification with a tendency to lower saturation indices with increasing depth, indicating possible evaporation, the Yellow and Purple Lakes were buffered, indicating precipitation and mixing reactions. PHREEQC speciation results showed that SO_4^{2+} dominated all three lakes and inflows, followed by Ca^{2+}, with the inflow to Blue Lake having the same species distribution as the Blue Lake itself. Predominance diagrams (Eh-pH) supported the results of the chemical thermodynamic PHREEQC calculations and were used to understand the dominant species and potential reactions in the system.

This study investigated the processes controlling the chemical composition of shallow post-mining lakes, namely the Blue, Purple, and Yellow Lakes, in the Wieściszowice region of southwestern Poland. As the results show, each of the three lakes should be separately considered since there is a noticeable difference in their chemical composition due to different natural and anthropogenic factors affecting their geochemical conditions. While the general processes of inflowing water flowing through weathered mining residues and leaching efflorescent salts from pyrite and rock weathering are similar around all three lakes, the differences result from diverse factors affecting each lake. Blue Lake, for example, is mainly recharged by the Rdzawy Potok River throughout the year and periodically by precipitation. On the other hand, Purple Lake most of the year is fed by the Neues-Glück-adit, which drains the eastern part of the hills, and the rainfall. The study shows that evaporation is a major contributor to the chemical composition of Purple Lake, resulting in a slow flow towards the bottom where a twofold increase in mineralisation and SO_4^{2-} is recorded with very high Fetot concentrations. Furthermore, this study also included the first-time isotopic sampling of the lakes in determining the spatiotemporal variability of water chemistry and isotopic composition. In the overall context, this study highlights the importance of considering the natural and anthropogenic factors that influence the geochemical conditions of any lake to understand its chemical composition fully.

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Remarks

This text is an extended abstract of a paper written by the authors using tables and figures used therein. Details can be found in the below mentioned publication.

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