IMPACT OF EXTERNAL CONDITIONS ON WATER QUALITY OF KAMENCOVÉ (ALUM) LAKE IN CHOMUTOV AND PROPOSAL OF REVITALIZING MEASURES

A. Jelínková, D. Fedorova

Czech University of Life Sciences Prague, Faculty of Environmental Sciences, Prague, Czech Republic

Kamencové Lake (also called Alum Lake) located in Chomutov (North Bohemian Brown Coal Basin, Czech Republic) is a worldwide unique for its lake water chemical composition (K Al $(SO_4)_2$ 12 H_2O) that naturally prevents algae growth. The region used to be a centre of heavy industry based on brown coal burning, with a crucial impact on the environment (especially acid rain) in 1980s. This fact was considered the key aspect influencing the lake water quality deterioration in the past, besides the growing popularity of the area for recreational purposes (increased risk of eutrophication) and the significant changes in the lake maintenance (increased risk of eutrophication, excessive bottom sedimentation). Due to the real threat of gradual losing the lake water unique characteristics, scientifically-based systematic measures reducing the potential risk of eutrophication need to be implemented. The present study builds on the results of previous surveys by Geofyzika Brno, Povodí Ohře, s.p. or Hydroprojekt Praha. Its aim is to assess the potential risk of eutrophication in Alum Lake and to propose remedial measures.

Alum Lake, North Bohemian Brown Coal Basin, eutrophication, water chemistry, alum water

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INTRODUCTION

Kamencové (Alum) Lake is a natural formation unique in the Czech Republic as well as worldwide. Lakes of similar origin - located in former stone shales mining areas are e.g. Tonteich Lake or the lake in Reinbek in Germany (G a b r i e l o v a , 1996). Its water, containing potassium alum (K Al $(SO4)_2$. 12 H_2O), was used for healing baths in the 19th century. It had positive effects on treating the upper respiratory tract, gynecological diseases, anemia, rheumatism or kidney diseases (K l e m e n t , 1940). Due to its properties the water also naturally inhibits the growth of algae and cyanobacteria.

Over the past decades, the unique lake water chemistry has been significantly influenced by external factors decreasing the lake water quality, in the sense of increasing the risk of eutrophication. In order to avoid the loss of the unique water properties, extensive research projects aimed at identifying the factors influencing the lake water quality were realized e.g. by Geofyzika Brno (C a h y n a , 1982), Povodí Ohře, s.p., Hydroprojekt Praha (K o s , 1981) in the past decades.

The main factors influencing the lake water quality (especially conductivity, pH value, content of sulphates, chlorides, nitrates and phosphorus) have been the quality of precipitation (in the past ‘acid rain’ – precipitation with pH bellow 5.6), fall of leaves from the trees located close to the lake, bathers, and also inappropriate maintenance of the lake, especially insufficient cleaning of bottom sediments. The last depth cleaning of the lake in 1993 was carried out by suction in a caisson using a suction dredger. About 40 000 m^3 of sediments were harvested during this cleaning. Most of the extracted material consisted of leaves from trees near the lake, the rest represented the supply by bathers (G a b r i e l o v a , 1996). Also due to the growth of bottom sediments, preventing the lake from submerging with mineralized water, the concern on eutrophication has become significant.

The aim of the present study was to assess the potential risk of eutrophication in the lake. The results from a previous research project (K o s , 1981) were used as a basis for the assessment of potential risk and comparison with the current state. The original methodology was updated and added with data stemming from the studies by local authorities and companies (Czech Hydrometeorological Institute – CHMI, Povodí Ohře, s.p.) and municipal resources (archive of Chomutov Municipality). Systematic measures to reduce the potential risk of eutrophication were proposed.

MATERIAL AND METHODS

Alum Lake is located on the North-East border of Chomutov (GPS location: 50°28′21″ N,13°25′31″ E), on the foot of the Železné hory (Ore) Mountains. The area of the lake is 159 100 m^2, the maximum depth of the lake is 3.25 m. The origin of the lake can be attributed to a combination of natural and anthropogenic factors. The bed of the lake is natural due to the existence of field depression, but the current shape of the lagoon is the consequence of slopes sliding and flooding of the surface alum slate. The alum and sulphur exploitation dates back to the years 1588–1785. It partially affected the locality of the lake. The cause of the flood, which is proclaimed to have the main impact on lake formation, was fire and the following fall of the drainage galley and water drifting into the mine in 1810. The further lake formation dates from 1813 to 1815. Since 1877, the lake has been around its current shape (G a b r i e l o v a , 1996). Near Alum Lake, there is situated the Otvice water reservoir. The reservoir is supplied with water from the Podkrušnohorský feeder showing properties different from those of the lake water (Fig. 1).

Geological characteristics of the site

Geologically, the studied territory is a part of the Tertiary North Bohemian Basin, the basement is formed by the crystalline with metamorphic rocks. Tertiary sediments consist mainly of clays, claystone, sands, sandstone, locally also brown coal. In the northern edge of the lake there is claystone with coal deposits in the overburden of the coal seam – stone shale which is overflown with underground water then rising through the cracks from the bottom of the lake (G a b r i e l o v a , 1996).

Origin and composition of alum water

The Tertiary sedimentation of the North Bohemian Basin began in the Oligocene and formed the main filling of the Basin. The prevailing sedimentary material were clay layers, sandstone with a mail on sealant and coloured with redeployed volcanic material. The basement of the lake is formed by the clay layer with a thickness of 8–27 m (C a h y n a 1982). The formation of the stone is bound to the oxidation processes of the bedrock. Pyrite leaching produces sulfuric acid which dissolves the clays to form ions (e.g. Na^+, K^+). Aluminum sulphate and potassium sulphate are formed independently of these, and after mixing, potassium alum – K Al $(SO_4)_2$ 12 H_2O – is formed (C a h y n a 1982). Therefore, to classify a water as ‘alum water’, it must exceed the following concentrations: content of ions of SO_4^{2-} about 400 mg l^{-1}, of Cl^- over 35 mg l^{-1}, of I over 5 mg l^{-1}, of Al over 1 mg l^{-1}. The water may also contain an increased amount of NH_4^+, however the ammonium cation must be of natural origin (C e r n o c h , 1996). Metals are most abundantly represented by ions of Ca^{2+}, Mg^{2+}, Na^+, K^+, Fe and Al with a total content of 700 mg l^{-1} (C a h y n a , 1982). The hydrolytic balance of the Al ions and the pH value are critical for alum water. Due to the sulfate salt content, the lake water pH values range from 2.5 to 4.0. Increasing of the water pH leads to hydrolysis of Al and oxidation of divalent iron and its excretion in the form of insoluble hydroxide and/or basic sulfates – iron and aluminum form clots that settle on the bottom of the lake. The pH limit for these reactions is 4.2 (Z a c e k , 1981). The changes of the values are introduced in Table 1.

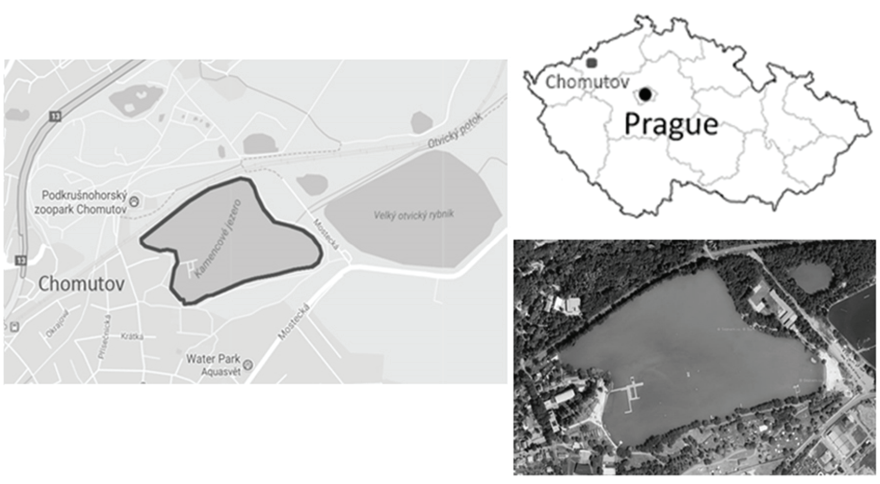

Fig. 1. Location of Alum Lake (www.mapy.cz)

Table 1. Overview of the concentrations of substances in alum water in years 1877–2016 (Municipality of Chomutov town archives)

Date	pH	Al_3^+ (mg l^{-1})	Fe (mg l^{-1})	K (mg l^{-1})	Cl (mg l^{-1})	SO_4^{-2} (mg l^{-1})	NH_4^+ (mg l^{-1})
1877	2.3	–	–	–	–	–	–
1902	2.3	117.6	64	–	–	955	–
1929	2.4	29	20	–	–	630	–
1947	2.4	18	9	–	–	520	–
1969	2.5	10	5.4	–	27.2	460	–
1971	4.1	10	5.6	–	–	360	–
1975	7.1	10	5.0	–	36.5	398	21.8
1979	3.2	10	5.4	–	33.4	421	10.9
1980	3.6	10	6.7	–	38.6	424	9.9
1981	3.1	10	7.5	–	31.9	349	8.6
7/2/1985	3.3	–	6.6	–	–	430	12.32
24/7/1985	3.0	–	7.0	–	–	530	19.25
23/7/1986	5.1	–	15.0	–	–	540	13.86
13/7/1987	4.9	–	4.5	–	–	410	8.855
4/7/1988	3.0	–	10.7	–	53	500	13.86
20/7/1989	3.0	–	–	–	45	515	13.84
16/7/1990	3.0	–	9.5	–	55	490	13.86
20/8/1991	2.9	–	7.5	–	51	528	12.3
2/7/1992	2.9	–	11.0	–	40	480	13.5
4/8/1993	2.1	–	12.0	21.3	48	586	13.2
21/7/1994	3.0	–	11.0	–	40	509	12.4
13/7/1995	2.8	–	8.0	24	41	461	7.26
11/7/1996	2.9	–	14.4	25.0	44	490	10.1
10/7/1997	3.0	–	13.6	23.0	52	499	8.81
3/8/1998	3.0	–	16.3	24.0	58	566	27.33
4/8/1999	3.0	–	19.5	22.0	47	470	9.6
18/7/2000	3.0	–	14.8	24.0	48	170	9.5
12/7/2001	3.1	–	10.4	20.8	48	430	11.5
15/7/2002	3.0	–	10.0	–	52	400	10.0
27/8/2003	3.1	8.39	10.7	22.1	54	400	9.1
30/5/2016	3.6	1.97	4.48	19.9	58	247	–

Abnormally acidic water prevents higher biological activity in the lake and so the Alum lake water is sometimes referred to as ‘Dead water’. Approximately thirty species of aquatic microorganisms and insects have been identified in the lake by biological research. In 1 ml of lake water, there live tens to hundreds of individuals (in common water up to hundreds of thousands of individuals). The most common are the genera Ochromonas, Eunotia, Nitzschia and Chlamydomonas (G a b r i e l o v a , 1996). ‘

Hydrological balance

As Alum Lake has no surface inflow, rainfall and underground springs can be considered as the main sources of water supply. Based on the lake hydrological balance the spring discharge was defined at 2.8–3.0 l s^{-1} (Z i t n y , 1981). When necessary, the water from the lake is diverted to Hutní Creek.

Characteristics of the Alum Lake catchment

The characteristics of the Alum Lake catchment (G a b r i e l o v a ,1996): catchment area 2.83 km^2, length of switchboard 9.39 km, medium length of the catchment 4.38 km, medium width of the catchment 0.646 km, lake area 0.16 km^2, share of the lake on the catchment area 0.057 l, relative height difference between the highest (578 meters above sea level) and the lowest (335 meters above sea level) lake point

Table 2. Brief hydrological balance of Alum Lake (CHMI, Geofyzika Brno, 1982)

		Input/calculated parameters	Balance of supply/losses (m^3 per year)	Share of total volume of water in lake (%)
Area		159 100 m^2		
Water volume		329 575 m^3		100
Rainfall total (565 mm per year; CHMI)	supply	90 400 m^3 per year	178 700	27.42
Water inflow (surface and ground water)		88 300 m^3 per year		26.79
Vapour	loss	116 800 m^3 per year	116 800	35.43
Outflow (surface or underground)		1.96 m^3s^{-1}	61 900	18.78

calculated for the period of keeping water in the lake for almost 2 years, which can be regarded as a relatively long time in terms of maintaining the quality of surface stagnant water

243 m. Hydrological characteristics of Alum Lake are mentioned in Table 2.

Main factors affecting the alum water chemistry

Precipitation quality and quantity. Rainfall is the most important factor influencing the lake water quality. Depending on its amount, increased mineralization or dilution of lake water takes place.

Precipitation activity (data from CHMI database): average rainfall for 1969–1980 was 514 mm per year (82.240 m^3 per year), average rainfall for 2004–2015 was 565 mm per year (90.400 m^3 per year).

Lake water quality differs depending on seasons (drought in the summer months, spring melting, spring circulation). Natural renewal of the lake water quality takes about 2–3 months (Cahyna, 1982).

The precipitation acidity is determined by the partial pressure of CO_2 in the atmosphere. Due to the high industrial activity in the North Bohemian Brown Coal Basin in the past, based on brown coal burning and insufficient desulphurization in the 1980s, SO_2 and NO_x were oxidized in the athmosphere and formed sulfuric and nitric acid, which reduced the pH of the local precipitations (Kopacek, 2005). The character of the precipitation, also called ‘acid rain’, subsequently significantly influenced the lake water chemistry – decreased pH values, increased the content of sulphates, nitrogen and other substances.

Phosphorus and nitrogen subsidies. In general, eutrophication can be defined as a process of nutrient enrichment of water, especially with nitrogen (N) and phosphorus (P) It can be divided into a natural one (the main source of substances is from the soil and the decomposition of dead organisms) and anthropogenic (N and P come mostly from agriculture). Lakes gain these substances through the water transport of solid material (sediments) from the shoreline erosion, or through the atmospheric deposition. It leads to overgrowth of the plankton and cyanobacteria, resulting in shading of the bottom where other plants grow. Subsequently, there is a rapid depletion of the nutrients dissolved in water, after that oxygen deficiency occurs. The system collapses and the organisms dwindle in the water. The accumulation of sediments begins to fill the basin and, with increasing interactions of water and sediment, the resuspension of nutrients occurs at the bottom of the lake (Luglie, Sechi, 1993). This anaerobic decomposition produces poisonous substances, e.g. instead of nitrogen or water, nitrogen in form of ammonia and methane are produced. (Kuskova, 2003). Schindler (2006) defines eutrophication as a process of excessive plant and algae growth as a consequence of increasing one or more growth limiting factors necessary for photosynthesis, such as sunlight, carbon dioxide, nutrient fertilizers, etc. This process leads to a further decrease of water quality, empasizing the processes related to eutrophication (Medici, Rinaldi, 2008). Many studies have dealt with the problem of euthrophication and measures to reduce it (Odum, 1969). For example, the study on Newman Lake, USA (MooreNo, 2009). It rises the question of biological response to P control and restoration of the lake. The study on Norway Lake Saebyvannet investigated the mineral and chemical composition of sediments and the content of total phosphorus (TP) and P pools (Lukawska-Matuszewska et al., 2013). First time the idea of the watershed impact on algae growth was proposed by Swedish limnologist Einar Naumann (Naumann, 1929). The early approach to the quantitative classification of the trophic lakes was made by Vollenweider (1968, 1975, 1976), who developed Naumann’s ideas into his own classification. The research was made upon the chemical results of several regional lake surveys (Harper, 1992).

In the present study, a model calculation based on the Vollenweider’s (1968) classification was used to assess the potential risk (not the status) of eutrophication in Alum Lake.

Table 3. Water criteria for eutrophication according to Vollenweider, 1968 (Cahyna, 1982)

Lake depth (m)	Possible pollution up to ($g\ m^{-2}$ per year)		Hazardous pollution above ($g\ m^{-2}$ per year)	
	P	N	P	N
5	0.07	1.0	0.13	2.0
10	0.1	1.5	0.2	3.0
50	0.25	4.0	0.5	8.0
100	0.4	6.0	0.8	12.0
150	0.5	7.5	1.0	15.0
200	0.6	9.0	1.2	18.0

Classification of the annual P and N load in Alum Lake (according to Vollenweider, 1968)

The classification is based on flat annual load of P and N. Water is classified according to flat annual load of P and N depending on the depth of the lake. The result shows the level of potential risk to lake water– possible or hazardous (Table 3).

Key factors considered for evaluation were the rainfall quality and intensivity and the nutrient loading in runoff from forested area near the lake for the years 1980 and 2014. These years were chosen to show the impact of the industrial change in the region (modern desulphurization technologies and heavy industry attenuation) on rainfall quality with the effect on lake water chemistry. Cultural euthrophication (bathers) was not included.

Rainfall quality and intensivity. The rainfall quality and intensivity data used for the model are presented in Table 4.

The average reported amount of P in precipitation for the North Bohemian Brown Coal Basin was 0.7 kg per 0.01 km^2 and the average amount of N was 8 kg per 0.01 km^2 per year in 1980 (Kos, 1981).

Nutrient loading in runoff from forested area near the lake. Sedimentation also plays a significant role in lakes eutrophication. Naturally eutrophication occurs over lakes aging and filling in with sediments (Carpenter, 1981).

For a mixed forest area with an afforestation of about 50% the based declared amount of P and N in the runoff (the considered area of the deciduous stands at a distance of up to 10 m from the shores of the lake is 0.03 km^2) was set by Kos (1981) as follows: 3–16 kg P per 1 km^2 (0.03–0.16 kg P per 0.01 km^2) per year, and 20–120 kg N per 1 km^2 (0.2–1.2 kg N per 0.01 km^2) per year.

From the total balance it has been calculated that Alum Lake is annually loaded with ca. 17.34 kg of P and 169.6 kg of N, after conversion to flat load representing 0.107 $g\ m^{-2}$ P and 1.04 $g\ m^{-2}$ N per year (Kos, 1981).

Cultural euthrophication in Alum Lake was calculated in the frame of the research carried out by Povodí Ohře s.p. in 1980 and the result was as follows: estimated load by 50 ml urine per bather: about 0.5 g N per person; number of days of the year considered: 10; number of bathers considered: 5000; contribution of P from recreational activity: 40 mg per person per year; total annual load of the lake due to recreational activities: 25 kg N, 2 kg P.

RESULTS

Classification of the annual P and N load in Alum Lake (according to Vollenweider, 1968)

There were two main criteria for the evaluation: the rainfall quantity and quality and the nutrient load in runoff from the forested area near the lake. Based on the original methodology used for calculation in 1980, a comparative calculation was made for the year 2014.

The average content of phosphorus and nitrogen in precipitation for the North Bohemia Brown Coal

Table 4. Comparison of rainfall quality and intensity in 1980/2014 (Kos 1981, CHMI database)

Index	Units	Average	
		year 1980[1]	year 2014[2]
Quantity		514 mm per year,82 240 m^3 per year	565 mm per year, 90 400 m^3 per year
pH value		4.6	4.99
Conductivity	$\mu S\ cm^{-1}$	75.1	38.2
Sulphates	$mg\ l^{-1}$	23.0	3.283
Chlorides	$mg\ l^{-1}$	3.1	0.885
Nitrates	$mg\ l^{-1}$	5.2	2.917
Ammonium ions	$mg\ l^{-1}$	2.4	1.16

average values of the measuring station [1]OHS Most, [2]Jezeří – UJEZ Most

Basin calculated on the basis of rainfall quality and quantity for the year 2014 was 0.77 kg P per 0.01 km^2 and 4.72 kg N per 0.01 km^2.

For the nutrient load in runoff from the forested area near the lake we considered the same values as in 1980 (the forested area around the lake has not undergone a major change). The comparison of the balance used for the classification according to Vollenweider (1968) for the years 1980 and 2014 is presented in Table 5. In terms of Vollenweider's (1968) classification, the flat load by P in 1980 (0.107 g m^{-2} per year) slowly approaches the classification 'dangerous pollution', while in 2014 (0.117 g m^{-2} P per year) it almost reaches it. The flat load by N in 1980 (1.04 g m^{-2} per year) is moving slightly above the limit of 'possible pollution', while for 2014 (0.65 g m^{-2} per year) it is classified as 'possible pollution'.

Table 5. Comparison of the balance used for classification according to Vollenweider (1968) for 1980 and 2014

	Phosphorus load		Nitrogen load	
	1980	2014	1980	2014
Total load (kg)	17.34	19.06	169.6	106.42
Flat load (g m^{-2} per year)	0.107	0.117	1.04	0.65

DISCUSSION

The applied classification of Vollenweider (1968) revealed that major part of the risk threatening Alum Lake water consists in rainfall quality and quantity. The positive effect of industrial progress and the overall improvement of the environment in the region was reflected in the decrease of lake water N load. The cultural euthrophication is the leading cause of water pollution for many basins being a fast growing problem in the developing world (Smith, Schindler, 2009).

The most noticeable effect of cultural euthrophication is the dense bloom of algae that reduces water quality and harms water clarity (Chislock et al., 2013

The assessment according to the ecological evaluation of Alum Lake by Vucka, Nesmerak's (1989) methodology, carried out by Hydroprojekt Praha, claims that the lake water has a very good ability to withstand the influence of external conditions and maintains a relatively stable quality. Concerning the lake's resilience to resist biodegradation, the lake should be included among the lakes with adverse natural conditions, with the possibility of being subject to degradation, and any external influence can lead to its biodegradation (Kos et al., 1981). Therefore, interventions into the lake ecosystem must be carried out professionally, with extreme caution.

Proposal of revitalizing measures

The proposed revitalizing measures are both of technical and organizational character. A comprehensive hydrogeological survey is a basis for the subsequent optimal interventions and measures, followed by regular monitoring of both the lake water quality and the outdoor lake conditions (water analyses at regular intervals, cleaning of bottom sediments, regular underwater monitoring).

The main technical measure preventing eutrophication of Lake Alum is the periodic revitalization work: sediment extraction from the bottom of the lake (approximately once in 5 years). The removal of sediments releases the path for underground mineral springs. It is also important not to interfere the chemistry of water (e.g. by the artificial addition of alum). The artificial alum was added in Alum Lake water several times in the past, leading to a temporary increase of mineralization and acidity of the lake water. Moreover, once the existence of underground springs has been proven, such interference is considered as a highly contra-productive (Gabrielova, 1996). To avoid coagulation of salts (Fe^{3+} and Al^{3+}), the pH of the water must be kept below 4.2. Another advice is the use of suitable materials corresponding to the lake's water character for landscaping around the lake (e.g. using washed river sand for beach treatment); to collect the leaves fallen on the water surface and around the lake from time to time (e.g. with a special rake – as practiced in the past); planting of evergreen shrubs along the shore of the lake, which could serve as biological barriers to protect the water surface from the flood of fallen leaves; rubbish or prevent the entrance to the lake outside the reserved areas; to eliminate the entrance to the lake directly from the banks – build up additional piers and entrances.

The organizational measures include avoiding the increase of recreational capacity. It is necessary to amend the operating rules of the lake: to ensure the needed control over the entrance to the lake outside the reserved areas, to perform regular inspections of the operation of the lake during the summer season.

CONCLUSION

Due to the chemical composition of the lake water, Alum Lake represents a unique natural phenomenon, which must be treated with due care. Despite of uncontrolled external influences and nonconceptional interventions, the lake water stays fairly stable in its quality. The fluctuations in the concentrations of certain substances can largely be attributed to the fact that since 1993 the lake has not been cleaned and the alum water springs have been flooded with a thick layer of bottom sediments. The rainfall activity is still the most important factor influencing the lake water chemistry. The application of modern desulphurization technologies and heavy industry attenuation in the North Bohemian Brown Coal Basin has changed the quality of precipitation and reduced the impact on water chemistry in the lake.

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Corresponding Author:

Ing. Andrea J e l í n k o v á , Ph.D., Czech University of Life Sciences Prague, Faculty of Environmental Sciences, Kamýcká 129, 165 21 Prague 6-Suchdol, Czech Republic, phone: +420 777 273 137, e-mail: cherry.name@seznam.cz