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ORIGINAL PAPER

Chemical water parameters of end pit lakes in abandoned coal mines

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Abstract

Open-pit mines have significant adverse water quality impacts and end pit lakes formed from abandoned open-pit coal mines have commonly environmental problems. Determining and monitoring of the chemical water characteristics of end pit lakes are very important and play a key role in understanding the anthropogenic impact. The purpose of this study was to determine the amount of different macro-elements (potassium (K), calcium (Ca), sodium (Na), magnesium (Mg), phosphorus (P)), heavy metals (iron (Fe), aluminum (Al), manganese (Mn), nickel (Ni), copper (Cu), zinc (Zn)), and different water parameters (acidity (pH), electrical conductivity (EC), temperature (°C), and dissolved oxygen (O_2)) in 11 end pit lakes formed after coal mining operations in Agacli-Istanbul, Turkey. All investigated characteristics in lake waters showed significant differences in temporal and between lakes. When the relationships between element concentrations and other parameters (pH, EC, °C, and O_2) were examined, pH emerged as the most effective factor has a wide range, and has a negative correlation with P, Ca, Mg, Fe, Al, Cu, Ni, Zn, and Mn. The EC in the lake waters was positively correlated with the changes of Ca, Mg, K, and P, while it showed a negative correlation with Na concentration. Besides, dissolved O_2 content was positively related to Fe and Cu and negatively related to water temperature change. Results showed that monitoring the water characteristics of end pit lakes is essential indicating the major concern with water pH. The results on water parameters may be a valuable basis for the preparation of management plans of the post-mining landscape.

Keywords Lake acidity · Coal mine · Dissolved oxygen · Electrical conductivity · Trace elements

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Introduction

Mines are undoubtedly needed to maintain and develop the level of civilization (Topay et al. 2007). Eighty-two percent of the world's fossil fuels are coal, 15% are petroleum, and 3% are natural gas (Akpınar et al. 1993). Therefore, mining, which is an important sector of the economy, covers all activities that provide the basic raw materials of energy and industry required for the socio-economic development of nations (Baykan 2004). If the mines are close to the surface and the layers on the mines provide the appropriate conditions, the production is done in the form of surface mining. Ninety percent of lignite production in Turkey is realized by open-pit mining (Kural 1998).

Open-pit mining usually concludes with deep excavations and causes significant damage to groundwater and other water resources (Unsal and Yazicigil 2016). Groundwater, direct precipitation, and runoff water fill large pits in mine excavation sites after mining, and they create bodies of water known as end pit lakes (Blanchette and Lund 2016). Factors such as the hydrogeology of the area around the pit, interactions with the groundwater regime, many physical influences controlling the hydrodynamic structure of the lake, the shape of the lake, and the climatic characteristics all affect the process of the filling of the pit lake and the steady state of the water (Huber et al. 2008). Under natural conditions, the filling of water in lakes can take decades or even centuries for large lakes. Pit shape, inflow-outflow of groundwater, direct precipitation, pit wall runoff, and evaporation are the most important factors that directly affect the amount of water and filling (Unsal and Yazicigil 2016). The extent of the adverse effects of open-pit mines depends on the geological structure, hydrological characteristics, area and depth of the open pit, soil properties, vegetation, and climatic conditions (Göktürk 2010).

In addition, end pit lakes can pose potential risks to the environment (Castendyk et al. 2015; Mhlongo et al. 2018; Paraguassú et al. 2019). On the other hand, they can offer some benefits if they are properly managed; thus, Marszelewski et al. (2017) and Santofimia et al. (2013) emphasized that end pit lakes can be used for many different purposes. Examples of useful purposes include recreation, industrial water use, aquaculture, drinking water supply, research, and education (Vandenberg and Litke 2018). However, water quality, morphology, receiving environment, and other characteristics are effective on the utilization possibilities of end pit lakes (Vandenberg and Litke 2018). Chemicals in water bodies can give adverse environmental effects to aquatic ecosystems and are among the substantial threats of environmental health. For example, pollutants along with heavy metals may cause abnormal changes in chemical water characteristics (acidity, salinity, alkalinity, etc.) (Nasiri et al. 2018). Also, higher amounts of macro-elements in water give negative effects (Nkansah et al. 2019); for this reason, removal of these chemicals from aquatic bodies can be needed (Jawaduddin et al. 2019).

The quality of water in pit lakes is difficult to predict and depends on many factors, including groundwater quality and the geological structure of the area (Marszelewski et al. 2017). Water flowing through coal mine waste rock becomes enriched in metallic and non-metallic elements, is high in water hardness, and, depending on the underlying geology, can be very acidic or alkaline (Gammons et al. 2009; Miller et al. 2013). In addition, there are many studies in the literature aimed at understanding the geochemical processes in lakes formed in open-pit mines (Luek and Rasmussen 2017; Şanlıyüksel and Yücel 2017; Vandenberg and Litke 2018).

The present study was conducted in Agacli coal mine region, an important and old coal mine near Istanbul. Coal was found in the Agacli region before 1908 because a topographic map of the area in 1908 shows the locations of coal mines (Tokgöz 2010). Mining activities began in 1914 taking place intensively between 1975 and 1995 and then sharply decreasing (from six million m^3 to one million m^3); and mining activities were abandoned to a large extent in the late 1990s (Kul et al. 2017). After the mining operation ended and the mine site was abandoned, there was not any process undertaken for the formation of mine lakes (Kul et al. 2017). The end pit mine lakes formed spontaneously by water filling the remaining large pits without any human interventions (Kul et al. 2017) despite a forestation program was started on the mine spoils in 1988 (Kantarci 1989), and landslides (Tokgöz 2010) and gully erosions (Kantarcı and Öztürk 2003; Öztürk 2002) were reported. Therefore, it was important and essential to know the water chemistry of the lakes. The present study was aimed to determine the quantity of elements (K, Ca, Na, Mg, P, Fe, Al, Mn, Ni, Cu, Zn) and the correlation of the investigated elements with water acidity, electrical conductivity, water temperature, and dissolved O_2 parameters in 11 end pit lakes in Agacli coal mine region, Istanbul, Turkey. All investigated water characteristics were sampled four times in 1 year and compared among lakes and temporarily.

Material and methods

Study site

Agacli coal mine area is generally located between the northern latitudes (41° 13′ 53″–41° 15′ 29″) and the eastern longitudes (28° 55′ 00″–28° 57′ 28″). The study area consists of 11 end pit lakes of different sizes and depths filled by runoff streams, groundwater, and rainwater after mining activities (Fig. 1). Physical properties of the lakes are given in Table 1. The study area has a Black Sea climate with an average rainfall of 836 mm between 2000 and 2016 and an average annual temperature of 14.7 °C (MGM 2016).

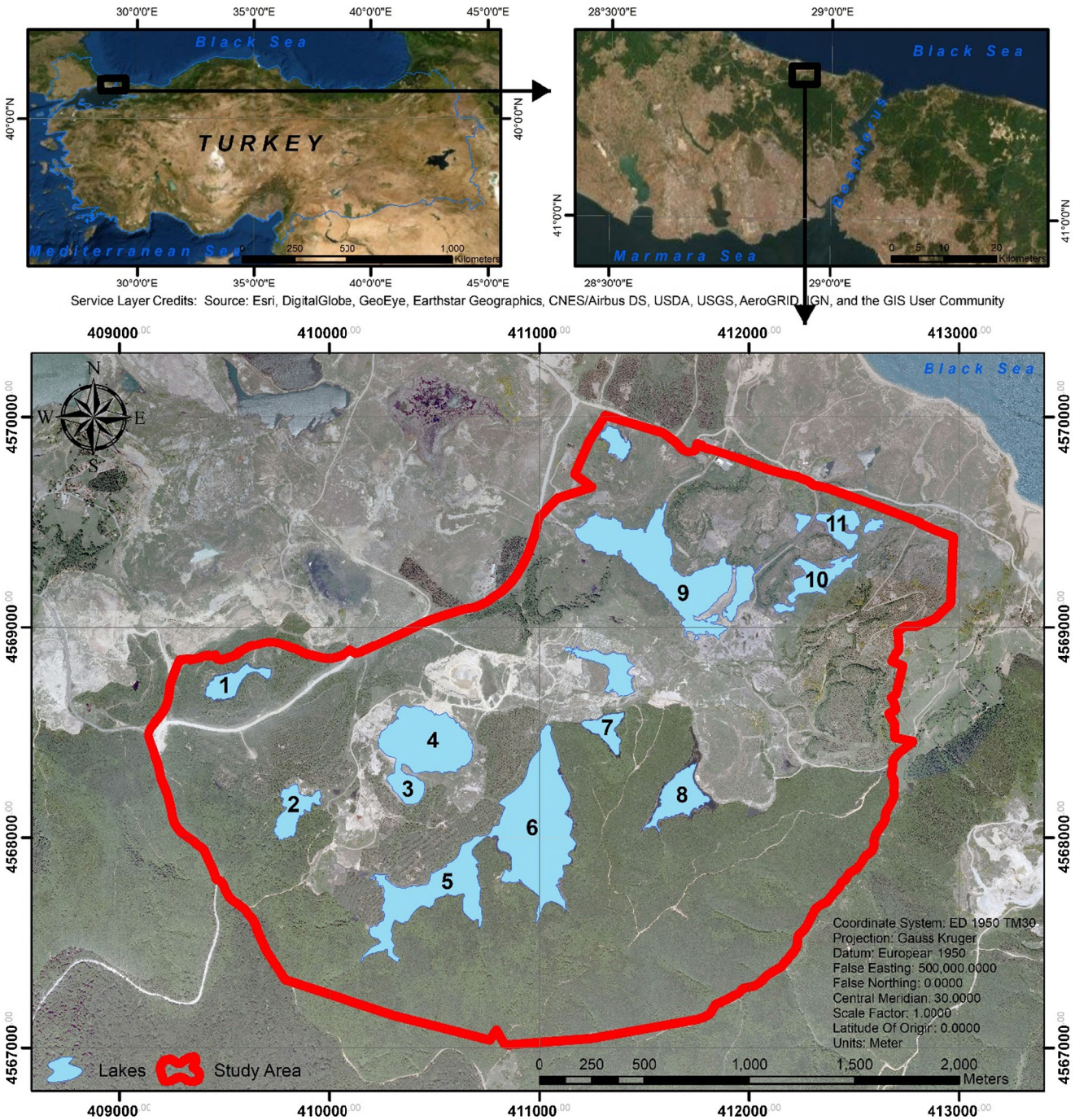


Fig. 1 Research area, end pit mine lakes, Ağaçlı-Istanbul

Field sampling and measurements

During the study, sampling and measurements were carried out at four different periods (February 2016, May 2016, August 2016, and November 2016) in the 11 lakes. In order to determine the quantity of elements (K, Ca, Na, Mg, P, Fe, Al, Mn, Ni, Cu, Zn) in the lakes, water samples from each lake were taken at four replicates (four corners of each lake) from a depth of approximately 2 cm at 2 m from the shore. At the same points, acidity, electrical conductivity, temperature, and dissolved O_2 measurements were taken with a multi-parameter portable meter (WTW Multi 3320).

Laboratory analysis

The water samples were stored in a refrigerator at + 4 °C until the analysis by adding concentrated nitric acid (65% HNO_3), keeping the acidity of samples

Table 1 Physical characteristics of mine lakes

Lake	Area (m^2)	Altitude (m)	Mean depth (m)	Max depth (m)	Circuit (m)	Length (m)	Mean width (m)
1	27,400	85	5–7	11	850	360	75
2	27,800	71	5–7	14	1000	300	90
3	16,300	56	5–8	10	580	200	85
4	107,100	50	10–12	16	1350	500	220
5	102,450	72	10–15	24	2700	850	120
6	197,050	71	20–25	36	3100	950	250
7	21,250	65	8–12	16	850	260	70
8	61,900	75	10–15	19	1250	550	120
9	177,100	10	5–8	14	4300	660	130
10	29,100	18	3–5	6	1350	400	80
11	21,900	15	4–6	7	850	230	80

around pH 2 in order to protect the chemical structure of the water samples, avoiding processes such as microbiological activity and oxidation (Shevenell et al. 1999). The samples were homogenized by mixing according to the lakes, and homogenized samples were then filtered into four replicates using filter paper (Whatman no. 41) and prepared for elementary analysis. Element concentrations (K, Ca, Na, Mg, P, Fe, Al, Mn, Ni, Cu, Zn) in these samples were determined on ICP-OES (Perkin Elmer Optima 7000 DV).

Table 2 Descriptive statistics on water characteristics in mine lakes

		Lake										
		1	2	3	4	5	6	7	8	9	10	11
pH	Mean	8.3	8.3	5.3	8.8	8.6	8.7	9.0	9.0	8.6	8.8	8.6
	SD	1.3	1.1	0.8	1.0	1.0	0.9	1.2	1.0	1.2	1.0	0.9
EC	Mean	1217.3	795.4	1184.8	1228.1	429.5	415.8	441.1	343.5	1282.1	1894.6	1466.6
	SD	57.6	50.6	66.1	102.8	20.7	9.8	12.8	14.5	52.4	133.6	107.8
T	Mean	16.7	18.0	17.3	18.3	17.1	17.4	17.6	17.1	16.9	17.1	17.0
	SD	8.6	8.9	8.4	9.3	9.0	8.7	9.4	8.8	8.5	9.6	9.2
O_2	Mean	8.4	10.8	10.9	11.8	9.7	10.6	10.8	10.7	9.6	8.5	8.9
	SD	1.21	3.23	2.83	2.50	2.79	2.56	1.93	1.75	2.12	2.64	2.17
K	Mean	4.24	3.03	4.88	5.02	2.39	3.02	1.98	2.59	4.84	9.02	4.83
	SD	0.83	0.46	0.29	0.28	0.27	0.38	0.52	0.74	1.12	1.53	0.93
P	Mean	0.08	0.04	0.07	0.07	0.06	0.04	0.03	0.03	0.07	0.08	0.07
	SD	0.04	0.01	0.01	0.01	0.03	0.01	0.01	0.01	0.01	0.02	0.02
Ca	Mean	92.70	67.34	128.44	134.64	38.09	31.32	24.19	28.72	134.90	173.10	119.33
	SD	41.40	20.60	25.67	26.18	10.02	6.75	6.86	11.38	41.60	61.70	9.75
Mg	Mean	24.32	16.58	35.56	35.04	11.27	10.66	6.48	7.35	36.56	53.86	37.12
	SD	6.57	2.88	5.96	2.67	1.72	1.48	1.20	1.68	6.40	20.68	3.33
Na	Mean	16.94	12.80	15.71	15.52	15.83	21.64	13.98	18.89	12.09	33.12	11.77
	SD	8.77	0.80	5.01	3.04	7.30	3.08	3.39	4.10	3.89	28.85	4.73
Fe	Mean	0.201	0.384	1.083	0.382	0.247	0.201	0.236	0.210	0.224	0.190	0.203
	SD	0.077	0.160	1.022	0.147	0.090	0.068	0.081	0.058	0.057	0.063	0.092
Al	Mean	0.070	0.073	2.345	0.171	0.189	0.054	0.067	0.054	0.063	0.047	0.053
	SD	0.025	0.048	1.501	0.115	0.208	0.023	0.028	0.042	0.048	0.031	0.036
Cu	Mean	0.017	0.017	0.022	0.020	0.019	0.019	0.016	0.016	0.017	0.016	0.016
	SD	0.002	0.002	0.003	0.004	0.004	0.003	0.004	0.003	0.002	0.002	0.002
Ni	Mean	0.008	0.008	0.355	0.047	0.012	0.004	0.004	0.002	0.007	0.005	0.004
	SD	0.002	0.003	0.067	0.044	0.007	0.001	0.002	0.001	0.004	0.002	0.002
Zn	Mean	0.022	0.011	0.129	0.020	0.017	0.012	0.010	0.010	0.011	0.010	0.009
	SD	0.008	0.001	0.038	0.010	0.005	0.002	0.004	0.004	0.003	0.004	0.006
Mn	Mean	0.041	0.251	5.001	0.499	0.557	0.057	0.015	0.053	0.099	0.054	0.034
	SD	0.008	0.212	0.684	0.539	0.632	0.076	0.006	0.025	0.105	0.058	0.018

SD standard deviation (±), *pH* acidity, *EC* electrical conductivity (μS/cm), O_2 dissolve oxygen (mg/l), *T* temperature (°C), *Ni* nickel, *Al* aluminum, *Fe* iron, *Ca* calcium, *Na* sodium, *K* potassium, *Zn* zinc, *Cu* copper, *Mg* magnesium, *Mn* manganese, *P* phosphorus. Concentrations of elements are mg/l

Table 3 Results of two-way ANOVA on water characteristics of mine lakes

Parameters	Variables	*Df*	Mean. sq.	*F*	*p*
pH	Time	3	28.391	71.67	0.000
	Lake	10	18.716	47.25	0.000
	Time × lake	30	1.758	4.44	0.000
EC (μS/cm)	Time	3	140,804	466.11	0.000
	Lake	10	478,207	15,830.20	0.000
	Time × lake	30	13,234	43.81	0.000
T (°C)	Time	3	4650.26	12,452.37	0.000
	Lake	10	3.45	9.23	0.000
	Time × lake	30	4.24	11.36	0.000
O_2 (mg/l)	Time	3	199.749	249.73	0.000
	Lake	10	20.151	25.19	0.000
	Time × lake	30	9.995	12.50	0.000
Ni (mg/l)	Time	3	5.146	456.37	0.000
	Lake	10	19.428	1722.92	0.000
	Time × lake	30	0.577	51.13	0.000
Al (mg/l)	Time	3	0.230	630.20	0.000
	Lake	10	0.193	528.54	0.000
	Time × lake	30	0.023	61.79	0.000
Fe (mg/l)	Time	3	4.732	3160.26	0.000
	Lake	10	1.636	1092.08	0.000
	Time × lake	30	0.205	137.14	0.000
Ca (mg/l)	Time	3	1.148	323.49	0.000
	Lake	10	6.478	1827.39	0.000
	Time × lake	30	0.226	63.74	0.000
Na (mg/l)	Time	3	0.007	121.63	0.000
	Lake	10	0.002	34.56	0.000
	Time × lake	30	0.002	28.74	0.000
K (mg/l)	Time	3	0.004	437.25	0.000
	Lake	10	0.009	1169.35	0.000
	Time × lake	30	0.001	22.83	0.000
Zn (mg/l)	Time	3	0.017	1365.32	0.000
	Lake	10	0.050	4154.76	0.000
	Time × lake	30	0.003	245.09	0.000
Cu (mg/l)	Time	3	0.003	400.16	0.000
	Lake	10	0.001	193.76	0.000
	Time × lake	30	0.001	88.43	0.000
Mg (mg/l)	Time	3	0.002	460.93	0.000
	Lake	10	0.020	6818.23	0.000
	Time × lake	30	0.001	120.75	0.000
Mn (mg/l)	Time	3	0.060	9251.54	0.000
	Lake	10	0.177	27,249.79	0.000
	Time × lake	30	0.014	2119.85	0.000
P (mg/l)	Time	3	0.016	1090.26	0.000
	Lake	10	0.013	905.37	0.000
	Time × lake	30	0.001	51.74	0.000

Ni nickel, *Al* aluminum, *Fe* iron, *Ca* calcium, *Na* sodium, *K* potassium, *Zn* zinc, *Cu* copper, *Mg* magnesium, *Mn* manganese, *P* phosphorus

Statistics

Water parameters—acidity, electrical conductivity, dissolved O_2, element contents (K, P, Ca, Mg, Na Fe, Al, Cu, Ni, Zn, and Mn)—which were determined in the laboratory and field were compared between lakes and temporally with two-way variance analysis (two-way ANOVA) at $\alpha = 0.05$ significance level. Also, Pearson's correlation analysis was performed to reveal the relationship between the determined parameters. The Minitab 17 program was used for all these operations.

Results

All investigated parameters and element concentrations in the water of the end pit lakes are given in Table 2, and their statistical comparison and evaluation are presented in Table 3. All investigated water parameters, macro-element, and heavy metal concentrations showed statistically significant differences on both temporal comparison and between lakes in two-way variance analysis (Table 3).

The overall mean pH ranged from 5.3 to 9.0 between lakes (Table 2), the lowest being measured as 4.53 in lake 3 in November 2016 and the highest being in lake 7 in August 2016 (Fig. 2). Except lake 3, water pH was generally alkaline reaction in the lakes. The electrical conductivity value ranged between 335.3 and 2072.5 μS/cm (between 415 and 1895 μS/cm on average), and the highest was in lake 10 in August 2016 and the lowest was in lake 8 in May 2016 (Fig. 2). In general, an increasing tendency in EC was observed in August 2016; however, a decreasing trend was observed in lakes 5, 6, 7, and 8 (Fig. 2). The change in the water temperature in the lakes reached the highest values in the May and August periods (Fig. 2). The highest temperature value was determined in lake 7 (August 2016) and the lowest was in lake 5 (February 2016) (Fig. 2). Dissolved oxygen (O_2) generally reached the highest levels in February 2016 (Fig. 2). The highest dissolved oxygen was detected in lake 2 in February 2016 and the lowest value was in lake 10 in May 2016 (Fig. 2).

In addition to the water parameters presented above, in temporal comparison, concentrations of macro-elements and heavy metals showed a significant difference among sampling times without any clear trend (Figs. 3 and 4). Macro-elements K, P, Ca, and Mg were remarkably lower in lakes 5, 6, 7, and 8 (Fig. 3). In general, the concentrations of heavy metals Fe, Al, Ni, Zn, and Mn were also found significantly higher in lake 3, and similar to macro-element concentrations, heavy metals were found to have lower values in lakes 5, 6, 7, and 8 in statistical comparison between lakes (Fig. 4).

The remarkable result of the correlation analysis on the interactions of the investigated parameters was the significant negative correlation of pH with concentrations of P,

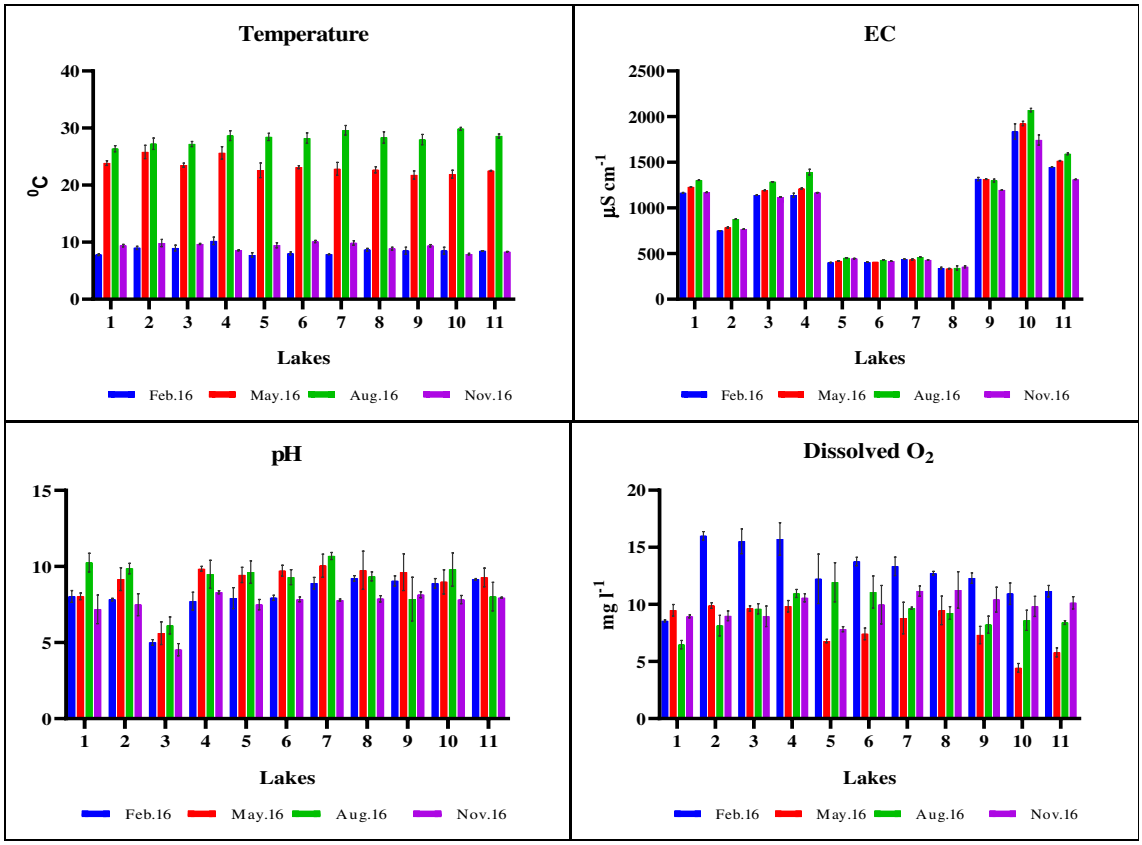


Fig. 2 Different water parameters of 11 different end pit mine lakes. Vertical bars indicate standard deviation

Ca, Mg, Fe, Cu, Ni, Zn, and Mn, except K (Table 4). In addition, the pH value showed a significant positive correlation with the change of Na concentration (Table 4). Electrical conductivity in lake waters was positively correlated with Ca, Mg, K, and P changes, despite being negatively correlated with Na concentration (Table 4). Dissolved oxygen content is also positively correlated to Fe and Cu and negatively related to changes of water temperature (Table 4).

Discussion

The pH is the most important parameter for pit lakes, because the mobility of most metals and metalloids is strongly pH-dependent (Marszelewski et al. 2017), and similarly strong relationships were reported for pH by Winterbourn et al. (2000). In general, the pH value of the lakes varied widely from severe acid to severe alkaline. Similarly, Samecka-Cymerman and Kempers (2001) and Şanlıyüksel and Yücel (2017) found that the pH of the mine lakes varied over a wide range (2.8–7.2 and 3.0–8.1, respectively). The change in acidity was statistically significant both temporally and between lakes. In our study, pH value tends to increase temporally in summer periods, which is likely due to the condensation that occurs as a result of the evaporation. Also, during this period, due to local climatic conditions, the lack of flow in the drainage water and the precipitation feeding mine lakes, and consequently the possible reductions on siltations and suspended particles, are the factors that may affect the changes.

Shevenell et al. (1999) explain the geo- and biochemistry in mine lakes that cause changes in the chemistry and flow of groundwater and surface waters feeding the lakes, indicating that this is due to seasonal climate fluctuations. The significant difference in pH changes between the lakes in our study may result from the changes due to the factors mentioned above. In mine lakes having near-neutral reactions, bicarbonates are generally the main reason for water pH above pH 6 (Brugam et al. 1983). In some cases, hydrolysis of transition metals such as iron(II), copper, and zinc may be effective in buffering the pH close to 7 (Nordstrom and Alpers 1997). In addition, acidification occurs with decomposition products of iron sulfate and sulfuric acid, and pyrites (Samecka-Cymerman and Kempers 2001). As a result of the study, it can be stated that the pH value was generally alkaline in mining lakes (except lake 3). These results were similar to the studies in the literature (Table 5). The alkaline character of the lakes may be due to the effect of the amount of bicarbonate, as mentioned above.

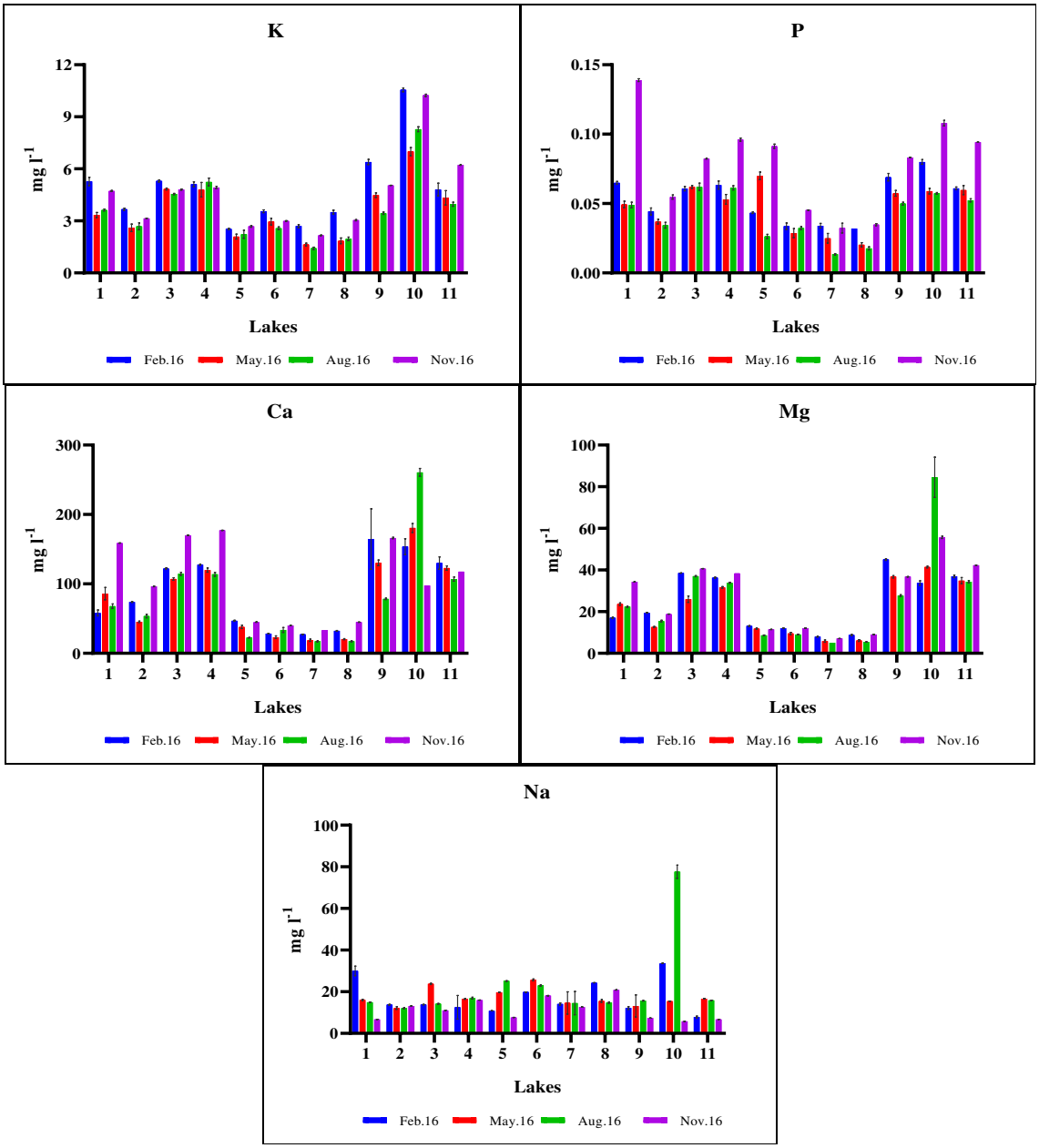


Fig. 3 Mean macro-element concentrations in water of 11 different end pit mine lakes. Vertical bars indicate standard deviation

In general, the electrical conductivity value was above 1000 μS/cm in the lakes (except lakes 5, 6, 7, and 8) and an increase was observed in August 2016. This result was also similar to many studies in the literature (Table 5). The change in electrical conductivity has a similar tendency to the results in the change of acidity and shows a significant change both temporally and between lakes. Pond et al. (2008) indicated that water conductivity should be interpreted as a direct conductivity toxicity and as a summary of many stressors resulting from mining operations. Williams (1998) stated that water salinization is based on ionic composition, temperature, air pressure, and ion concentrations. Accordingly, in our study, the lower electrical conductivity values in lakes 5, 6, 7, and 8 may be due to a low cation amount in the lakes, which will be clearly seen in the element concentration section. The electrical conductivity values in the water of mine lakes were strongly dependent on water temperatures (Karakas et al. 2003). In the results we obtained, the electrical conductivity values increased in the summer period depending on the water temperature. Salinity may also increase through time due to evapo-concentration processes (McCullough et al. 2013; Niccoli 2009). In addition, similar to the present study, Fisher and Lawrence (2006) declared that electrical conductivity shows slightly seasonal fluctuations in the upper layers of mine lake water, and winter rainfalls cause the reduction of salinity.

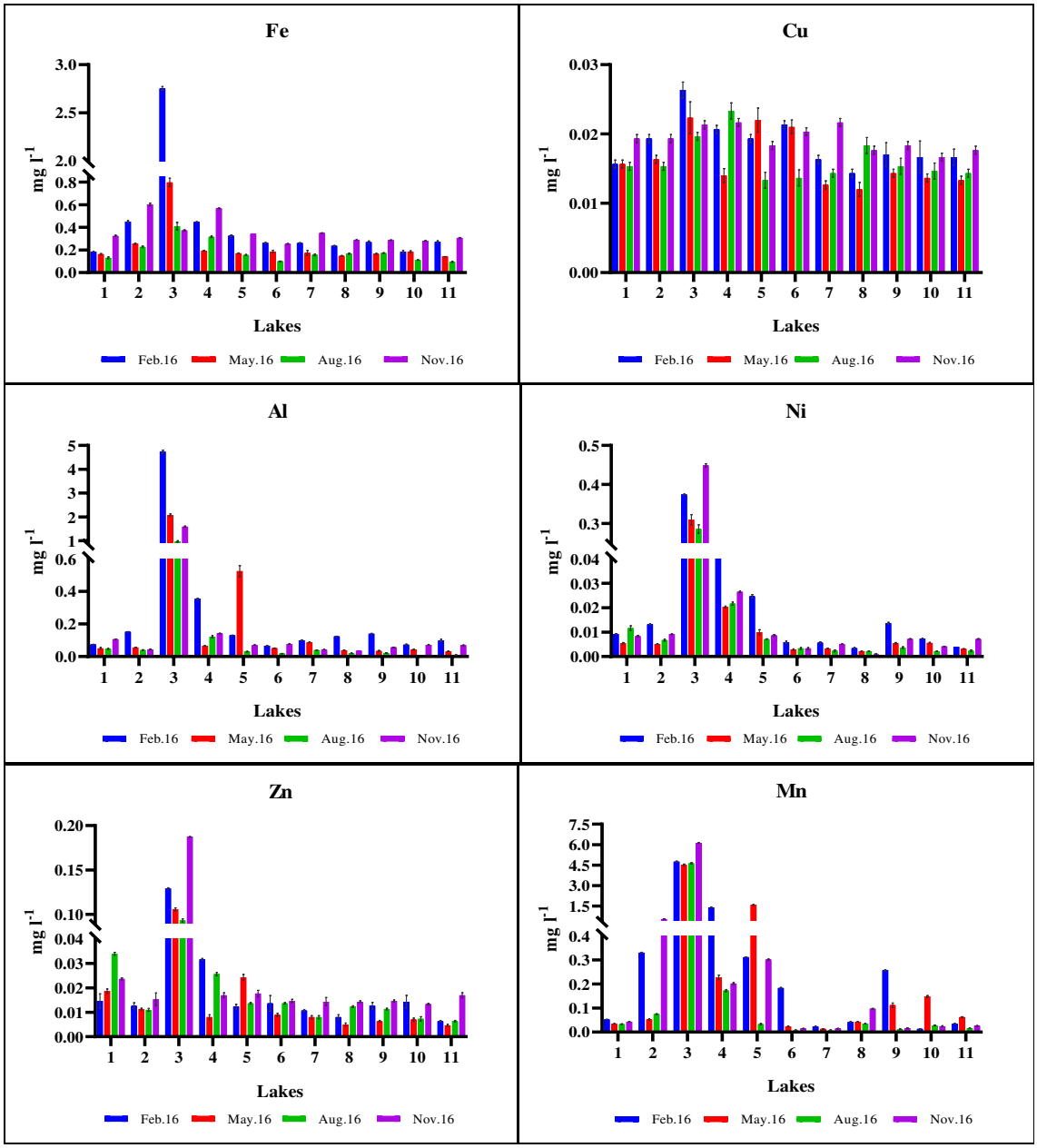


Fig. 4 Mean heavy metal concentrations in water of 11 different end pit mine lakes. Vertical bars indicate standard deviation

Water temperature in the lakes reached the highest values in the May and August periods, depending on the air temperature. The lake temperature showed a statistically significant change between the lakes. This result can be caused from differences in the water density of lakes due to different sizes and cation concentrations. Similarly, literature review in Table 5 showed that water temperature in end pit mine lakes can change in a wide range between 0.6 °C (Marszelewski et al. 2017) and 34 °C (Mishra et al. 2008).

Dissolved oxygen values showed statistically significant differences between lakes and temporally; present results (8.4–11.8 mg/l) were also close to values in literature ranging from 4 mg/l (Şanliyüksel et al. 2016) to 14.1 mg/l (Marszelewski et al. 2017). Dissolved oxygen (O_2) is essential for aquatic life forms; therefore, the amount of dissolved oxygen measured in the present study generally reached the highest levels during the winter period. Many mine lakes contain highly dissolved oxygen in their shallow parts due to a combination of gas exchange and wave interference (Gammons et al. 2009). Similar to the present study, Fisher and Lawrence (2006) found that dissolved oxygen content had fluctuations due to seasonal changes in the water temperature.

When heavy metal and macro-elements of lake waters are evaluated temporally, it is observed that the concentrations of K, P, Ca, and Mg are remarkably lower in lakes 5, 6, 7, and 8. This can be the result of geochemical processes such as

Table 4 Results of Pearson correlation analysis on water characteristics of mine lakes

	Ni	Al	Fe	Ca	Na	K	Zn	Cu	Mg	Mn	P	pH	EC	T
Al	*0.83*													
Fe	*0.62*	*0.91*												
Ca	*0.30*	0.20	0.18											
Na	−0.13	−0.07	−0.12	*−0.46*										
K	0.13	0.11	0.11	*0.73*	*−0.43*									
Zn	*0.98*	*0.79*	*0.56*	0.28	−0.14	0.11								
Cu	*0.49*	*0.55*	*0.60*	0.13	−0.11	0.07	*0.50*							
Mg	*0.32*	0.24	0.20	*0.90*	*−0.52*	*0.89*	0.29	0.14						
Mn	*0.98*	*0.81*	*0.57*	0.27	−0.10	0.09	*0.96*	*0.50*	0.28					
P	0.18	0.12	0.14	*0.71*	*−0.62*	*0.63*	0.23	0.29	*0.73*	0.19				
pH	*−0.77*	*−0.65*	*−0.58*	*−0.33*	*0.33*	−0.19	*−0.76*	*−0.59*	*−0.34*	*−0.75*	*−0.44*			
EC	0.14	0.09	0.04	*0.84*	*−0.42*	*0.83*	0.12	−0.08	*0.92*	0.10	*0.56*	−0.12		
T	−0.08	−0.12	−0.28	−0.20	*0.42*	−0.27	−0.09	*−0.38*	−0.19	−0.05	*−0.43*	*0.46*	0.08	
O_2	0.19	0.29	*0.43*	−0.12	0.01	0.01	0.12	*0.38*	−0.08	0.13	−0.12	−0.28	−0.26	*−0.48*

pH acidity, *EC* electrical conductivity, O_2 dissolve oxygen, *Ni* nickel, *Al* aluminum, *Fe* iron, *Ca* calcium, *Na* sodium, *K* potassium, *Zn* zinc, *Cu* copper, *Mg* magnesium, *Mn* manganese, *P* phosphorus. Significant differences ($p \leq 0.05$) are italicized

dissolution of minerals, precipitation, and photochemical reactions. Fe, Al, Ni, Zn, and Mn values were significantly higher in lake 3, indicating the high amount of heavy metals, likely due to the acidity of water and lower pH value compared with the other lakes. Schultze et al. (2010) emphasized that the concentration levels of metals increase with acidification. Similarly, Eary (1999) stated also that the Al, Cd, Cu, Fe, Mn, Pb, and Zn elements have reached high values in acidic lake water conditions. In a similar study, Pb, Cu, and Zn, including many metallic elements, were significantly soluble in acidic water (Shevenell et al. 1999). Concentrations of all the elements in the lakes show statistically significant differences both temporally and between lakes. Evaporation, changes in the chemistry, and flow of groundwater and surface waters that feed the lakes probably change the geo- and biochemical characteristics of lake water (ibid.), possibly causing significant differences in element concentrations between lakes. Furthermore, Luek and Rasmussen (2017) found that the chemical features reduced water quality in coal mining end pit lakes compared with natural reference lakes; however, there are no reference lakes around the study area to compare the results of the present study. In addition, the amounts of the element depositions of lakes can be different because the lakes are of different sizes and in different stages, although that measurement was not done in the study. Indeed, Mishra et al. (2008) emphasized that most heavy metals accumulate at the base in aquatic systems.

The most remarkable result on the interactions of the parameters determined in the lake water is the significant negative correlation of pH with P, Ca, Mg, Fe, Al, Cu, Ni, Zn, and Mn. In addition, pH showed a significant positive correlation with the change in Na concentration. Many researchers found that heavy metal contents in mine lakes showed a strong negative relationship with pH (Mishra et al. 2008; Samecka-Cymerman and Kempers 2001). Contrary to the present study, Eary (1999) determined that Na and K showed a negative relationship with pH, except for Ca and Mg. Electrical conductivity in the lake waters was positively correlated with Ca, Mg, K, and P changes; however, it was negatively correlated with Na concentration. In addition, dissolved oxygen content was in positive correlation with Fe and Cu and negatively correlated to water temperature, which was likely due to the many factors mentioned above.

Conclusion

In conclusion, all characteristics in the end pit lake waters showed significant differences in temporal and between the lakes, indicating that different lakes in one mining area may have different chemical water characteristics. Among the investigated water parameters, pH has emerged as the most effective factor, especially since it has a wide range and has a negative correlation with water element concentrations. Lake 3, in particular, has different properties to the other lakes, especially in terms of heavy metal concentrations and very acidic water pH. As limitations of the study, the measurements were carried out four times in 1 year approximately 25 years after the end of mining activities, and there were no background values for chemical parameters of waters in the end pit lakes. Also, the lakes were sampled from one depth;

Table 5 Some literature review on chemical water characteristics of end pit mine lakes

Parameters	Luek and Rasmussen (2017)	Limit values of EMA Permit 11,678 water quality limits (Vandenberg and Litke 2017)	Mishra et al. (2008)	Santofimia et al. (2013)	Samecka-Cymerman, and Kempers, (2001)	Denimal et al. (2005)	Şanlıyüksel et al. (2016)	Gupta et al. (2012)	Şanlıyüksel and Yücel (2017)	Marszelewski et al. (2017)
Al	–	–	–	280 mg/l	8–4400 μg/l	–	16.8–360.6 mg/l	–	48–445,621 mg/l	–
Fe	0.007 mg/l	1 Mg/L	–	750 mg/l	2–4790 μg/l	10–300 μg/l	7.7–329.7 mg/l	0.118–0.152 mg/l	237–389,567 mg/l	–
Ca	65.66 mg/l	–	–	–	21–98 μg/l	146–148 mg/l	85.47–520.1 mg/l	114.17–137.17 mg/l	21.27–472.6 mg/l	–
Na	204 mg/l	–	–	–	–	13–18.6 mg/l	43.97–265.7 mg/l	31.98–51.9 mg/l	12.5–272 mg/l	–
K	1822 mg/l	–	–	–	2.4–12 μg/l	7.1–8 mg/l	0.95–15.8 mg/l	8.23–18.53 mg/l	1.55–42.16 mg/l	–
Zn	0.001 mg/l	0.03 Mg/L	–	300–953 mg/l	86–751 μg/l	–	0.43–15.7 mg/l	0.146–0.23 mg/l	354–10,881 mg/l	–
Cu	–	0.012 Mg/L	29.15–156.12 μg/l	16–75 mg/l	3–198 μg/l	–	–	0.09–0.156 mg/l	–	–
Mg	50.9 mg/l	–	–	0.6 mg/l	14–60 μg/l	5.39–23 mg/l	28.74–357.8 mg/l	101.83–115 mg/l	49.36–646.1 mg/l	–
Mn	–	–	29.5–65.7 μg/l	10–225 mg/l	7–1480 μg/l	20–4500 μg/l	98–225.6 mg/l	0.295–0.393 mg/l	215–165,520 mg/l	–
P	0.003 mg/l	0.09 Mg/L	–	–	–	–	–	–	–	0.013–0.112 mg/l
pH	8.41	6–9.5	6.5–8.99	2.7–3.0	2.8–7.2	6.8–9.3	2.59–3.79	7.68–8.05	3.01–8.05	8.06–8.57
EC	1430 μS/cm	–	–	8.5–12 mS/cm	–	1500 μS/cm	1040–6430 μS/cm	4.99–7.64 mS/cm	1125–5690 μS/cm	377–882 μS/cm
Temperature (°C)	–	–	24–34	–	–	5–24	–	–	–	0.6–2.28
O_2	–	–	–	–	–	–	4–6.45 mg/l (DO)	–	–	8.9–14.1 mg/l

samplings at different depths can give more detailed results for future research and restoration alternatives of end pit mine lakes. All these parameters should be taken into consideration in future studies, and all are necessary to assess whether the lakes are suitable for further development as recreational sites and/or water supply reservoirs; they will provide valuable information on subsequent phases in these aquatic systems.

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References

Akpınar N, Kara D, Ünal E Açık ocak madenciliği sonrası alan kullanım planlaması. In: Türkiye XIII. Madencilik Kongresi, 10–14 Mayıs 1993. TMMOB, pp 327–340, (in Turkish)

Baykan RA (2004) Türkiye Çevre Atlası. Türkiye Çevre ve Orman Bakanlığı, CED ve Planlama Genel Müdürlüğü, Çevre Envanteri Dairesi Başkanlığı, Ankara. (in Turkish)

Blanchette ML, Lund MA (2016) Pit lakes are a global legacy of mining: an integrated approach to achieving sustainable ecosystems and value for communities. Curr Opin Environ Sustain 23:28–34. https://doi.org/10.1016/j.cosust.2016.11.012

Brugam RB, Carlson MA, Chakraverty S, Lusk M (1983) Post-mining neutralization of acidic surface mine lakes. Water Resources Center University of Illinois, Urbana, Washington, D.C.

Castendyk D, Eary L, Balistrieri LS (2015) Modeling and management of pit lake water chemistry 1. Theor Appl Geochem 57:267–288. https://doi.org/10.1016/j.apgeochem.2014.09.004

Denimal S, Bertrand C, Mudry J, Paquette Y, Hochart M, Steinmann M (2005) Evolution of the aqueous geochemistry of mine pit lakes – Blanzy–Montceau-les-Mines coal basin (Massif Central, France): origin of sulfate contents; effects of stratification on water quality. Appl Geochem 20(5):825–839. https://doi.org/10.1016/j.apgeochem.2004.11.015

Eary LE (1999) Geochemical and equilibrium trends in mine pit lakes. Appl Geochem 14:963–987. https://doi.org/10.1016/S0883-2927(99)00049-9

Fisher TS, Lawrence GA (2006) Treatment of acid rock drainage in a meromictic mine pit lake. J Environ Eng 132:515–526. https://doi.org/10.1061/(ASCE)0733-9372(2006)132:4(515)

Gammons CH, Harris LN, Castro JM, Cott PA, Hanna BW (2009) Creating lakes from open pit mines: processes and considerations, emphasis on northern environments

Göktürk AF (2010) Kapatılmış sızma (Konya) cıva madenlerinin çevre üzerine etkilerinin incelenmesi. Doktora (Doctoral Dissertation), Selçuk Üniversitesi. (in Turkish)

Gupta S, Nayek S, Saha RN (2012) Major ion chemistry and metal distribution in coal mine pit lake contaminated with industrial effluents: constraints of weathering and anthropogenic inputs. Environ Earth Sci 67(7):2053–2061. https://doi.org/10.1007/s12665-012-1644-9

Huber A, Ivey GN, Wake G, Oldham CE (2008) Near-surface wind-induced mixing in a mine lake. J Hydraul Eng 134:1464–1472. https://doi.org/10.1061/(ASCE)0733-9429(2008)134:10(1464)

Jawaduddin M, Memon SA, Bheel N, Ali F, Ahmed N, Abro AW (2019) Synthetic grey water treatment through FeCl3-activated carbon obtained from cotton stalks and river sand. Civil Eng J 5:340–348. https://doi.org/10.28991/cej-2019-03091249

Kantarci M (1989) Land use and main ecological research and assessment of open pit coal mining area for forestation at the northern part of Catalca Peninsula (Agaclı/Istanbul region). Journal of the Faculty of Forestry, Istanbul University 38:60–90. (In Turkish)

Kantarcı M, Öztürk M (2003) Surface erosion induced by rainfall on the Agacli reclaimed site and preventing effects of the reforestation. In: O S, L S, K K, H T (eds) 3rd Atmosphere science symposium, Istanbul, 2003. ITU Meteorological Department, pp 107–130. (In Turkish)

Karakas G, Brookland I, Boehrer B (2003) Physical characteristics of acidic mining lake 111. Aquat Sci 65:297–307. https://doi.org/10.1007/s00027-003-0651-z

Kul AA et al (2017) Terk edilmiş maden sahalarında oluşan sulak alanlar ve yakın çevrelerinden yararlanma imkânlarının araştırılması (Çiftalan-Kısırkaya Örneği). TC. Orman Genel Müdürlüğü, Proje Sonuç Raporu. Proje Numarası: 10.8301/2013-2015-2017. (in Turkish)

Kural O (1998) Kömür: özellikleri, teknolojisi ve çevre ilişkileri. İTÜ, İstanbul

Luek A, Rasmussen JB (2017) Chemical, physical, and biological factors shape littoral invertebrate community structure in coal-mining end-pit lakes. Environ Manag 59:652–664. https://doi.org/10.1007/s00267-017-0819-2

Marszelewski W, Dembowska EA, Napiórkowski P, Solarczyk A (2017) Understanding abiotic and biotic conditions in post-mining pit lakes for efficient management: a case study (Poland). Mine Water Environ 36:418–428. https://doi.org/10.1007/s10230-017-0434-8

McCullough CD, Marchand G, Unseld J (2013) Mine closure of pit lakes as terminal sinks: best available practice when options are limited? Mine Water Environ 32:302–313. https://doi.org/10.1007/s10230-013-0235-7

MGM (2016) Tarım ve Orman Bakanlığı. Meteoroloji Genel Müdürlüğü, Ankara. (in Turkish)

Mhlongo S, Mativenga PT, Marnewick A (2018) Water quality in a mining and water-stressed region. J Clean Prod 171:446–456. https://doi.org/10.1016/j.jclepro.2017.10.030

Miller L, Rasmussen J, Palace V, Sterling G, Hontela A (2013) Selenium bioaccumulation in stocked fish as an indicator of fishery potential in pit lakes on reclaimed coal mines in Alberta, Canada. Environ Manag 52:72–84. https://doi.org/10.1007/s00267-013-0038-4

Mishra VK, Upadhyay AR, Pandey SK, Tripathi B (2008) Concentrations of heavy metals and aquatic macrophytes of Govind Ballabh Pant Sagar an anthropogenic lake affected by coal mining effluent. Environ Monit Assess 141:49–58. https://doi.org/10.1007/s10661-007-9877-x

Nasiri EF, Kebria DY, Qaderi F (2018) An experimental study on the simultaneous phenol and chromium removal from water using titanium dioxide photocatalyst. Civil Eng J 4:585–593. https://doi.org/10.28991/cej-0309117

Niccoli WL (2009) Hydrologic characteristics and classifications of pit lakes. In: Castendyk D, Eary T (eds) Mine pit lakes: characteristics, predictive modeling, and sustainability. Society for mining, metallurgy, and exploration, vol 3. Colorado, USA, pp 33–43

Nkansah MA, Donkoh M, Akoto O, Ephraim JH (2019) Preliminary studies on the use of sawdust and peanut shell powder as adsorbents for phosphorus removal from water. Emerging Sci J 3:33–40. https://doi.org/10.28991/esj-2019-01166

Nordstrom DK, Alpers CN (1997) Geochemistry of acid mine waters. In: Plumlee GS, Logsdon MJ, Filipek LF (eds) The environmental geochemistry of mineral deposits: part a: processes, techniques, and health issues part B: case studies and research topics, vol 7A. Society of Economic Geologists, pp 1–28

Öztürk M (2002) Evaluation of water erosion in the Ağaçlı region İstanbul, Turkey. Doctoral dissertation, Bogazici University. Institute of Environmental Sciences

Paraguassú L, Leite MG, Moreira FW, Mendonça FP, Eskinazi-Sant'Anna EM (2019) Impacts of mining in artificial lake of Iron Quadrangle-MG: past marks and changes of the present. Environ Earth Sci 78:167. https://doi.org/10.1007/s12665-019-8158-7

Pond GJ, Passmore ME, Borsuk FA, Reynolds L, Rose CJ (2008) Downstream effects of mountaintop coal mining: comparing biological conditions using family-and genus-level macroinvertebrate bioassessment tools. J N Am Benthol Soc 27:717–737. https://doi.org/10.1899/08-015.1

Samecka-Cymerman A, Kempers A (2001) Concentrations of heavy metals and plant nutrients in water, sediments and aquatic macrophytes of anthropogenic lakes (former open cut brown coal mines) differing in stage of acidification. Sci Total Environ 281:87–98. https://doi.org/10.1016/S0048-9697(01)00838-5

Santofimia E, López-Pamo E, Montero E (2013) Environmental management of Aznalcóllar Mine and its influence in the hydrogeochemical of the pit lake. Water Environ Res 85:706–714. https://doi.org/10.2175/106143013X13698672323263

Schultze M, Pokrandt K-H, Hille W (2010) Pit lakes of the central German lignite mining district: creation, morphometry and water quality aspects. Limnologica-Ecology and Management of Inland Waters 40:148–155. https://doi.org/10.1016/j.limno.2009.11.006

Shevenell L, Connors KA, Henry CD (1999) Controls on pit lake water quality at sixteen open-pit mines in Nevada. Appl Geochem 14:669–687. https://doi.org/10.1016/S0883-2927(98)00091-2

Şanliyüksel DY, Balci N, Baba A (2016) Generation of acid mine lakes associated with abandoned coal mines in northwest Turkey. Arch Environ Contam Toxicol 70:757–782. https://doi.org/10.1007/s00244-016-0270-z

Şanlıyüksel DY, Yücel MA (2017) Terk edilmiş kömür ocaklarında oluşan maden göllerinin hidrokimyasal özelliklerinin belirlenmesi ve insansız hava aracı ile üç boyutlu modellenmesi. Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi 23:780–791. (in Turkish). https://doi.org/10.5505/pajes.2016.37431

Tokgöz N (2010) Case study of the Agacli landslide–gully complex during post-coal-mining reclamation and afforestation. Environ Earth Sci 59:1559–1567. https://doi.org/10.1007/s12665-009-0141-2

Topay M, Aydın ŞS, Koçan N (2007) Taş Ocaklarının Peyzaja Etkileri ve Yeniden Kullanımlarına Yönelik Çözüm Önerileri: Bartın İli Örneği. Türkiye Ormancılık Dergisi 8:134–144. (in Turkish)

Unsal B, Yazicigil H (2016) Assessment of open pit dewatering requirements and pit lake formation for the Kışladağ gold mine, Uşak, Turkey. Mine Water and the Environment 35:180–198 https://doi.org/10.1007/s10230-015-0345-5

Vandenberg J, Litke S (2018) Beneficial use of springer pit lake at Mount Polley Mine. Mine Water Environ 37:663–672. https://doi.org/10.1007/s10230-017-0504-y

Williams WD (1998) Salinity as a determinant of the structure of biological communities in salt lakes. Hydrobiologia 381:191–201. https://doi.org/10.1023/A:1003287826503

Winterbourn M, McDiffett W, Eppley S (2000) Aluminium and iron burdens of aquatic biota in New Zealand streams contaminated by acid mine drainage: effects of trophic level. Sci Total Environ 254:45–54. https://doi.org/10.1016/S0048-9697(00)00437-X