Modeling a Physical Mechanism for Removal of Trace Elements from Pit Lake Surface Waters

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Abstract
Dissolved trace metal concentrations exhibit a seasonal cycle in surface waters of the Main Zone pit lake at the Equity mine site near Houston, British Columbia, Canada. Elevated concentrations associated with enhanced metal flux rates during the late spring ice and snow melt decrease over the subsequent summer months. A numerical model of pit lake physical and geochemical water properties demonstrates that the primary mechanism for removal of dissolved trace metals is the entrainment and downward transport of surface waters by the seasonal discharge of relatively dense slurry from an acid mine drainage water neutralization plant.

Key words: entrainment, numerical model, trace metal removal, zinc, surface water, slurry, density flow, Canada

Introduction
The Equity mine site is located in south-central British Columbia, Canada (54°11.59'N, 126°15.90'W). The two Equity pits produced silver, copper and gold from 1981 to January, 1994. Subsequently, both pits flooded with groundwater and surface runoff. In addition, the Main Zone pit receives seasonal surface discharge of relatively dense slurry from a nearby acid mine drainage water neutralization plant as well as runoff from the Waterline pit lake (Table 1).

Table 1 *Properties of the Main Zone (MZ) and Waterline (WL) pit lakes*

Pit Lake	Surface Elev. (m)	Depth (m)	Area (m^2)	Volume (m^3x10^6)
MZ	1255	130	175,812	9.80
WL	1270	45	37,979	0.70
MZ:WL		2.9:1	4.6:1	14:1

Water quality in the Main Zone pit lake is characterized by elevated trace metal concentrations in the epilimnion (particularly zinc) during late spring and summer, and good water quality throughout the hypolimnion. The water level in the Main Zone is managed by pumping water from a depth of 20 m to a nearby stream.

The slurry discharged to the surface of the Main Zone pit lake contains high concentrations of zinc particulates and low concentrations of dissolved zinc. It penetrates downward along the pit wall to the bottom layer of the lake as a density flow. This is evident in the high particulate zinc concentrations found below 100 m in conjunction with high turbidity (Fig 1a). In addition, the slurry is well oxygenated and delivers dissolved oxygen to the hypolimnion (Fig 1b). In contrast, the Waterline pit lake remains permanently stratified with respect to oxygen despite being much shallower (Fig. 1b).

Typically, from November through May, both pit lakes are covered by up to 3 m of ice. During late spring and early summer, drainage into the lakes is greatly enhanced by melting snow and ice. In addition, the flow of surface water from Waterline into Main Zone increases. The latter flow, combined with runoff down the pit walls, increases the flux of trace metals into the Main Zone surface waters. The value for [Zn] measured at 1 m depth during June was 800 µg/L. This value subsequently decreased to 250 µg/L in August, and to 40 µg/L by October (Fig 2).

Experiments carried out within limnocorrals located in the Main Zone pit lake show that algae can facilitate removal of dissolved zinc through both surface adsorption and biological uptake. High rates of removal were observed after fertilization of surface waters stimulated algal growth. The Main Zone pit lake is oligotrophic, however, and naturally occurring algal concentrations are insufficient to account for the observed rates of zinc removal.

Figure 1 *Vertical profiles of: (a) dissolved & total [Zn], and transmissivity in the Main Zone pit lake. (b) dissolved oxygen in the Waterline and Main Zone pit lakes during October*

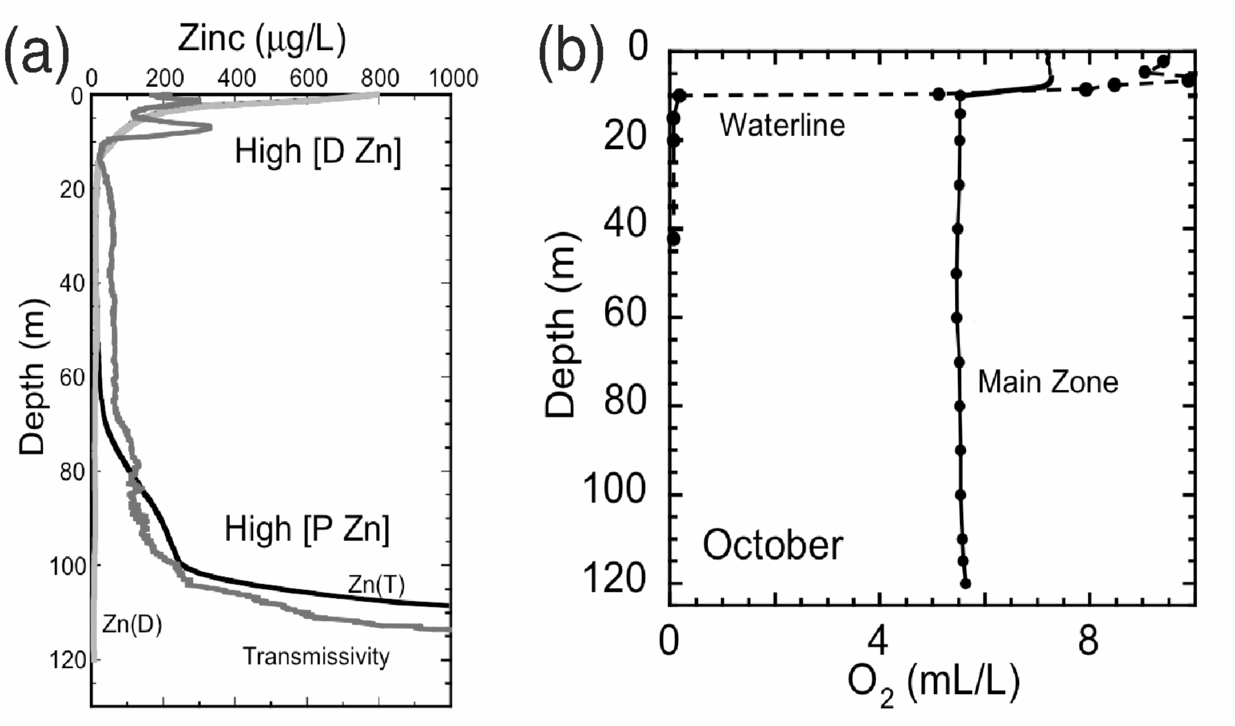
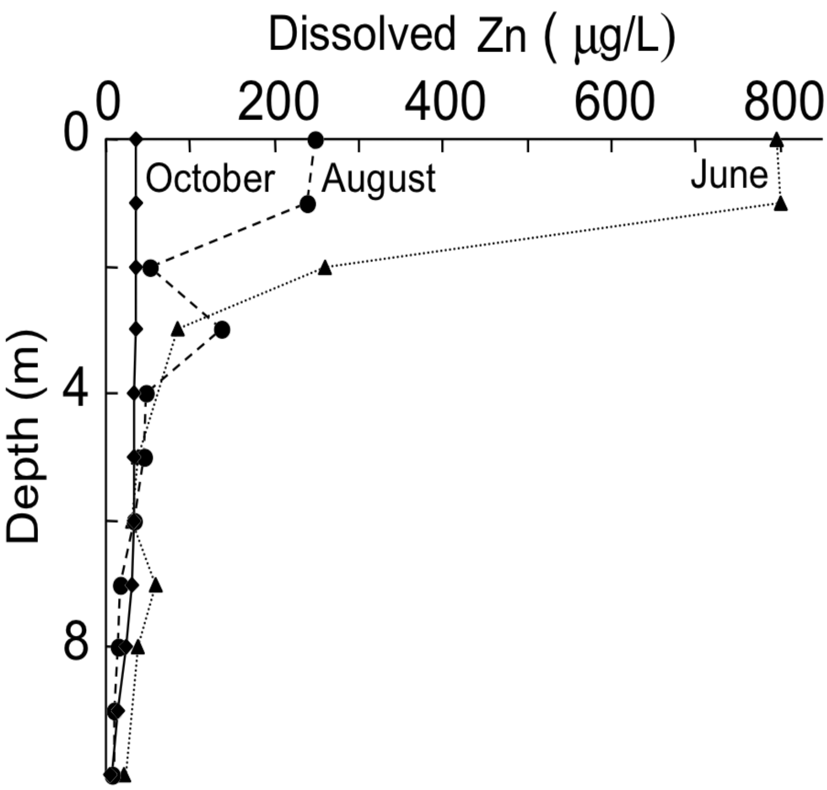


Figure 2 *Vertical profiles of [Zn] in the Main Zone pit lake during June, August and October, 2001*

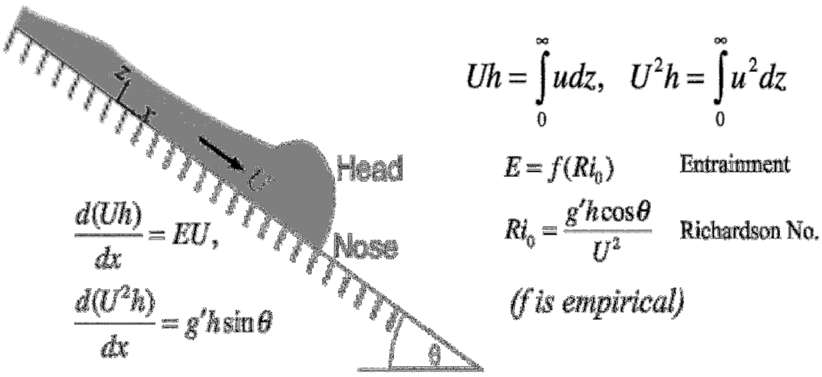


Density Flows

Density flows occur in pit lakes when a liquid or slurry enters less dense receiving waters and travels downward along the lake bottom in response to the Earth's gravity. The behavior of the density flow depends on its volume flux and excess density relative to the lake water. As the flow accelerates toward the lake bottom, the velocity gradient between the ambient, quiescent lake water and the boundary of the density flow generates shear turbulence. This induces mixing between the two water masses, resulting in a transfer of momentum from the density flow to the lake water.

The vertical component of this momentum causes some of the lake surface water to move downward with the slurry. At the same time, the mixing of slurry with lake water increases the volume of the density flow, thereby decreasing its relative density and causing it to decelerate. Depending on the volume flux and density of the slurry, and the density and depth of the lake, the density flow will either reach the lake bottom or will separate from the pit wall near a level of neutral buoyancy above the lake bottom. A schematic of a density flow together with the governing equations are shown in Fig. 3.

Figure 3 *Schematic and equations describing the properties of a pit lake density flow*



The Numerical Model

Lorax has developed a numerical model (PitMod) to simulate the physical and geochemical properties of pit lakes. Like the widely used DYRESM model from the University of Western Australia, PitMod is one-dimensional and therefore assumes lateral near-homogeneity. PitMod presently has two advantages over DYRESM with respect to simulating the evolution of pit lakes:

- PitMod includes a module for calculating the formation and removal of surface ice.
- PitMod is coupled to the PHREEQC geochemical speciation model for calculating the detailed vertical and temporal distribution of pH, dissolved oxygen, and a complete suite of geochemical species.

From late June, 2001 through late August, 2002 a comprehensive set of physical and water quality measurements were made in the Main Zone and Waterline pit lakes as part of a three year Canadian federal (NSERC) and industry funded study. Additional data were used to construct a detailed water balance for the lake during the same period, including: lake surface level; precipitation and evaporation; and pumping and slurry discharge rates (Table 2).

These data provided inputs for a 425 day PitMod simulation of the evolution of water properties in the Main Zone pit lake. For this simulation all geochemical processes were ignored and the PHREEQC module was not utilized. All changes in modeled concentrations were therefore the result of physical processes only.

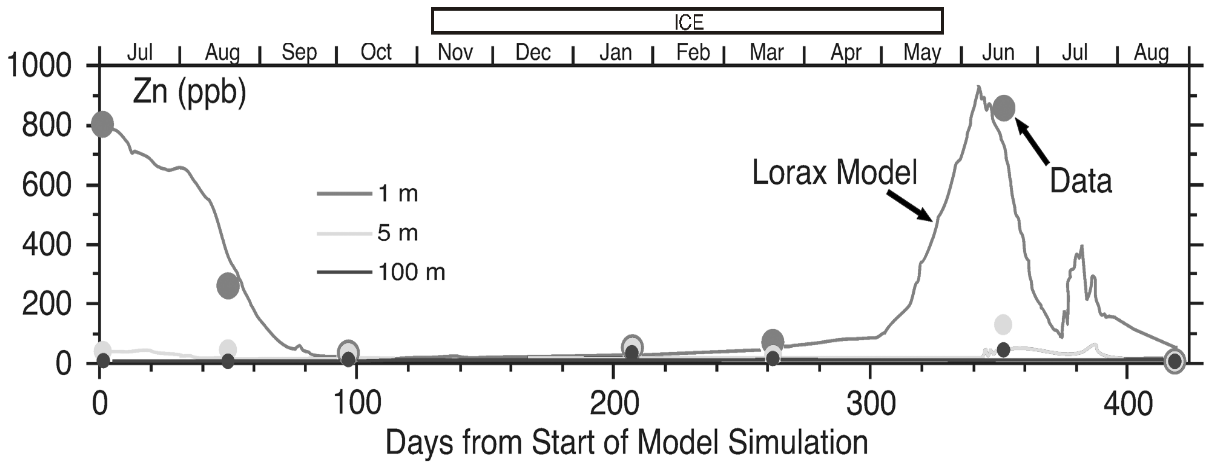
Time-series of zinc and copper concentrations were extracted from the model output corresponding to depths of 1, 5, and 100 m in the Main Zone pit lake and then compared with field measurements at the same depths. The data reveal two occurrences of elevated zinc and copper concentrations at 1 m depth in June of both 2001 and 2002. In both cases subsequent measurements revealed a large decrease over the following two to three months.

The model time-series for zinc agree well with the measured zinc concentrations (Fig. 4). In the absence of any geochemical or biological mechanism in the model, the results strongly support the hypothesis that the entrainment and subsequent downward transport of surface waters by the relatively dense slurry is responsible for the rapid removal of dissolved trace metals from the surface waters of the Main Zone pit lake, and consequently, that this may be an important mechanism for the removal of trace metals in other pit lakes that receive similar inflows of relatively dense slurries.

Table 2 *Mean water balance for the Main Zone pit lake during the period simulated by the model from June 29, 2001 to August 28, 2002*

Slurry Inflow at Surface	30.0 L/s	63.4%
Waterline Inflow	9.6 L/s	20.4%
Surface Inflow	4.7 L/s	9.9%
Net Precip / Evap	3.0 L/s	6.3%
Total	**47.3 L/s**	**100%**

Figure 4 *Comparison of modeled and measured Zn concentrations (ppb) in the Main Zone pit lake at 1, 5 and 100 m depth*



Summary and Conclusions

A two year field program took place during 2001 and 2002 at the Equity Mine's Main Zone and Waterline pit lakes. This included limnocorral experiments to investigate the removal of dissolved trace metals from lake surface waters by algae stimulated to grow by the addition of fertilizer. In addition, coincident physical and water quality data were collected from the lakes.

A follow-up modeling study used the PitMod numerical model developed by Lorax Environmental to simulate a 425 day period during which near-surface concentrations of copper and zinc were observed to increase markedly during the late spring snow and ice melt, and then decrease steadily to background levels over the ensuing two to three months.

The water balance for the Main Zone pit lake features seasonal surface discharge of relatively dense slurry from an acid mine drainage water neutralization plant. The slurry behaves as a density flow, entraining ambient lake water as it travels downward along the pit walls into the bottom layer of the lake.

Time-series of modeled zinc and copper concentrations at depths of 1, 5, and 100 m in the Main Zone pit lake agree well with corresponding measured values. The results suggest that the discharge of slurry to this lake is the primary mechanism for the removal of trace metals from the surface layer. It is therefore expected that this may be an important mechanism for trace metal removal in other pit lakes that receive a similar dense surface discharge.