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Trace elements in water, sediments, porewater, and biota polluted by tailings from an abandoned gold mine in British Columbia, Canada

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Abstract

The concentrations of major and trace elements in different environmental compartments (e.g., water, suspended and bottom sediments, sediment porewater, and biota) of Jack of Clubs Lake (JCL), Wells, British Columbia (Canada), were determined to assess the biogeochemical effects of abandoned gold mine tailings on the aquatic ecosystem of JCL in the Fraser River drainage basin. Arsenic and Pb were transported from the tailings to the lake, where they accumulated in bottom sediments in concentrations up to 1104 and 281 $\mu g/g$, respectively. Although the benthic community in the lake was only partially affected, there was evidence that the tailings inhibited a variety of microbial activities in the lake sediments. The concentrations of As, Cd, Cu and Pb in invertebrates collected from streams flowing through mine tailings, and from vegetation growing on the tailings, suggest a potential for contamination of the food chain of the surrounding ecosystems.

1. Introduction

Environmental effects of past gold mining activities have recently received considerable attention in Canada and other countries. The main environmental concerns of gold mining include adverse effects on the health of gold miners (Becklane et al., 1987; Cowie et al., 1989; Hnizdo and Sluiscremer, 1991), the management and treatment of mine tailings (Halverson and Raponi, 1987; Wilson, 1991; Suttill, 1988; Shakesby and Whitlow, 1991; Norris, 1986), and the distribution of trace elements in water and sediments of streams affected by mine discharges (Azcue and Nriagu, 1993; Davis et al., 1991; Malm et al., 1990).

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Gold mining has been a major activity in Canada for over a century, and the Cariboo region in British Columbia (B.C.) has been an important gold mining area since the 1800's. The town of Wells, B.C., on the northeast shore of Jack of Clubs Lake (JCL), was built on tailings from the old Lowhee Gold Mine. During its 33 years of operation (1933 to 1966), the Cariboo Gold Quartz Mining company produced in excess of five million dollars worth of gold.

Potential health risks associated with the development of a community recreation site on the abandoned tailing deposits at Wells, contamination of groundwater, and transport of contaminants in tailing particles by wind have been studied recently (Andrews, 1989; Galbraith, 1991). However, there is only limited information on the effects of the abandoned gold mine tailings on the aquatic ecosystem of JCL and the Willow River, a tributary of the Fraser River, B.C. A multidisciplinary study was initiated to determine biogeochemical effects of the gold mine tailings on ecosystems in and adjacent to JCL (Mudroch et al., 1993).

The main objectives of this study were (1) to determine the distribution of major and trace elements in the different environmental compartments, such as water, suspended and bottom sediments, sediment porewater, and biota of Jack of Clubs Lake; and (2) to determine the effects of the abandoned tailings on the biota in the lake and the adjacent terrane.

2. Materials and methods

2.1. Study area

Jack of Clubs Lake (JCL) is in the Barkerville Terrane, which is underlain mostly by clastic sedimentary rocks, principally Precambrian and Palaeozoic sandstone, greywacke, and black and green pelite, with minor proportions of limestone and mafic volcanic rocks (Struik, 1988). The tailings from the milling and gold extraction were discharged into the northeast end of JCL, changing its original morphometry. The lake is nearly 2.4 km long and 0.5 km wide, with a mean depth of 19 m and a maximum depth of 63 m. At present, approximately 25 ha of land adjacent to the lake are covered with the gold mine tailings to a maximum thickness of about 4.5 m (Fig. 1).

Lowhee Creek flows through tailings deposited on the shore of JCL before it empties into the northeast end of the lake. During spring runoff the waters of the creek flood an extensive area of the tailings. A man-made channel dug through the tailings at the northeast end of the lake drains into the Willow River, the only outlet of the lake, which flows for 130 km before discharging into the Fraser River. Part of the water flowing through this channel originates as groundwater seepage from the tailings and does not reach the lake. Bowron Lake (BL), located about 30 km east of Wells, was selected as a control or reference lake for the study (Fig. 1). This lake is in the Bowron Lake Provincial Park, and there are no reports of mining activities, past or present, along the lake. The surface area of the lake is over 121,600 hectares. The Bowron River drains the north side of the lake and enters the Fraser River near Prince George.

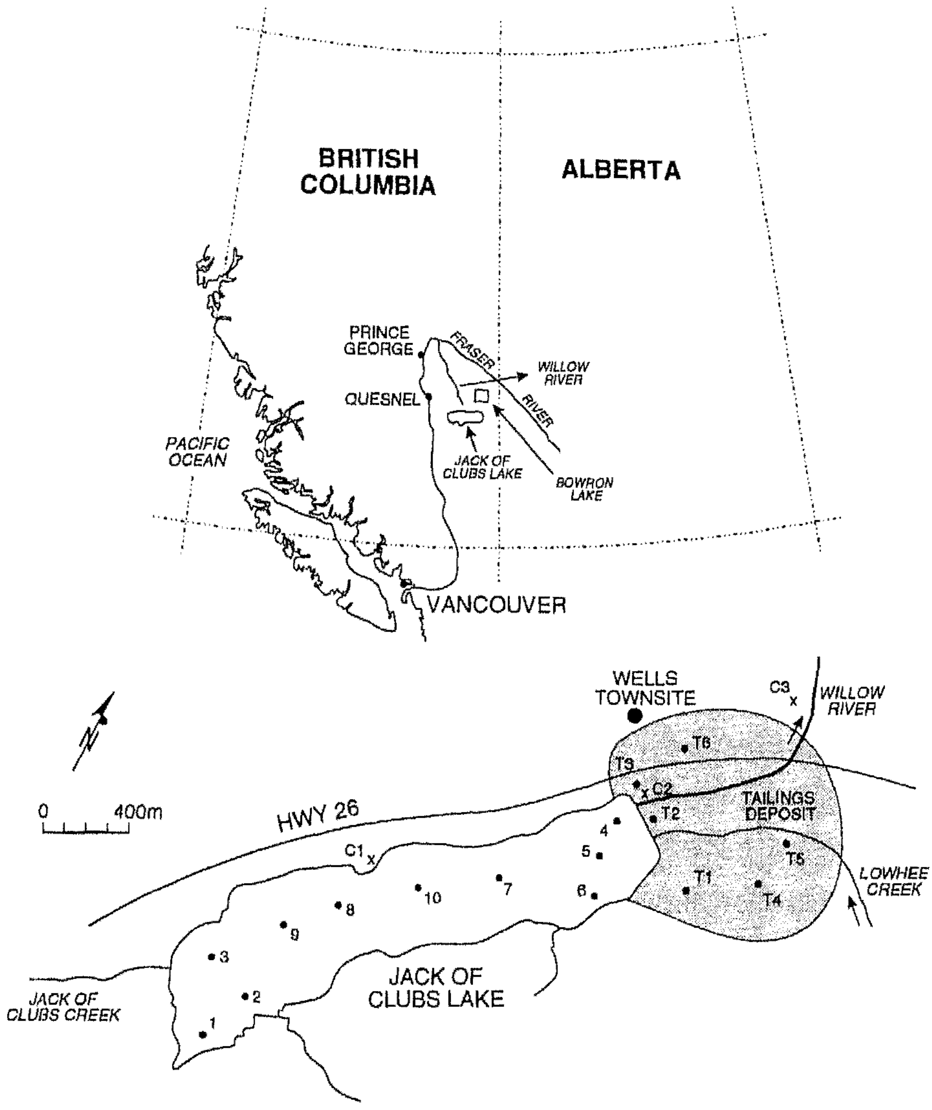

Fig. 1. General map of the study area and location of the sampling stations. T1 to T6 sampling sites in the tailings; 1 to 10 sampling sites in the lake; C1 to C3 centrifuge locations for suspended sediment sampling.

2.2. Sample collection

Ten sampling stations were established in JCL (Fig. 1). Water samples from JCL were collected 1m below the surface and 1m above the bottom using a van Dorn bottle. Water samples were also collected in adjacent streams (Fig. 1). The samples were filtered in the field within a few hours of collection using a Millipore glass filter apparatus with 0.45 μm cellulose acetate filters. Groundwater was sampled by piezometers previously inserted into the tailings. The water level in each piezometer was measured and the standing water was pumped out. The water in the piezometers was allowed to recover overnight, and the next day any water which had accumulated during the night was pumped out at a low flow rate, using prewashed polypropylene tubing attached to an in-line 0.45 μm filter.

Samples of surface sediments were collected at the 10 sampling stations in JCL using a Miniponar grab sampler. A modified Kajak-Brinkhurst corer was used to collect sediment cores for determination of concentration profiles of major and trace elements in the sediments. Sediment cores were divided into 1-cm sections. The sediment fractions were kept in sealed plastic bags at 4°C during transport to the laboratory where they were frozen and stored prior to analysis. Sediment core sections 0 to 5, and 5 to 10 cm were extruded from the core liner under an atmosphere of N_2 and squeezed separately to collect the sediment porewater using a squeezer assembly designed by Kalil and Goldhaber (1973). During the squeezing process the porewater was passed through a 0.45 μm Millipore filter. Porewater samples from individual sediment sections were collected in vials pre-acidified with two drops of ultra pure conc. HNO_3. Suspended sediments were recovered from three locations in the study area (C1, C2, and C3 in Fig. 1). About 2000 litres of water were pumped into a Westfalia separator (Rosa et al., 1991) at a flow rate of 4 L/min to collect the suspended sediments, which were then freeze-dried, weighed, homogenized by grinding, and analyzed for major and trace elements.

Sediment samples for determination of benthic invertebrate community structure were collected by a modified Kajak-Brinkhurst corer using a plexiglas core liner with an inside diameter of 6.6 cm. Only the top 10 cm from each core was used in this study. The surface area of the sample was 34.2 cm^2, and the volume was 342 cm^3. The sediment was placed in a glass tray, homogenized with a plastic spoon and transferred to plastic vials. The samples were stored at 4°C in the field and freeze-dried on arrival in the laboratory. The same procedure was used to collect invertebrates from the tailings for chemical analysis. Sediment samples collected for the determination of benthic invertebrates were sieved in the field using a 250 μm mesh sieve. Sieved samples were preserved in 4% formalin for sorting and identification in the laboratory (Reynoldson et al., 1991). Eleven species of lower vegetation and leaves, needles and branches of four species of trees (Engelmann spruce, willow, lodgepole pine, and subalpine fir) were collected at the tailings and along creeks and lakes distant from the tailings (Azcue and Mudroch, 1993).

Samples of surface and bottom water and bottom sediments were also collected from two sites in the control or reference lake (Bowron Lake). The data from the two sites were averaged, and the averaged data were simply designated as Bowron Lake. This lake was not surveyed for benthos because of its different size, morphometry, and water depth compared to JCL.

2.3. Analytical methods

Particle size distributions in wet lake sediment samples were estimated by the "sieve and sedigraph method", using a Warman cyclosizer (WR-200) and sieves (LC-10B) (Duncan and Lahie, 1979). Carbon analyses were performed on freeze-dried samples using LECO-12 Carbon Analyzer, and loss on ignition was determined by ashing dry sediment at 450°C to constant weight (i.e. for about 3 h).

Sediment samples for the study of the microbial communities were collected from three sites in JCL: one close to the northeast end, where the tailings were deposited (station 4); a second one at the centre of the lake (station 9); and a third one near the southwest end, which is farthest from the tailing deposits (station 1) (Fig. 1). Soon after collection of the samples, the sediment pH and Eh were measured. The sediments were then analyzed for microbial dehydrogenase and alkaline phosphatase activity and for microbial CO_2 production and denitrification under both aerobic and anaerobic conditions (Jackson, 1988; Liu and Strachan, 1981). Operationally defined "bio-available" metal species in the solid phase were determined by dividing the material into two sets of subsamples and then extracting one set with 0.5 M $CaCl_2$ and the other one with a solution of DTPA. The extractions were performed under an atmosphere of N_2. In addition, sedimentary humic matter was extracted with 0.1 M NaOH under N_2, and the UV–visible absorption spectra and Fe and organic C content of the extracts were recorded. Humic content was estimated by measuring the absorbance of the extract at 465 nm, and the degree of "humic" as distinct from "fulvic" character of the humic matter was estimated by means of the absorbance ratio A_{465nm}/A_{665nm} (otherwise known as the "E_4/E_6" ratio) Fe and Mn oxyhydroxides in sediments were determined by sequential extraction with N_2-purged solutions of NH_2OH : HCl and citrate–dithionite, in that order, followed by analysis of extracts for Fe and Mn (Schnitzer and Khan, 1972).

The lake and stream waters were analyzed for 47 parameters at the Geological Survey of Canada (Finch et al., 1992). Trace elements in all samples (sediment, porewater and biota) were determined by ICP (AES and MS). Major cations were determined by air–acetylene AAS. Cesium at 0.1% was used as an ionization buffer and La at 0.5% as a releasing agent. Anions were determined by ion chromatography with detection by conductivity using a Dionex Ion Chromatograph according to the method described by Smee et al. (1978). Standard solutions were prepared in the same matrix as the samples and the blank solution. Accuracy and precision of the method was monitored by analysis of reference materials (NBS 1643c, NBS 2704, and NBS 1645). Suspended sediments were analyzed by the techniques described by Mudroch and Duncan (1986).

3. Results and discussion

Both JCL and Bowron Lake were thermally stratified at the time of sample collection. Conductivity and pH in Bowron Lake decreased with depth, following the same pattern as temperature. In JCL, conductivity values fell to a minimum (ca. 65 μS/cm) in the thermocline and increased in the hypolimnion (up to 86 μS/cm). This increase was probably due to the release of SO_4^{2-} from contaminated bottom sediments. The average concentrations of SO_4^{2-} in JCL were 19.6 mg/L and 9.8 mg/L, in the hypolimnion and epilimnion, respectively. The oxygen concentration was greater than 7.5 mg/L at all sampling stations. Jack of Clubs Lake was characterized by low primary production, based on the chlorophyll levels (0.3 μg/L), and low concentrations of particulate nutrients. Microbial activities in the sediments were found to be suppressed by tailings deposited in the lake (see below). The low primary production in JCL may also reflect adverse effects of the tailings.

Table 1
Average concentration (μg/L) of dissolved (<0.45 μm) trace elements in different water bodies in Wells, B.C. Data presented as arithmetic mean with standard deviation and range

	As	Cd	Cu	Pb	Zn
Jack of Clubs Lake	0.28 ± 0.02 (0.2–0.41)	0.03 ± 0.01 (0.01–0.13)	1.37 ± 1.5 (0.3–13.8)	0.06 ± 0.05 (0.02–0.45)	1.2 ± 0.7 (0.5–6.1)
Willow River	0.59 ± 0.19 (0.29–0.85)	0.04 ± 0.02 (0.01–0.27)	2.4 ± 0.9 (0.8–3.9)	0.09 ± 0.03 (0.03–0.14)	0.87 ± 0.47 (0.7–13.7)
Lowhee Creek	1.5 ± 1.1 (0.21–2.08)	0.38 ± 0.3 (0.01–1.4)	3.6 ± 2.9 (0.4–6.3)	0.18 ± 014 (0.02–1.73)	2.6 ± 1.6 (0.2–6.1)
Bowron Lake	<0.2	<0.01	0.6	<0.02	<0.1
Ground water from tailings	162 ± 60 (102–281)	84 ± 45 (35–131)	27 ± 22 (0.001–55)	243 ± 85 (129–322)	209 ± 96 (53–296)
Porewater from Lake	122 ± 90 (51–361)	8.3 ± 16 (1.0–54)	39 ± 25 (1.0–81)	19 ± 11 (5.0–38)	131 ± 125 (17–796)

The greatest concentrations of As, Cd, Cu, Pb, and Zn in the water occurred in a seep characterized by pH 2.7 situated on the downslope of the abandoned Cariboo Gold Quartz mine tailings. Regardless of these anomalous levels of trace elements (i.e. up to 556 μg/L of As) in the streams flowing into JCL, concentrations in the lake water were low (Table 1), and the pH of the lake water was close to 7.0. Concentrations of trace elements were virtually the same in the surface and bottom waters. The results indicated limited migration of the trace elements from the sediments into the overlying water. Due to the difference in groundwater flow rates through the sediments and tailings and the low permeability of the tailings, the majority of the groundwater flows in the deeper sediments or discharge to surface watercourses (Rescan, 1990). In some cases the concentrations of trace elements in bottom water were lower, as shown for As, implying that As was being removed from solution as the pH increased and Fe and Mn oxyhydroxides precipitated at the sediment–water interface. Although the concentrations of trace elements in JCL water were different from those of Bowron Lake, concentrations of major ions were fairly similar with the exception of SO_4^{2-} (ca. 10–20 mg/L in JCL vs. 2 mg/L in Bowron Lake). The concentrations of major and trace elements, with the exception of As, Ni and Cu, in waters of BL and JCL were not statistically different.

Concentrations of As in sediment porewater were four orders of magnitude greater than in the lake water (Table 1). The average As and Zn concentrations in the groundwater from the tailings were similar to the levels found in the sediment porewater in the lake. However, the average groundwater concentrations of Pb and Cd were much greater than those in the porewater. Previous studies (Rescan, 1990) showed that groundwater has a lateral component of flow away from the tailings and is directed strongly to the northwest and mildly southward into the lake. Groundwater velocity in the tailings is approximately 0.004 m/day towards the lake and 0.015 m/day towards the northwest. In the suspended sediments, the greatest concentrations of As, Pb, Zn, Cd and Cr were found in the samples collected from the Willow River at the outflow from JCL. However, the concentrations of these particle-associated trace elements were greater in the bottom sediments of the lake, suggesting limited transport of these elements into the river. The concentrations of major and trace elements in suspended sediments in the Willow River decreased with increasing

Table 2
Trace element concentrations in the bottom sediments, suspended particles ($\mu g/g$) and biota ($\mu g/g$ dry weight). Data presented as arithmetic mean with standard deviation and range

	As	Cd	Cu	Pb	Zn
Bottom sediments					
Jack of Clubs Lake	342±296	1.86±1.3	63.8±11.7	152±63	354±96
	(80–1104)	(0.2–5.25)	(40–76)	(68–281)	(174–450)
Bowron Lake	21±7.2	1.4±0.7	47±8.6	37±19	137±46
	(8.8–25.4)	(0.2–1.8)	(28–63)	(8–61)	(71–156)
Tailings	903±467	3.9±2.7	29±15	467±107	303±123
	(396–2000)	(1.6–12.0)	(11–37)	(68–281)	(174–516)
Suspended particles					
Jack of Clubs Lake	601±436	4.5±1.1	58±17	262±194	184±29
	(244–1215)	(2.9–6.2)	(42–82)	(103–535)	(157–225)
Biota					
Vegetation	11.2±10.6	0.83±0.6	7.4±5.1	6.3±6.1	40±27
	(1.86–54)	(0.02–4.1)	(3.0–18.1)	(0.01–27)	(11.6–80)
Invertebrates	721±307	25±7.9	301±83	435±257	830±484
	(288–915)	(18.7–36)	(298–583)	(137–764)	456–1514

distance from the lake. Arsenic, Fe, Mn, and Pb concentrations were significantly greater in the tailings than in the bottom sediments of JCL, suggesting limited solubility of As and Pb in the tailings. This was most likely due to adsorption of As and Pb onto and/or co-precipitation with ferric oxyhydroxides in the tailings (Azcue et al., 1994).

The average concentrations of trace elements in the bottom sediments of the lake and in the tailings are presented in Table 2. Generally, the concentrations in the tailings are considerably greater than in JCL sediments. However, they are comparable with tailings at other mining areas (Azcue and Nriagu, 1993; Sidle et al., 1991; Adriano, 1986). A peak in the concentrations of several trace elements (particularly Fe, As, Ni, Zn and Cu) at 4 to 6 cm depth in the sediment collected at station 10 in JCL, most likely reflects the inputs of these elements from past gold mining activities at the Cariboo Gold mine around 1940 (Fig. 2). This assumes the annual sedimentation rate of 1 to 2 mm in the lake. The loading of As and Pb from the tailings to the lake is evidenced by a concentration gradient of these elements from the end of the lake where the tailings were deposited (with concentrations of As and Pb in the sediments — 1104 and 281 $\mu g/g$, respectively), to the opposite end (with 98 and 88 $\mu g/g$ of As and Pb, respectively). Elevated concentrations of Pb (up to 3470 $\mu g/g$) were found in the < 13 μm size fraction, with decreasing concentrations with increasing size fractions. Consequently, large quantities of Pb bound to the fine silt and clay fractions may be mobilized by erosion of the fine particles of the tailings. On the other hand, As preferentially bound to coarser sediment fractions (i.e., silt) tends to be less mobile by erosional processes (Azcue et al., 1994).

The elevated concentrations of As, Pb and Cd observed in the invertebrates and vegetation collected from the tailings (Table 2) are comparable to reported values from heavily contaminated environments (Besser and Rabeni, 1987) and confirm the high bio-availability of these elements in the tailings. Preliminary examination of the benthic community

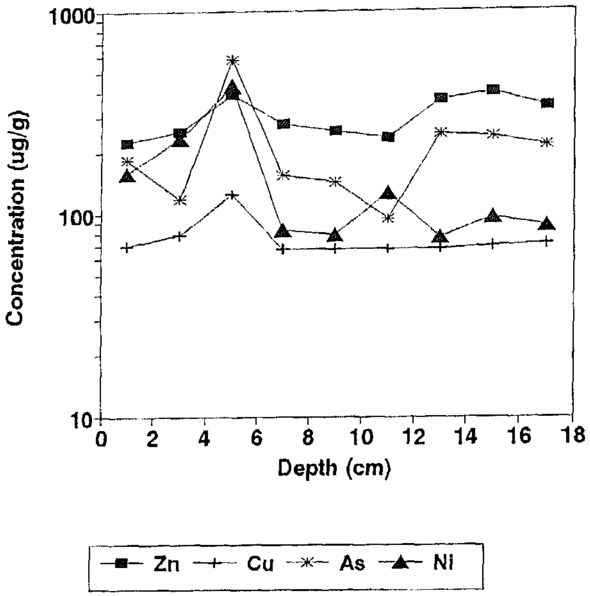

Fig. 2. Profiles of total zinc, copper, arsenic, and nickel in sediments of Jack of Clubs at station 10.

structure in the lake did not demonstrate conclusively that mine tailings had significantly impacted the lake. There was, however, some indication of reduced overall numbers of benthic organisms at station 5. The bivalves appear to be particularly sensitive, as indicated by their reduced numbers at stations 4 and 5. However, without reference data from similar lakes in the study area it is difficult to determine what type of benthic community could be expected. Trace element concentrations in some of the plants growing on the tailings suggested preferential accumulation of certain elements, such as As, Cd, Cr, and Pb. In general, deep-rooted species accumulated greater concentrations of trace elements than did shallow-rooted ones.

Chemical analyses and assays of microbial activities performed on samples of bottom sediments collected along a transect from one end of the lake to the other showed clear evidence of environmental impacts by the tailings deposited at the northeast end of JCL (Table 3). For example, a wide range of microbial activities, including heterotrophic CO_2 production, denitrification, biochemical reactions catalyzed by alkaline phosphatase and dehydrogenase, and the process of humification, tend to be suppressed by the tailings. The most probable mechanisms of inhibition were the poisoning of enzymes by certain bio-available species of Cu and Pb (possibly aggravated slightly by a small reduction in the sediment pH), the dilution of organic nutrient substrates, smothering of microbes by mineral detritus from the tailings, and partial suppression of the production of organic nutrient substrates owing to inhibition of plankton and other aquatic organisms (Table 3). The cause of the observed inhibition of sedimentary microbes has not been determined with certainty, but it could have been any one of these phenomena or a combination of them.

In conclusion, there is evidence that As, Zn, and Pb have been transported from the tailings into the lake. Arsenic was present in anomalously high concentrations in sediments at the northeast end of JCL and at considerably lower values in the rest of the lake. Moreover,

Table 3
Measurements of microbial activities, solvent-extractable metal species, and various data characterising the sediment samples from JCL and BL arranged in the expected order of decreasing severity in pollution (going from left to right)

Sampling site	JCL-4	JCL-9	JCL-1	BL
pH	6.55	6.6	6.7	6.8
Loss of ignition (%)	4.05	5.7	10.4	15.6
Alkaline phosphatase activity (units/g/h)	0.16	0.28	0.61	1.24
Total dehydrogenase activity (μmol/g/h)	52.5	125.3	182.5	205.9
CO_2 produced by day 10 (μmol/g) under anaerobic conditions	4.78	4.74	9.67	10.4
N_2O produced by day 10 (μmol/g) in presence of acetylene under anaerobic conditions	4.03	6.66	35.5	25.6
$CaCl_2$-extractable Cu (μg/g)	0.174	0.086	0.079	0.059
DTPA-extractable Pb (μg/g)	1.58	1.63	0.49	0.68
$A_{465\ nm}$/g	0.038	0.101	0.272	0.319
$A_{465\ nm}/A_{665\ nm}$	8.27	7.22	6.97	6.32
$NH_2OH \cdot HCl$-extractable Fe (mg/g)	0.714	1.795	4.44	6.51
NaOH-extractable Fe (mg/g)	0.047	0.125	1.60	1.21

the data suggest that the tailings inhibit a variety of microbial activities, including enzyme function, CO_2 production, humification of organic matter, and denitrification. However, the benthic community in the lake does not appear to be impaired. Capping with clean material and revegetation of the abandoned mine tailings, though not a final solution, was recommended to minimize erosion of the tailings by water and wind with subsequent transport into the surrounding environment.

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