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Tale of two pit lakes: Initial results of a three-year study of the Main Zone and Waterline pit lakes near Houston, British Columbia, Canada

Introduction

Pit lakes are becoming increasingly common in North America as well as in the rest of the world. They are created as openpit mines fill passively with ground water and surface inflows on cessation of mining activity. In many instances, the water quality in these pit lakes does not meet regulatory requirements due to a number of influences. The most important are the oxidation of sulfide minerals and the associated release of acid and metals and the flushing of soluble metals during pit filling. Examples of pit lakes with severe water-quality problems include the Berkeley Pit lake (Butte, MT) and the Liberty Pit lake (Nevada), whose waters are characterized by a pH near 3 and Cu concentrations as high as ~150 mg/L (Miller et al., 1996; Davis and Eary, 1997). The importance of the problem can be seen in the fact that some of these sites in the United States are Superfund sites.

In an effort to advance the understanding of the controls of pit lake chemistry, a three-year research program was initiated by scientists at Lorax Environmental Services and the University of British Columbia. The pro-

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gram was jointly sponsored by the Natural Sciences and Engineering Research Council (NSERC) of Canada and by industry. This paper presents an overview of the program, as well as a summary of initial results of the field survey. Despite the limited field data, the results allow identification of some of the controls of the chemistry of the lakes and point to additional questions to be addressed in the near future.

Site description

The Equity Silver Mine, located near Houston, BC, Canada, operated from 1980 through 1994. Ore was extracted from three openpits as well as underground workings. Since mine closure in 1994, one of the pits (the Southern Tail pit) has been backfilled with waste rock and tailings, while the Waterline and Main Zone pits were allowed to fill with a combination of ground water, surface runoff and precipitation. Lakes now fill these latter two pits.

The Main Zone pit lake is roughly 400 x 800 m (1,310 x 2,620 ft) and has a maximum water depth of a little more than 120 m (390 ft). Hydroxide sludges are

Abstract

The Main Zone and Waterline pit lakes at the Equity Silver Mine near Houston, BC, Canada, are the sites of a three-year research program. Its primary goals are to understand the controls on metal concentrations in the lakes. The program used mesocosms to test a variety of remediation strategies and verify and improve an existing coupled physical-geochemical model to improve predictions of pit lake water quality. Initial data from two summer surveys in the Main Zone pit lake reveal elevated dissolved metal concentrations (Zn as high as 800 µg/L) in a 2-m- (6.6-ft-) deep mixed layer and reveal elevated particulate metal concentrations towards the bottom of the water column. Hydrox-

ide sludge, a byproduct of acid rock drainage (ARD) treatment, is being discharged to the surface waters of the Main Zone pit lake. The sludge sinks rapidly to the lake bottom, which leads to deep waters with elevated levels of dissolved O₂ and total metals.

By contrast, the deep waters of the proximal Waterline pit lake are mildly reducing, manifested by depletion of O₂ and elevated levels of dissolved Fe. These reducing conditions have led to elevated levels of As (up to 1,500 µg/L) in Waterline pit deep waters. The contrasting behavior of these two pit lakes, as well as the processes controlling metal concentrations in the lakes, is discussed.

FIGURE 1

View of the Equity main zone pit sampling raft, with assorted sampling equipment.



discharged periodically by a pipe to a gully tens of meters from the Main Zone pit, down which the sludge flows into the surface waters of the lake.

The Waterline pit lake, located immediately to the north, is about 100-m (330-ft) wide x about 500-m (1,600-ft) long. It is now a little more than 40-m (130-ft) deep. No sludge is discharged to the Waterline pit lake. The elevation of the surface of this pit lake is roughly 5 m (16.4 ft) higher than that of the Main Zone pit. Hence, Waterline surface waters flow into the Main Zone pit at 5 to 10 L/sec (80 to 160 gpm) during the summer. During the

open-water season, the only other significant inflow into the Main Zone pit (in terms of water flux) is the hydroxide sludge inputs at ~5 L/sec (80 gpm) on average.

Sampling and analysis methods

Much of the sampling on the Main Zone pit lake was carried out on a 5- x 5-m (16- x 16-ft) raft (Fig. 1). It was installed above the deepest portion of the lake during the initial field survey. This raft is anchored to four points above the pit wall. The raft houses a meteorological station that incorporates temperature, relative humidity and solar irradiance sensors, as well as an anemometer and a tipping-bucket rain gauge. The raft also incorporates two 0.6- x 0.9-m (2- x 3-ft) sampling ports. One sampling port is used to deploy a thermistor string and a current meter. The second is used to collect the vertical chemical profiles. In addition, during the summer of 2002, the raft served as the support base for the mesocosms, or limnocorrals, in which remediation strategies were tested.

Profiling several physical parameters was carried out using a Seabird conductivity, temperature and depth meter (CTD). In addition to the standard sensors of conductivity, temperature and pressure (which can be converted to depth), the instrument was outfitted with a fluorometer and a transmissometer. The fluorometer measures in situ fluorescence, which can be correlated to the concentration of chlorophyll. The transmissometer measures light transmission, which is related to suspended-matter concentration. A schematic presentation of the sampling raft and equipment is shown in Fig. 2.

Water samples were collected in a 5-L (1.3-gal) Go-Flo bottle using a hand-operated winch outfitted with a trace-metal-clean Kevlar line. Sample processing was carried out immediately after sample collection either on the raft (for Main Zone pit samples) or on a 4-m (13-ft) rowboat (for Waterline Pit samples). Nutrient and metal samples were collected in acid-washed LDPE bottles. Dissolved samples were filtered through 0.45- μ m acid-

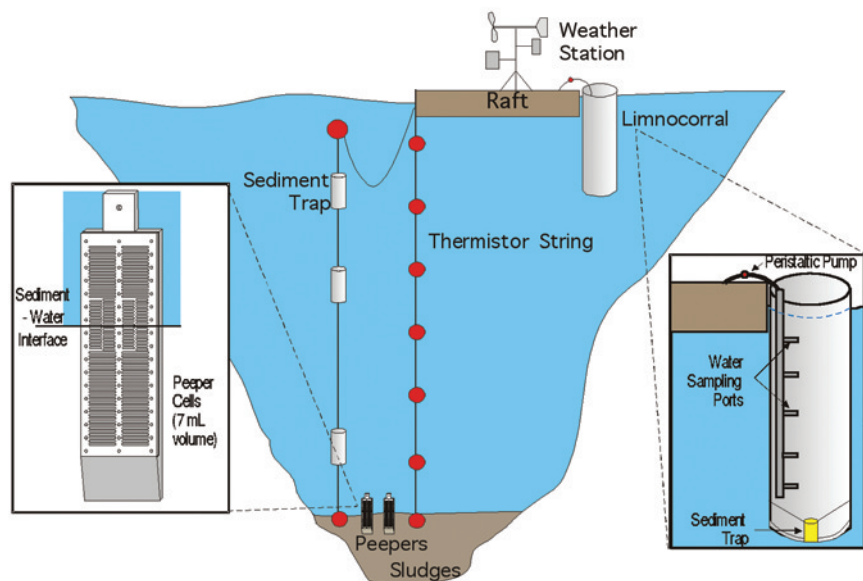
washed cellulose-acetate filters. Samples for chlorophyll a were collected by filtering 100 to 500 mL of water through 25-mm GFF filters. Nutrient and chlorophyll samples were kept cold in coolers during sampling and transported to the laboratory where they were frozen within six hours of collection. Dissolved O₂ was determined on selected samples in duplicate by the Winkler method. Metal concentrations were determined by ICP-MS by the methods of Martin et al. (2001).

Research program overview

The three-year research program consists of three primary components. The first component is a two-year whole-lake field survey. It is aimed at identifying and quantifying the dominant processes controlling metal concentrations in the pit lakes. This portion will attempt to identify the sinks for metal removal

FIGURE 2

Schematic of field deployment of sampling equipment in the pit lakes at the Equity silver site.



from the water column, as well as the sources, and will address how physical processes (mixing) influence metal distribution. Processes to be evaluated that could be removing metals include biological metal uptake, scavenging (adsorption) to settling particulate material and diffusive metal uptake in the sediments. Sediment traps (Fig. 2) have been deployed to permit quantification of metal removal on settling particulate material. Processes to be evaluated that could lead to metal additions include leaching from the pit walls, direct inflows and metal release from the sludge as it is being discharged to the water column or after deposition on the bottom.

The second component of the field program, carried out in the second year, involved experimental pit lake manipulations, designed to test a variety of remediation strategies in enclosures, or limnocorrals. A number of possible remediation strategies could be evaluated, including:

- the addition of nutrients that might increase biological productivity and remove metals by biological uptake and scavenging mechanisms,
- the addition of clays that could remove metals by scavenging processes and
- the addition of hydroxide sludge that may remove metals by scavenging processes.

The sludge is a byproduct of ongoing ARD treatment and is, thus, readily available. However, because it contains elevated concentrations of particulate metals derived from the treatment process, its addition could lead to the release of soluble metals to the water column. This possibility will also be evaluated.

Finally, after the whole lake surveys and the enclosure manipulations are complete, the data will be used to validate and improve an existing coupled physical-chemical pit lake model (Crusius and Dunbar, 2002). The model considers physical and chemical processes in the lake.

The physical component simulates temporal changes in the water density throughout the lake. It does this by considering the influences of salinity and temperature, which determine water density, as well as processes such as winds and heating by the sun, which can perturb the density structure. In addition, the physical component predicts the oxygen concentration of the water column based on estimates of oxygen consumption in the water and in the sediments. The physical component of the model was developed to interpret the long-term behavior of the Island Copper Pit Lake (Dunbar and Hodgins, 1990).

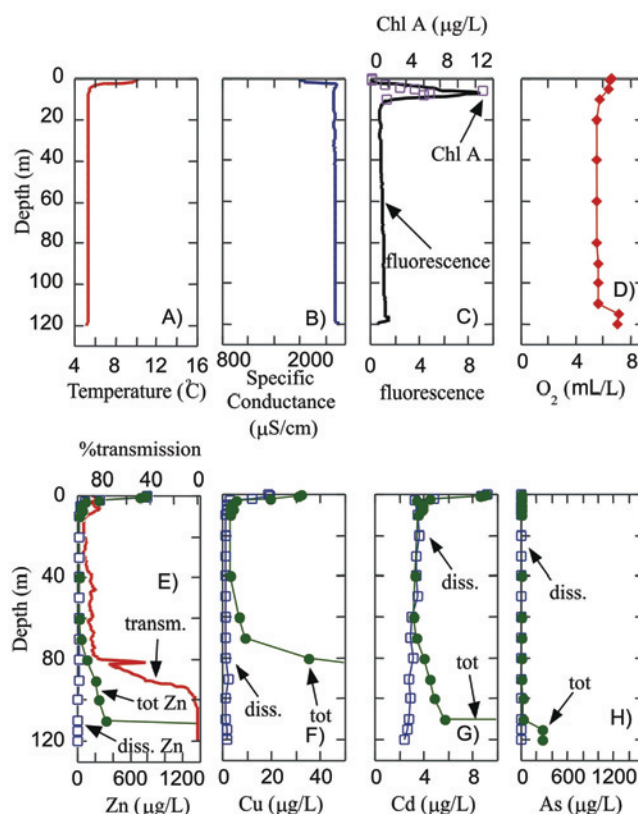
The chemical component of the model requires inputs in the form of chemical concentrations. It makes predictions of the changes in lake chemistry over time as driven by the oxygen consumption, physical mixing, etc. This chemical portion of the model is PHREEQC, a chemical speciation model developed by the U.S. Geological Survey (USGS) (Parkhurst and Appelo, 2000). The net effect of the physical and chemical processes on pit lake water properties is determined by the model by cycling repeatedly between the physical and chemical portions.

Initial field results

The two-year field program commenced in late June

FIGURE 3

Profiles of temperature; conductivity; chlorophyll a; fluorescence; dissolved O₂; percent light transmission; and Zn, Cu, Cd and As concentrations in the Main Zone pit lake from the sampling period June 21-29, 2001. The scales for the metal profiles are intended to optimize viewing of the dissolved metal profiles. Hence, some of the total metal profiles extend off scale at the bottom.



of 2001, so this paper presents only the initial results. However, the data amassed to date already shed considerable light on the processes controlling metal concentrations in the pit lakes. Results from both the Main Zone pit lake and the Waterline pit lake are presented below.

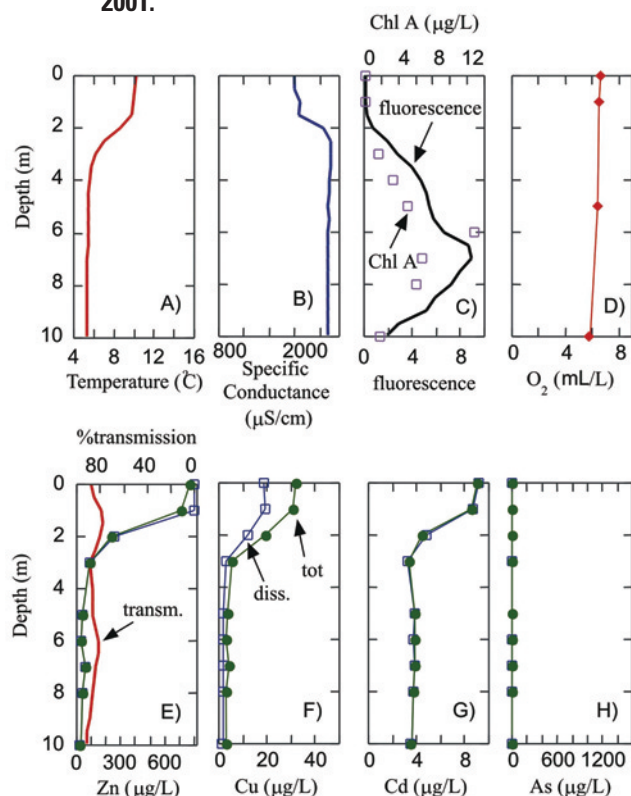
Main Zone pit lake

Stratification and other physical properties: In late June and in mid-August, the Main Zone pit lake was strongly stratified due to a combination of elevated temperatures and low conductivity in the surface waters (Figs. 3a,b through 6a,b). The low-conductivity surface waters most likely result from a combination of snowmelt, surface runoff and inflow from the Waterline pit. However, the contrast between surface-water and deep-water conductivity was much reduced in August. This was undoubtedly due to a combination of reduced inflows of low-conductivity water to the lake surface and enhanced mixing between surface and underlying waters of higher conductivity.

During June and August, a significant biomass of phytoplankton was present in a well-defined region at a

FIGURE 4

Expanded profiles, top 10 m (33 ft), of temperature; conductivity; chlorophyll a; fluorescence; dissolved O₂; percent light transmission; and Zn, Cu, Cd and As concentrations in the Main Zone pit lake from the sampling period June 21-29, 2001.



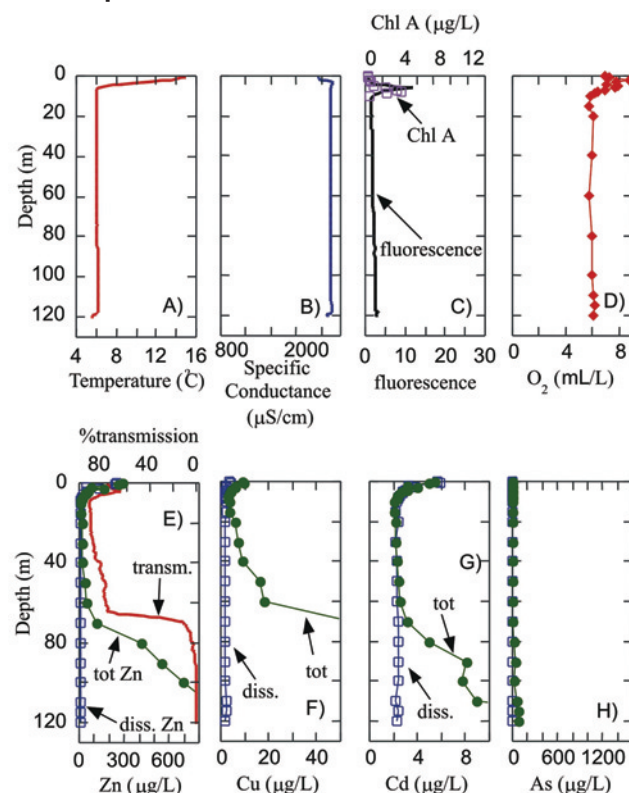
depth of from 4 to 9 m (13 to 30 ft) as indicated by measurements of chlorophyll a and in situ fluorescence (Figs. 3c through Fig. 6c). The fluorescence values can thus be used as a proxy for algal biomass (the depth offset between the fluorescence and chlorophyll a data (Fig. 4c) reflects discrepancies in sampling depth that are being reconciled). Preliminary nutrient data can be used to assess the controls on biological productivity in the lake. Dissolved phosphate is present at levels below the detection limit (0.2 μM) at all depths (data not shown). This is not surprising, given the known tendency of phosphate to be scavenged by iron oxyhydroxides, which are abundant in the sludge discharged to the pit surface. The concentration of nitrate in the water, by contrast, is 20 μM at the surface and 40 μM at greater depths. The molar ratio of N/P is thus greater than 100, much higher than the typical algal value of ~7. This suggests that biological productivity is limited by the availability of phosphate.

The entire water column was well oxygenated during June and August (Figs. 3d through 6d). This is presumably because the rapidly sinking hydroxide sludge was carrying significant quantities of dissolved oxygen to the deep waters of the pit.

Water-column metals: The shape of the metal concentration profiles, the temporal variability in concentrations and the contrast between the Main Zone pit and Waterline pit metal concentrations all shed considerable

FIGURE 5

Profiles of temperature; conductivity; chlorophyll a; fluorescence; dissolved O₂; percent light transmission; and Zn, Cu, Cd and As concentrations in the Main Zone pit lake from the sampling period August 13-17, 2001. The scales for the metal profiles are intended to optimize viewing of the dissolved metal profiles. Hence, some of the total metal profiles extend off scale at the bottom.



light on the processes controlling metal concentrations in each lake.

The highest dissolved concentrations of many metals (Zn, Cu and Cd) in the Main Zone pit lake were present in a 2- to 3-m- (6.6- to 9.8-ft-) thick mixed layer during June and August (Figs. 3e, f, g through 6e, f, g). This suggested that the origin of the contamination is surface inflows. The contamination remains in the surface water because of the strong stratification (Figs. 3a, b and 4a, b). Concentrations decrease rapidly below the mixed layer to much lower values in deeper waters of the pit. Note that surface water concentrations of Zn, Cu and Cd decreased substantially between June and August. Research is ongoing to determine the process or processes controlling metal removal over this interval.

Considerable evidence suggests that the properties of the Main Zone pit lake are affected by the regular discharge of hydroxide sludge, a byproduct of ARD treatment, to surface waters. Throughout the pit, from a depth of about 70 m (230 ft) and extending to the pit bottom at about 120 m (390 ft), there is a plume of metal-rich particulate matter. This plume is evident in the form of elevated total metal concentrations (Figs. 3e, f, g) through 6e, f, g), as well as reduced light transmission (Figs. 3e through 6e) and elevated levels of suspended particulate

matter (not shown). Evidence to date suggests that this plume is sinking to the deep reaches of the lake soon after reaching the lake surface. The evidence for such behavior includes rapid southward currents in the deep reaches of the lake (data not shown) and elevated dissolved O_2 levels in lake deep waters (Figs. 3d through 6d), with the oxygen being delivered in the sinking deep water.

It is worth noting that the sludge inputs do not appear to result in increases in dissolved metal levels either in the surface waters or in deep waters. Evidence for this stems from two sources. Metal concentrations in Main Zone pit surface waters are of a similar magnitude to those in the surface waters of the Waterline pit (Figs. 4e, f, g; 6e, f, g and 7e, f, g), which is immediately upstream of the Main Zone pit and has had no sludge discharged into it. Therefore, the preliminary evidence suggests a common source of metals to the surface waters of both lakes, most likely the pit walls. Additional evidence for no contribution from the sludge to the dissolved metal concentrations stems from the lack of dissolved metal enrichment in the deep waters of the Main Zone pit, despite extremely high concentrations of particulate, sludge-derived metal (Figs. 3e, f, g through 6e, f, g). Indeed, it is possible that dissolved metals are actually being removed (scavenged) by the settling sludge material, although confirmation of this will require additional study.

Waterline pit lake

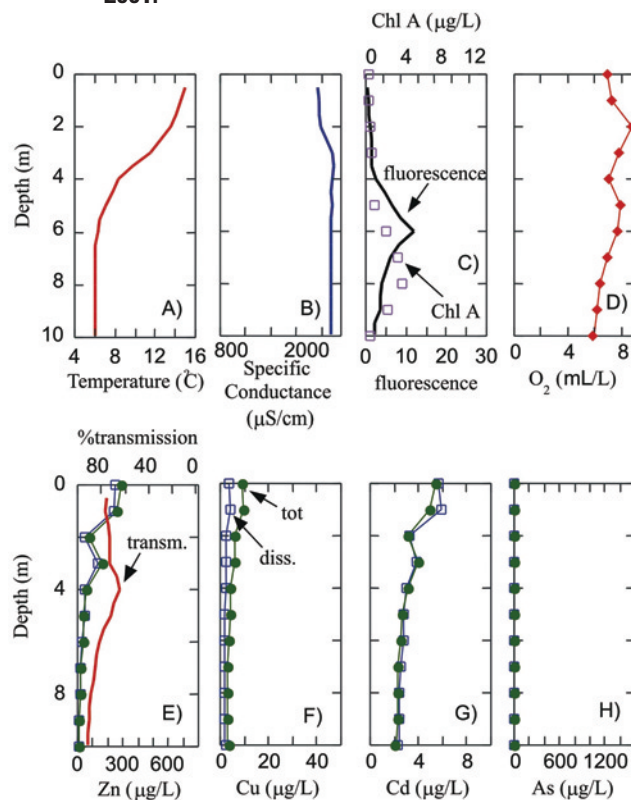
Stratification and other physical properties: The water column of the Waterline pit lake is more strongly stratified than the Main Zone pit lake. This is because the conductivity of the Waterline surface water is roughly half that of the Main Zone pit surface (Figs. 4B, 6B and 7B). The cause of this difference is being examined. However, it most likely reflects either a greater inflow of low-conductivity fresh water to the Waterline lake surface, the reduced mixing of the Waterline water column because it is better protected from the wind or an increases in the conductivity of the Main Zone pit lake surface waters due to hydroxide sludge inputs.

Unlike the Main Zone pit, there is no significant algal biomass in the Waterline pit. The fluorescence values are extremely low and constant with depth, entirely unlike the Main Zone pit lake water column (contrast Figs. 3c through 6c with Fig. 7c). The low biomass in the Waterline pit indicates a limitation of biological productivity by some means. One possibility being examined is that algal productivity is limited by phosphate availability, as is often the case in freshwater lakes (Schindler, 1974). This explanation requires that there be a source of phosphate to the Main Zone pit that is not available to the Waterline pit. One such possible source of phosphate is the hydroxide sludge delivered to the Main Zone pit lake (although the low dissolved-phosphate values measured in Main Zone pit waters suggest the phosphate must be released from a particulate form prior to uptake by algae; see discussion of Main Zone nutrient concentrations above).

The Waterline pit lake water column also maintains different concentrations of dissolved oxygen compared with the Main Zone pit lake. Dissolved oxygen concentrations decrease below the mixed layer to undetectable concentrations (Fig. 7d). This is due to the strong chemi-

FIGURE 6

Expanded profiles, top 10 m (33 ft), of temperature; conductivity; chlorophyll a; fluorescence; dissolved O_2 ; percent light transmission; and Zn, Cu, Cd and As concentrations in the Main Zone pit lake from the sampling period August 13-17, 2001.



cal stratification in this pit, which isolates the deep waters from inputs of atmospheric O_2 . Note that the dissolved- O_2 data are from early October, because sampling of the Waterline pit, was not incorporated into the original field survey plans. However, Waterline pit deep waters are inferred to have been anoxic in August (and most likely earlier), from the elevated concentrations of dissolved Fe measured (analyses in progress).

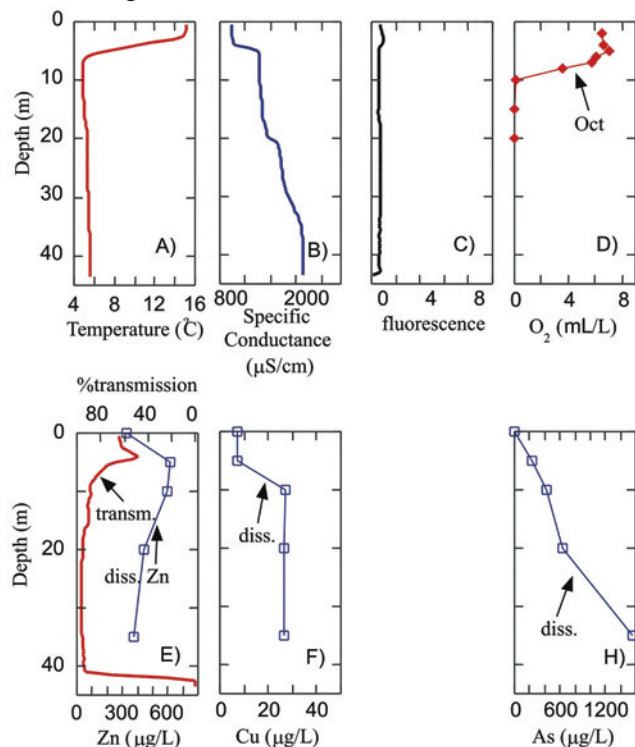
Water-column metals: As a result of the mildly reducing conditions in the Waterline pit deep waters, profiles of the dissolved metals are significantly different from those in Main Zone pit. Most notably, levels of dissolved As reach concentrations of about 1,500 $\mu\text{g/L}$ in the deep waters of the pit (Fig. 7h). These are much higher than observed in the Main Zone pit lake waters (Figs. 3h through 6h). These elevated levels of As most likely result from dissolution of iron oxyhydroxide phases, which are known to scavenge As. When the deep water column becomes anoxic, dissolved Fe is released into solution from solid-phase iron oxyhydroxides in the underlying sediment, and dissolved As is released as well. Indeed, elevated levels of dissolved Fe (as high as 30,000 $\mu\text{g/L}$) have been observed in the deep waters of the Waterline pit lake (data not shown).

Summary and conclusions

The Main Zone and Waterline pit lakes at the former Equity Silver Mine near Houston, BC, Canada,

FIGURE 7

Profiles of temperature; conductivity; chlorophyll a; fluorescence; dissolved O₂; percent light transmission; and Zn, Cu, Cd and As concentrations in the Waterline pit lake from the sampling period August 13-17, 2001.



are the sites of a three-year research program with the following three primary goals:

- understanding controls on metal concentrations in the lakes,
- using mesocosms to test a variety of remediation strategies and
- verifying and improving an existing coupled physi-

cal-geochemical model with the goal of improving our ability to predict pit lake water quality.

Initial data from summer surveys in the Main Zone pit lake reveal elevated dissolved metal concentrations (Zn as high as 800 mg/L) present in a 2-m- (6.6-ft-) deep mixed layer and elevated particulate metal concentrations towards the bottom of the water column. Hydroxide sludge, a byproduct of ARD treatment, is being discharged to the surface waters of the Main Zone pit lake. The sludge sinks rapidly to the lake bottom, leading to deep waters with elevated levels of dissolved O₂ and total metals.

By contrast, the deep waters of the Waterline pit lake are mildly reducing, manifested by depletion of O₂ and elevated levels of dissolved Fe. These reducing conditions have led to elevated levels of As (up to 1,500 µg/L) in Waterline pit deep waters. ■

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