A RISK ASSESSMENT / RISK MANAGEMENT PERSPECTIVE ON MERCURY CONTAMINATED SEDIMENTS IN MINING AFFECTED PINCHI LAKE, BC.

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ABSTRACT

The Pinchi Mine, located on the merciferous Pinchi Fault region of BC, produced metallic mercury from 1940 to 1944 (historical operation) and from 1968 to 1975 (modern operation). Between 2010 and 2012, the mine underwent decommissioning and reclamation to ensure that the terrestrial areas affected by the mine do not pose unacceptable risks to ecological resources. The historical operations included placement of roasted ores (calcines) in Pinchi Lake adjacent to the site, resulting in highly elevated mercury concentrations in nearshore sediments (subsurface calcines). This source, as well as aerial deposition of elemental Hg during the roasting process during both operations, broadly elevated sediment mercury concentrations throughout the lake. In 1997, inorganic and methylmercury concentrations were measured in pore water and sediment at different depths in sediment cores and showed that subsurface calcine sediment was a significant contributor of inorganic mercury to the lake, notwithstanding slow burial by cleaner sediments. In 2001, a sediment quality triad (chemistry, toxicity, benthos) study showed no correlation between sediment inorganic mercury concentration, toxicity or benthic community structure. However, benthic organisms living in subsurface calcine sediment were elevated in total and methylmercury concentrations relative to benthos elsewhere in the lake. This paper reviews and integrates historical sediment investigations using a risk assessment and risk management framework to guide further investigations and support long-term decision-making regarding Pinchi Lake sediment.

KEY WORDS

Mercury, methylmercury, sediment quality triad, Pinchi Mine, Pinchi Lake, risk assessment, risk management.

OVERVIEW

The Pinchi Mine, located on the merciferous Pinchi Fault region of BC (Figure 1), produced metallic mercury from 1940 to 1944 (historical operation) and from 1968 to 1975 (modern operation). The historical operations included deposition of roasted ores (calcines) into Pinchi Lake adjacent to the site, resulting in highly elevated mercury concentrations in nearshore sediments (subsurface calcines) and beyond. A series of investigations have been conducted over the years to characterize the environmental significance of the subsurface calcine area and Pinchi Lake in general. This paper[1] summarizes key findings of previous investigations relevant to the subsurface calcine area and presents the results within a risk assessment/risk management framework to support informed management.

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[1] Note that a companion paper by Baker et al. in these proceedings addresses temporal changes in fish mercury concentrations in Pinchi Lake.

Figure 1. Pinchi Mine Site, BC, with inset showing general location of subsurface calcine sediments in Pinchi Lake.

BACKGROUND

Mercury (inorganic and organic [methylmercury]) are the main contaminants of potential concern (COPC) for this site. Methylmercury (MHg) is important because this is the most toxic form of mercury. Although it normally comprises only a small percentage of the total mercury in environmental media, it is readily taken up by organisms, biomagnifies up the food chain, and can be toxic at low concentrations. Total mercury (THg; sum of inorganic and organic mercury species) is the most commonly measured mercury analysis. Secondary COPCs in subsurface calcine sediments were arsenic, antimony, chromium, and nickel. The location of the subsurface calcine area is shown in Figure 1 (lower left inset) relative to the upland portion of the site.

EARLIER STUDIES

Advancements in the late 1960s in the understanding of mercury's toxicity in aquatic systems prompted the first sampling at Pinchi Lake. Peterson et al. (1970) conducted a regional survey of heavy metals in sport fish in lakes along the Pinchi Fault in 1970. Lake trout from Pinchi Lake contained dramatically elevated mercury concentrations (over 4 mg/kg wet weight). Monitoring conducted over the next four decades showed substantial decreases through 2000, then more modest reductions in fish tissue mercury concentrations since then (see Baker et al. 2014 for details).

The first quantitative survey of mercury in sediment in Pinchi Lake took place in 1976-1978. Ableson and Gustavson (1979) measured total mercury concentrations in surface sediments offshore of the mine site to determine the spatial extent of mercury in subsurface calcine sediments. Concentrations were highest directly offshore of the mine site (i.e., subsurface calcine area) and diminished east and west of this peak zone with increasing depth and distance offshore. Cores collected in 1978 showed maximum mercury concentrations occurring in the top 5 cm. Martin et al. (1995 Draft Report) collected sediment cores again in 1986, showing lower concentrations in both the 0 to 5 cm and 5 to 10 cm horizons.

LATER STUDIES

From 1995 through 2001, Teck Cominco commissioned detailed investigations to examine the mine site and its relationship with Pinchi Lake with respect to environmental contamination (primarily mercury, but also other metals) in lake water, tributary streams, sediment, pore water, groundwater, lower trophic level biota (i.e., zooplankton and benthos), and fish (EVS 1996, EVS et al. 1999a, b, EVS 2001, EVS and Azimuth 2002). Subsequently, follow-up monitoring was conducted in 2006 (fish and lake ecology in Pinchi, Tezzeron and Stuart Lakes; Azimuth 2008) and 2011 (fish in Pinchi Lake; Azimuth 2013) to (1) continue tracking temporal trends in fish mercury concentrations in Pinchi Lake and (2) serve as the "benchmark" for describing the basic trophic structure of Pinchi Lake to help interpret any future changes in fish mercury concentrations. This work was conducted by a multidisciplinary team that included mercury specialists. Key results from these investigations relevant to assessing the environmental significance of contaminated sediments in the subsurface calcine area (both locally and to the lake as a whole) are described within a risk-based framework.

CONCEPTUAL MODEL/RISK ASSESSMENT

Conceptual models are commonly used in risk assessments to depict important contaminant-related processes such as sources, release mechanisms, transport pathways, exposure routes, and receptors. While a formal risk assessment, *per se,* of mine-related contamination in Pinchi Lake has not been conducted, the aforementioned environmental investigations characterizing conditions in Pinchi Lake (including the subsurface calcines) were guided by a systematic risk-based approach that ultimately integrated information pertaining to the physical, chemical, biological, ecological, and toxicological nature of the site to help inform management decisions (Figure 2).

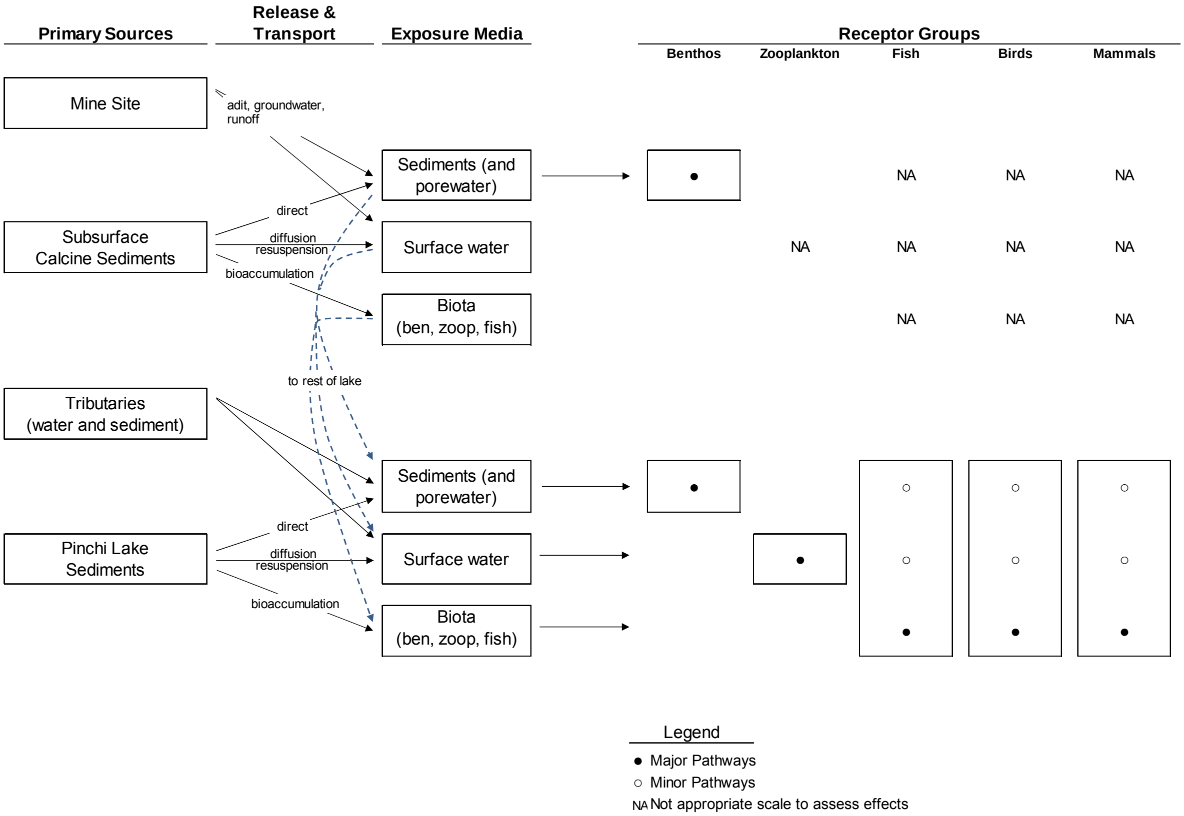

Figure 2. Conceptual model showing subsurface calcine sediments relative to other mercury sources to Pinchi Lake receptors.

Available data for key aspects of the conceptual model are summarized below (with emphasis on subsurface calcines and lake sediments; the relative importance of all sources to Pinchi Lake is discussed in the last bullet below):

- *Primary Sources* – Surface sediment mercury[2] concentrations (Figure 3) are elevated throughout Pinchi Lake, but particularly so in the subsurface calcine area. Sediment core data from 1997 (Figure 4) shows the strong signal of the historical operations (e.g., as seen in the peaks in the deep portions of the east and west basins; dating confirmed with lead isotopes) and more recent deposition of cleaner sediments at the surface; the recovery pattern is weaker in other portions of the lake, including the subsurface calcines (possibly due to higher biologically-induced mixing). Total mercury and methylmercury concentrations in sediments and porewater were substantially higher in the subsurface calcines than the rest of the lake. Core data show that the thickness of the subsurface calcines is approximately 10 cm.

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[2] Secondary contaminants present in the calcines include arsenic and antimony, among others; the magnitude of contamination is far less for these metals.

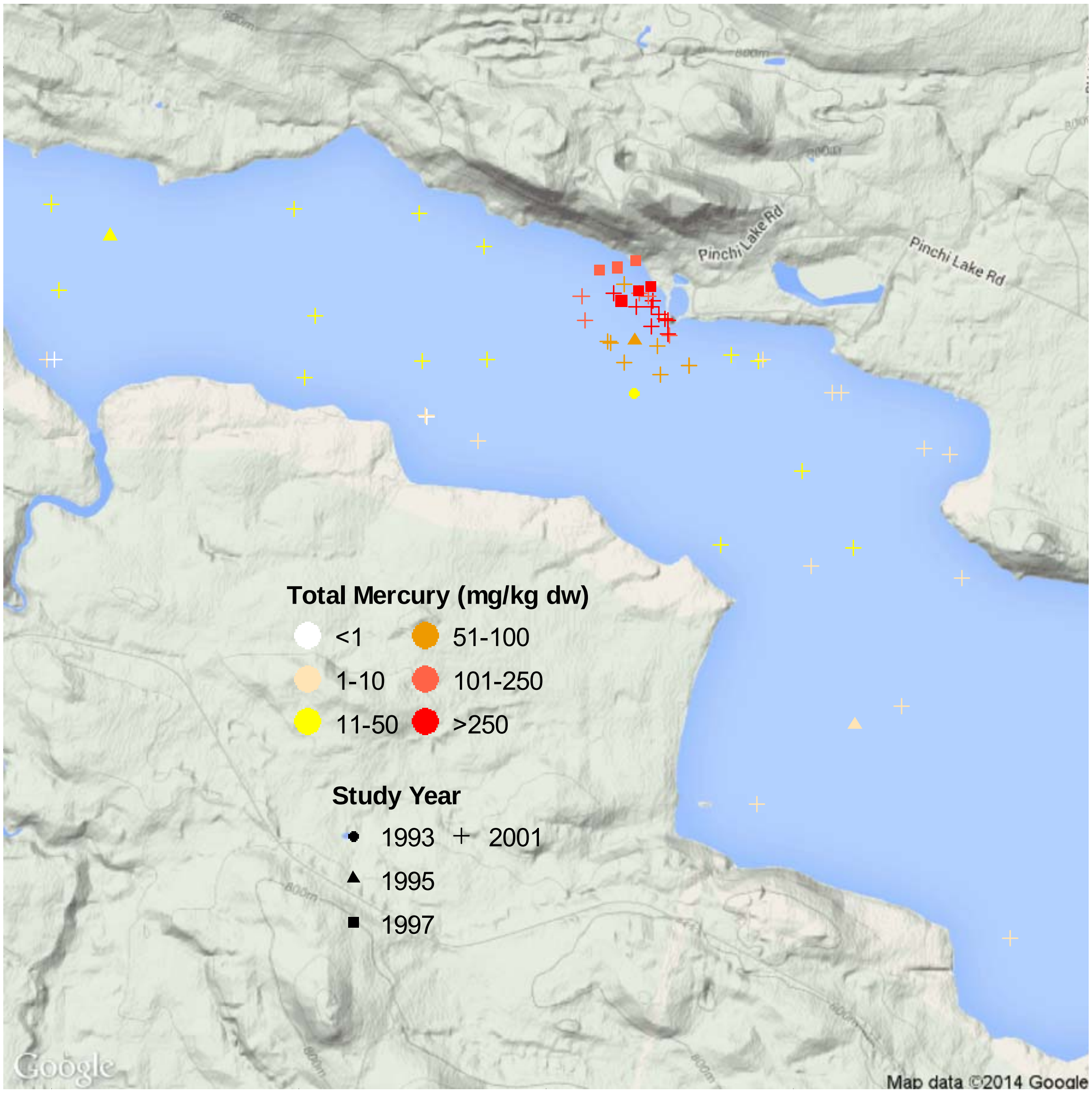


Figure 3. Horizontal extent of total mercury in surface sediments based on compilation of data.

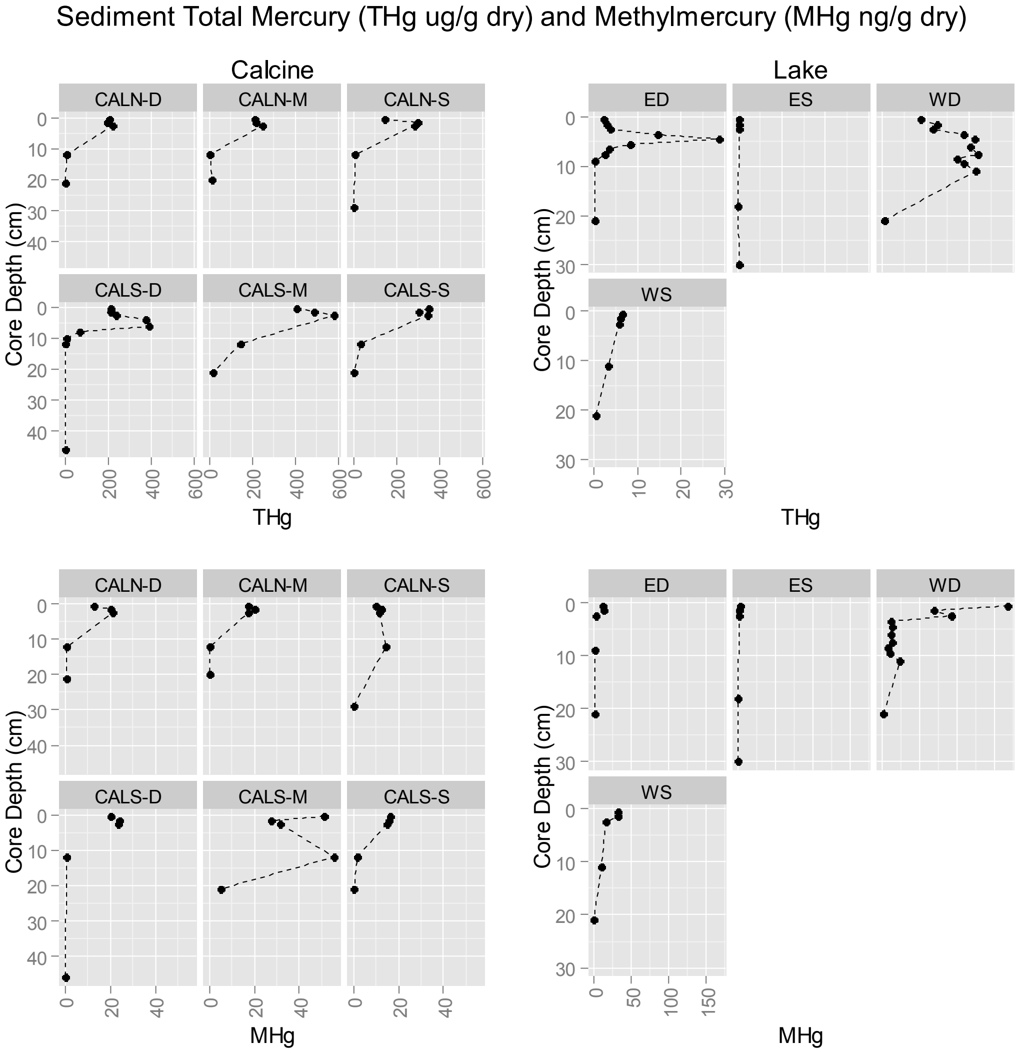


Figure 4. Vertical extent of total (top) and methylmercury (bottom) in subsurface calcines (CAL north [N] and south [S] transects; D = deep, M = medium, S = shallow) and lake sediments (East Basin deep [ES] and shallow [ES]; West Basin deep [WD] and shallow [WS]) from 1997 study.

- *Release/Transport and Exposure Media* – Three primary pathways are present from sediments: direct contact by biota with contaminants in sediment and/or porewater, transport via diffusion/re-suspension to the water column and biota bioaccumulation. Direct exposure is higher in the subsurface calcine area (see *Primary Sources* above) relative to the rest of lake. Diffusion modelling based on porewater gradients (from the 1997 sediment cores) close to the sediment/water interface showed the subsurface calcines as a source for total mercury, but not for methylmercury (see below for more discussion). Surface water mercury concentrations (Figure 5) were variable, but were generally higher in unfiltered samples from the subsurface calcine area. Biota tissue concentrations (Figure 6) showed consistently higher total and methylmercury in sediment-associated biota (i.e., benthos [chironomids] and bivalve mollusks) in the subsurface calcines; mercury concentrations in zooplankton were much lower than the other biota and patterns more variable.

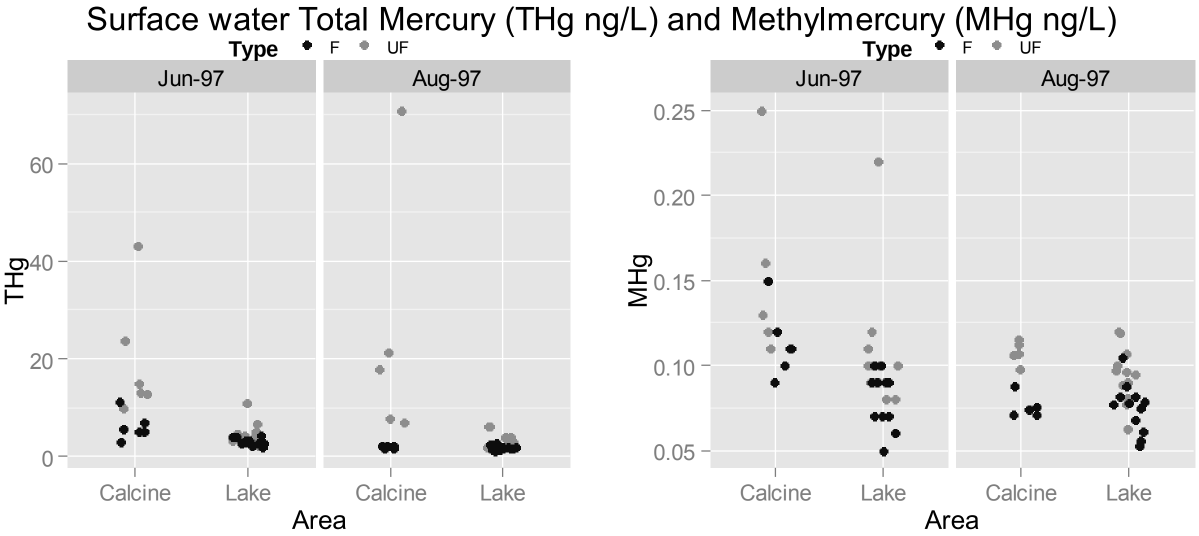


Figure 5. Surface water total and methylmercury concentrations for filtered (F) and unfiltered (UF) water collected above the subsurface calcine area and other portions of Pinchi Lake in June and August 1997.

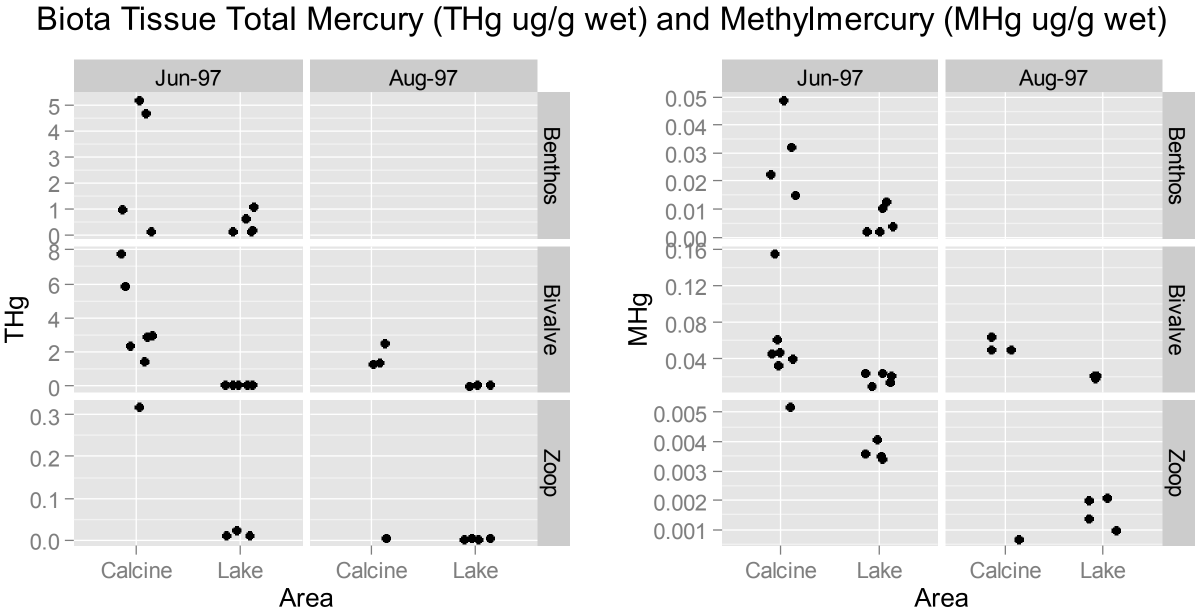
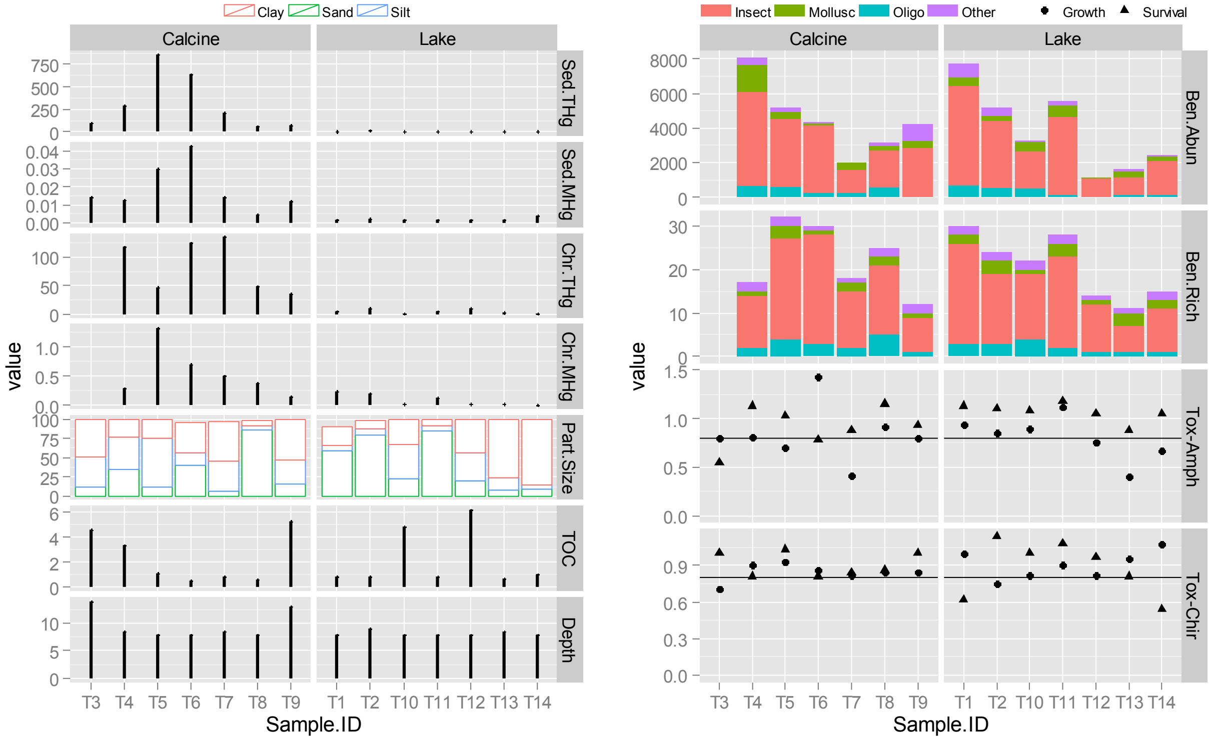


Figure 6. Biota tissue total and methylmercury concentrations samples collected in the subsurface calcine area and other portions of Pinchi Lake in June and August 1997.

- *Receptors* – Spatial scale is important is making inferences regarding effects to receptors. Apart from benthic invertebrates, which live directly in the sediment and are relatively immobile, the whole lake is a more ecologically relevant spatial scale for assessing effects than the subsurface calcine area for the other receptors. However, the relative importance of the subsurface calcine area to overall exposure can still be estimated for these receptors (e.g., fish, birds and mammals; see last bullet in this section for more discussion). Results are discussed by receptor group:

- *Benthos* – The potential for direct effects and bioaccumulation by benthos in the subsurface calcines was investigated in 2001 (EVS and Azimuth 2002). Benthic community (abundance and richness), sediment toxicity (midge and amphipod survival and growth), bioaccumulation (midge tissue concentrations), and sediment chemistry was assessed at 14 stations spanning a wide exposure gradient within and outside the subsurface calcine area. While exposure metrics (Figure 7 [left]) showed substantial differences between areas, the pattern was not evident in any response metric (Figure 7 [right]). Correlations between exposure and response metrics (Table 1) point to sediment grain size explaining the observed differences in response metrics. Thus, despite a clear gradient in mercury exposure, the most obvious patterns in benthos were related to physical conditions.



Note: Sed.THg = sediment total mercury (ug/g dw); Sed.MHg = sediment methylmercury (ug/g dw); Chr.THg = chironomid tissue total mercury (ug/g dw); Chr.MHg = chironomid tissue methylmercury (ug/g dw); Part.Size = particle size (%); TOC = total organic carbon (%); Depth (m); Ben.Abun = benthos total abundance (#/m^2); Ben.Rich = benthos taxa richness (# taxa/grab); Tox-Amph = amphipod toxicity (% of control); Tox-Chir = chironomids toxicity (% of control); the two toxicity plots show the 20% response (i.e., 0.8 of control) line.

Figure 7. Exposure (left) and response (right) metrics from 2001 sediment toxicity/bioaccumulation study of the subsurface calcine area at the Pinchi Mine Site, BC.

Table 1. Correlations (Spearman) between exposure and response metrics from 2001 sediment toxicity/bioaccumulation study of the subsurface calcine area at the Pinchi Mine Site, BC.

	Benthic Community		**Sediment Toxicity**			
	Total	**Total**	***Chironomus***		***Hyalella***	
	Abundance	**Richness**	**Survival**	**Growth**	**Survival**	**Growth**
Sediment Mercury						
Total Mercury	0.434	0.49	0.113	-0.091	-0.179	0.176
Methylmercury	0.044	0.187	0.003	-0.097	-0.45	-0.11
Tissue (Chironomid) Mercury						
Total Mercury	0.148	0.248	0.047	-0.299	-0.234	0.077
Methylmercury	0.407	**0.682**	0.116	-0.133	-0.105	0.286
Other Sediment COPCs						
Antimony	0.024	0.066	0.003	-0.151	-0.51	-0.275
Arsenic	-0.077	-0.165	-0.366	0.144	**-0.677**	-0.506
Chromium	0.16	0.03	0.329	-0.186	-0.123	-0.146
Nickel	0.016	-0.179	0.304	-0.227	-0.24	-0.352
Biophysical						
Sand	**0.571**	0.525	0.288	-0.172	**0.739**	**0.879**
Silt	0.011	-0.017	0.321	-0.346	-0.353	-0.253
Clay	**-0.637**	**-0.63**	-0.437	0.211	**-0.781**	**-0.676**
TOC	-0.116	-0.42	0.194	-0.236	-0.029	-0.377
Depth.m	0.038	-0.534	0.176	-0.315	-0.258	-0.388

Bold values indicate statistically significant spearman correlations (critical rs = 0.560 for α[2]=0.05, p<0.05, n=13).

- *Zooplankton* – from a direct toxicity perspective, mercury concentrations in surface waters in Pinchi Lake are typically much lower than guidelines developed for direct toxicity (e.g., CCME's water quality guideline of 26 ng/L for total and 4 ng/L for methylmercury), so no effects would be expected. This conclusion is corroborated by the 2006 lake ecology study (Azimuth 2008), which documented a community typical of boreal lakes.
- *Fish* – see Baker et al. (this issue) for detailed discussion of fish mercury concentrations; fish populations appear healthy and there are no systematic differences compared to Stuart and Tezzeron Lakes.
- *Birds and mammals* – two main lines of evidence have been used to assess wildlife: food chain modelling and direct ecological studies. The Pinchi Mine Site ecological risk assessment (Azimuth 2009) concluded that predicted exposures to birds and mammals feeding in Pinchi Lake did not pose unacceptable risks. For birds, this result is consistent with a field study on fish-eating birds documented higher mercury concentrations in Pinchi Lake birds, but showed no apparent effects to egg production, fledging success or

growth (Weech et al. 2006; see Baker et al. 2014 for more detail). A similar study is underway for river otter.

- *Relative Importance of Mercury Sources to Pinchi Lake* – One of the goals of the 1996-2001 studies was to quantify the relative contributions of a range of sources to Pinchi Lake. The 1997 data was used to estimate contributions from each major source to Pinchi Lake water using a mass-balance approach (Figure 8 [left]). Mine Site sources (consisting of contributions from the 750 Adit and groundwater inputs through the foreshore calcines and former lagoons) were low for both total and methylmercury. While the subsurface calcine area was estimated to contribute 25% of total mercury loadings to Pinchi Lake water, it was not an important source for methylmercury. The 1997 and 2001 chironomid (midge larvae) tissue methylmercury concentrations and the spatial boundaries of the various sampling locations were used to estimate the relative contributions to the Pinchi Lake benthic-based food chain (Figure 8 [right]). The deep and shallow zones of the subsurface calcine area combined to contribute 5% of the methylmercury loading associated with chironomids in the benthic food chain of Pinchi Lake.

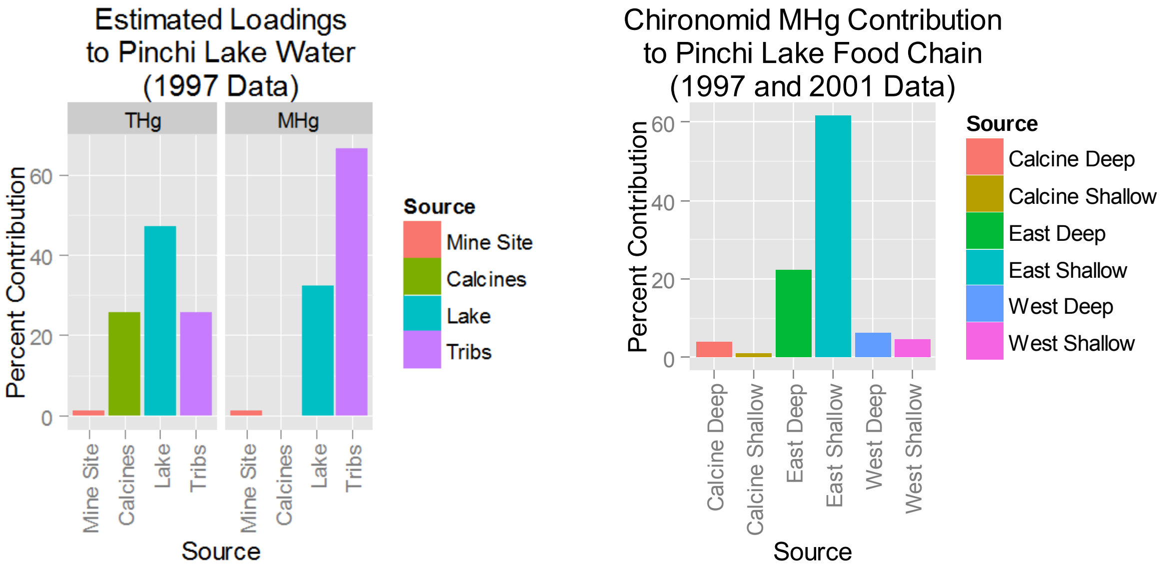


Figure 8. Relative importance of key mercury sources to Pinchi Lake water (left) and benthic food chain (right).

IMPLICATIONS FOR RISK MANAGEMENT

The subsurface calcine area, a legacy of historical wartime mine operations, contains substantially elevated total and methylmercury concentrations in sediment. While vertical profiling conducted in 1997 showed some recovery (i.e., lowered concentrations due to burial with cleaner material) in most subsurface calcine cores, residual surface sediment concentrations remained high and were mirrored in benthos and bivalve tissue concentrations relative to other areas in Pinchi Lake (EVS et al. 1999a,b; EVS and Azimuth 2002). Notwithstanding, there is no evidence of adverse effects to benthos, zooplankton, fish, birds, and mammals (EVS and Azimuth 2002; Azimuth 2008). Furthermore, available data suggests that the relative contribution of the subsurface calcine area to Pinchi Lake biota mercury exposure is relatively low.

The risk management strategy for mine-related contamination in Pinchi Lake (including subsurface calcines) employed since 2001 has been dedicated towards monitoring of natural attenuation, based primarily on documenting temporal trends in fish mercury concentrations. Lake trout (Salvelinus namaycush) and lake whitefish (Coregonus clupeaformis) are the prime target species: lake trout is the top aquatic predator, integrating mercury exposure over the entire food chain (i.e., making this endpoint perhaps the most important indicator of mercury dynamics in Pinchi Lake); whitefish are lower in the food web and are the preferred food source for lake trout (i.e., changes to this endpoint should ultimately be reflected in lake trout tissue mercury). Baker et al. (2014) present the fish monitoring results, which have shown continued reductions in fish mercury concentrations, albeit at slower rates since 2000.

The Pinchi Lake monitoring program was expanded in 2006 to include a full suite of lake ecology components (e.g., limnology, water chemistry, sediment chemistry, phytoplankton community, zooplankton mercury and community, benthic invertebrate mercury and community, more fish species, and stable isotope analysis to document food web relationships) and extended to include Tezzeron and Stuart lakes as regional reference areas. The rationale of this change was to better support the interpretation of fish tissue mercury concentrations by having a better understanding of lake ecology and associated mercury dynamics. This program, to be conducted every decade, is part of the proposed long-term monitoring program for the Pinchi Lake Mine (Teck 2012 DRAFT); the next planned event is 2016.

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