

Modeling copper transport in the sediments of Torch Lake, Houghton County, MI

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Introduction

Torch Lake was inundated with copper mine tailings from 1868-1968. Copper concentrations in the sediment continue to pose a significant risk to the benthos¹. The U.S.EPA has chosen the "No Action" alternative for the lake, but several studies have questioned whether the sediments of Torch Lake are undergoing natural remediation. While copper concentrations in the water column have decreased since the end of mining operations, sediment copper concentrations have not declined^{2,3}.

Copper in the mine tailings primarily exists in readily soluble carbonate and oxide forms, whereas a large fraction of copper in the post-mining sediment is associated with organic matter⁴. This suggests that diffusion of copper in pore waters may be transporting labile copper from the mine tailings upwards, where it is complexed with organic matter in the post-mining sediment. The objective of this study was to develop and apply a mathematical model to the sediments of Torch Lake to investigate the cause of the persistently elevated copper concentrations in surficial sediments, and to estimate the time required for natural sedimentation processes to return these concentrations to an acceptable level.

Methods

A series of sediment cores were taken from Torch Lake in 2004 and 2005 (Figure 1). Cores were dated using ²¹⁰Pb and ¹³⁷Cs and analyzed for solid-phase and porewater total copper concentrations, bulk density and porosity, and organic matter content.

A 1-D numerical model was developed using an Eulerian frame of reference relative to the sediment-water interface in which compaction is treated as an advective process (Figure 2). The spatial derivatives associated with advection and diffusion are represented by second-order finite difference approximations and solved using Euler integration. Copper adsorption is represented by a Langmuir isotherm.

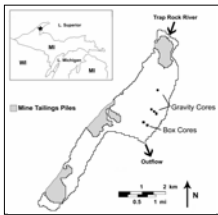


Figure 1. map of Torch Lake showing coring locations (this study only)

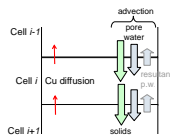


Figure 2. Conceptual representation of numerical model. The model is based on the theoretical treatment of Abril⁵.

Results/Discussion

Visual inspection of Torch Lake cores reveals a clear distinction between mine tailings and post-mining sediment (Figure 3). The two sediment types are also visible in bulk density profiles (Figure 4). The discontinuity was utilized to facilitate ²¹⁰Pb dating⁶. Post-mining sedimentation rates are low, 0.016-0.026 g cm⁻² yr⁻¹ (5-9 mm yr⁻¹), as compared with mining-era sedimentation rates of 1-2 g cm⁻² yr⁻¹.

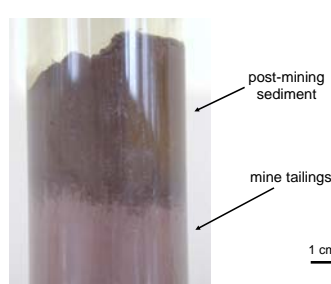


Figure 3. Typical Torch Lake sediment core. The sediment column contains up to 8 meters of clay-size copper mine tailings, overlain with 3 to 7 cm of organic-rich (~12% organic matter content) post-mining sediment. Note the clear distinction between the sediment layers.

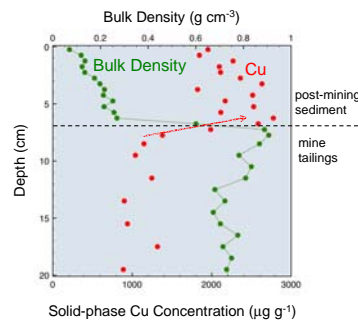


Figure 4. Bulk density (green symbols) and solid-phase copper (red symbols) measurements from sediment core taken at a water depth of 20 meters. The transition from post-mining sediment to mine tailings coincides with the discontinuity in bulk density profiles (~7 cm depth). The copper profiles reveal higher concentrations in the post-mining sediment than in the mine tailings, with a minimal decrease in concentration in more recently-deposited sediment.

Copper concentrations in post-mining sediment are 1.5 to 2 times greater than in the underlying mine tailings (Figure 4). All Cu concentrations are significantly higher than the NOAA SQiRT Probable Effects Level (PEL) of 197 µg g⁻¹.

Because Cu profiles reveal near-constant concentrations throughout the post-mining sediment, a Langmuir isotherm was selected to represent Cu partitioning in the model. Adsorption parameters were determined based on data from this and previous studies (Figure 5).

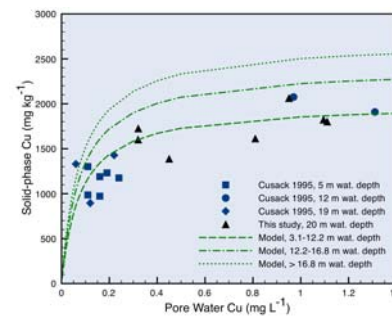


Figure 5. Modeled copper adsorption isotherms. The Langmuir adsorption constant was determined from a least-squares fit to all of the data points. The sorptive capacity was adjusted to fit the model to the sediment copper profiles shown in Figure 4. The resulting partition coefficients (log K_d) range from 4.4 to 4.5.

The numerical model provides a good fit to measured copper concentrations (Figure 6). The model predicts a rapid decrease in solid-phase copper concentrations in surficial sediment (uppermost 1-2 cm). Finer sampling resolution would be required to verify this prediction.

Recent sediment trap studies support model predictions⁷. Copper concentrations in settling solids are similar to concentrations predicted by the modeled isotherm for sediment in equilibrium with lake water concentrations (~22 µg L⁻¹). Furthermore, Cu accumulation rates in post-mining sediment are higher than rates of Cu deposition to sediment traps, supporting the hypothesis that upward diffusion from the mine tailings supplies Cu to surface sediments.

Model forecasts predict little change in solid-phase copper concentrations between 36 and 100 years after the cessation of mining activities (Figure 6). The mine tailings have been effectively capped (copper fluxes from the sediment to the water column have been reduced by an order of magnitude, and the lake water concentrations appear to be at steady state⁸). Therefore, assuming no reduction in copper inputs from the watershed, concentrations at the sediment-water interface will remain nearly unchanged for a prolonged period.

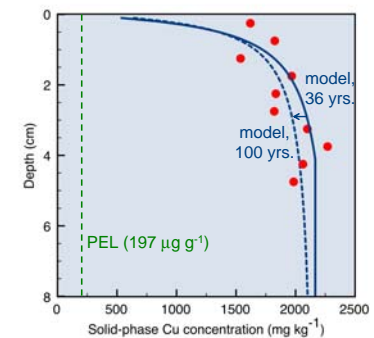


Figure 6. Model results compared to sediment copper measurements at a water depth of 13 meters. The solid line represents t=36 years (2004); the dashed line represents t=100 years. Little decrease is seen in sediment copper concentrations with time. Concentrations at the sediment-water interface remain nearly constant.

Conclusions

Torch Lake has made little progress towards recovery in terms of solid-phase Cu concentrations. Though Cu flux from the sediments to the lake has been attenuated, Cu concentrations in the post-mining sediment remain nearly 2x greater than those in the mine tailings, and an order of magnitude greater than the PEL.

Because pore water diffusion is delivering copper to the post-mining sediment from a very large pool, no significant reductions in solid-phase copper concentrations will be realized in the foreseeable future.

References

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