Historic Tailings Disposal in Lakes: A Review of Post Depositional Lake Recovery

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Abstract
The use of water covers to reduce the risks of acid rock drainage and metal leaching is a well established mine waste management practice. Water covers may be maintained over wastes within constructed impoundments or wastes may also be deposited into natural water bodies and natural basins that host aquatic ecosystems. The use of natural water bodies for mine waste disposal has generated significant controversy in Canada in recent years. While financial and technical arguments are made on the side of industry, critics are concerned with the loss of ecological and social values associated with the receiving lakes. Some proponents argue that lake ecosystems may retain or regain many of the same, or different but still valuable, ecological and social features post-disposal. A review of the published and grey literature was conducted to examine to what degree lakes do or do not retain or regain ecological and social values post-disposal. The studies reviewed support the idea that lakes can achieve a degree of recovery, but evidence of long-term environmental damage exists. The full extent of tailings induced damage and recovery is not known due to research gaps and uncertainty.

Key Words: subaqueous disposal, mine waste, aquatic ecosystem

Introduction

The destruction of aquatic ecosystems by using their natural basins as depositories for mine waste has elicited considerable attention and controversy in Canada in recent years. Though less common in the United States, at least one project in Alaska has also drawn criticism for proposing to use an alpine lake basin for disposal of tailings. While both Canada and the U.S. have legislation designed to protect water bodies from hazardous wastes such as tailings, regulatory amendments that enable the disposal of mine waste in natural water bodies were introduced in both countries in 2002.

In Canada, Schedule 2 of the Fisheries Act's Metal Mining Effluent Regulations allows the reclassification of natural water bodies as tailings impoundment areas, removing the protections of the Act against "deleterious substances" and damage to fish and fish habitat. In the USA, the definition of "fill" was changed to include mine waste, allowing it to be dumped into water bodies using Army Corps of Engineers authorisations. Both regulations have been the subject of court challenges.

A summary of concerns expressed by critics of this disposal practice are provided below (Hart 2011):

- Lakes and lake ecosystems have a symbolic and iconic status for many Canadians who do not want to see them impacted by industrial activity.
- Lakes and other water bodies may have profound spiritual, cultural and historic values for Indigenous peoples, which may be expressed as the water bodies being sacred. The use of the lakes as mine waste disposal sites is an affront to these values.
- The use of a natural water body for disposal of wastes by a private company provides private benefit by impacting an important public good – representing a privatisation of the resource and a subsidy to industry.
- Lake ecosystems that are isolated from larger watersheds may have unique biological and ecological features that have evolved over time and which are inadequately considered in their designation as mine waste disposal areas.
- Habitat compensation practices designed to achieve a policy of "no net loss" have not been successful in replacing equivalent habitats.

- Alternatives to using natural water bodies are not given adequate consideration and supposedly "objective" alternatives assessments are perceived as being biased and pre-determined.
- Alternatives assessments and mitigation measures do not consider the full range of ecological and social values associated with the water bodies.

One of the justifications offered for this waste disposal practice by the Mining Association of Canada (MAC 2008) and individual project proponents is that natural water bodies may recover to healthy ecosystems after dumping of the wastes has ended. In order to better understand the implications of this practice the authors have reviewed available published and grey literature to determine the extent of documented recovery of water bodies in Canada that have received underwater mine tailings or waste rock deposition. We use the term recovery to mean a spectrum of improvements to biological functioning of the disturbed ecosystem. Specifically, we searched the literature for evidence of impacts and recovery for the following ecological features: physical substrate, water chemistry, sediment chemistry, benthos, zooplankton, phytoplankton, fish, aquatic macrophytes, ecosystem sustainability, ecosystem stability, contaminant fate and transport and socio-economic values.

Research Methods

Research sources for this paper include scientific journals, company websites, federal and provincial websites, and direct information requests from relevant companies and government departments. Twenty-nine lakes containing subaqueous tailings were identified. Due to the challenges of tracking down grey literature, not all water bodies could be thoroughly researched in the time frame of this paper. As a result, this analysis focuses on the 10 lakes described in Table 1.

Table 1: The 10 lakes and mine sites analyzed in this review.

Water Body	Mine Name	Company Name	Mine Resource	Operation Dates
Benson Lake, BC	Benson Lake Coast Copper Mine	Cominco Ltd.	copper, iron	1962-1973
Brucejack Lake, BC	Sulphurets Exploration Project	Newhawk Gold Mines Ltd.	gold, silver	excavation: 1986-1990
Buttle Lake, BC (S Basin)	Lynx Mine and Myra Mine	Westmin Resources	copper, lead, gold, silver, zinc	1966-present
Garrow Lake, NU	Polaris Mine	Cominco Ltd.	lead, zinc	1980-2002
Giauque Lake, NT	Discovery Mine	Discovery Mine Ltd.	gold	1944-1969
Kootenay Lake, BC (Galena & Bluebell Bay)	Bluebell Mine	Cominco Ltd. (1930-1972)	lead, silver, zinc	1895-1929; 1952-1972
Mandy Lake, MB	Mandy Mine	Hudson Bay Mining & Smelting Co.	copper, gold, silver, zinc	1940s-1970s
Red Indian Lake, NL	Buchans Mine	American Smelting & Refining Co.	copper, lead, gold, silver, zinc	1928-1984
Summit Lake, BC	Summit Lake Gold Mine	Scottie Gold Mines Ltd.	gold	1981-1984
Thompson Lake, NT	Thompson-Lundmark Mine	Thompson-Lundmark Gold Mines Ltd.	gold	1941-1949

It should be noted that Garrow Lake is hypersaline, with bottom water up to 2.6 times saltier than seawater. A salinity gradient makes Garrow meromictic, keeping bottom water and surface water separated. Partial mixing between the two layers does occur in the fall (Dickman 1991).

In many cases tailings disposal occurred prior to regulatory requirements for the collection of pre-disposal ecosystem information. Due to the consequent lack of baseline data, this review includes other empirical standards for recovery assessment, such as the Canadian Environmental Quality Guidelines (CEQG) which are used within this study as key reference points for water and sediments. The CEQG are national, scientifically derived guidelines for parameter levels that should not result in risk to "biota, their functions, or any interactions that are integral to sustaining health of ecosystems." They do not integrate site-specific conditions, but are useful tools for broadly assessing risk. Where the water and sediment CEQGs for the protection of freshwater aquatic life were not mentioned in the original studies, data presented were compared to the guidelines. No CEQGs currently exist foraluminum, antimony, cobalt, iron and nickel in sediments, or antimony, cobalt and chromium in water. Guidelines for cadmium, copper, lead and nickel are water hardness dependent and therefore not analysed by this review in the absence of reported hardness values (CCME 1999).

Results

Table 2 outlines key information regarding the waste disposal in the 10 lakes of interest. Long-term (>10 years span) monitoring data and analyses were found for five lakes. An important confounding factor in our research was that eight of the lakes (excluding Garrow and Summit) are known to have been affected by metal leaching/acid rock drainage (ML/ARD) from land-based tailings or effluent dumping not under regulations. Another challenge was the variation in the physical extent of tailings deposition relative to the size and depth of each lake. This has not been accounted for in our analysis.

Table 2 Information pertinent to subaqueous tailings disposal in the 10 lakes reviewed. *Indicates dates of mine operation where no dates specifying period of tailings disposal were found. "nk" means not known.

Water Body	Lake Area (ha)	Waste (t)	ARD Potential	Subaqueous Disposal (yrs.)
Benson Lake, BC	77	nk	Yes	copper: 1962-1973 (10.5); iron: 1963-1970 (7.5)
Brucejack Lake, BC	81	1.24×10^5	Yes	1999 (1 month)
Buttle Lake, BC (S Basin)	4 204	5.5×10^6	Yes	1966-1984 (18)
Garrow Lake, NU	500	2×10^7	Yes	1980-2002 (22)
Giauque Lake, NT	2 000	nk	Yes	1965-1968 (4)
Kootenay Lake, BC (Galena & Bluebell Bay)	40 700	Galena: 1.95×10^6 Bluebell: nk	Yes	1895-1929* (34); 1952-1972* (21)
Mandy Lake, MB	24	7.3×10^4	Yes	1943-1944 (2)
Red Indian Lake, NL	18 044	nk	nk	1928-1966 (39)
Summit Lake, BC	nk	nk	Yes	1981-1984* (4)
Thompson Lake, NT	300	nk	nk	1941-1949* (9)

Physical habitat recovery

Smothering of benthos by tailings was noted at Benson Lake during tailings deposition (Rescan 1990a) but no analyses specifically investigated the changes in sediment habitat types pre and post tailings disposal in any lakes. Neither were the effects of water depth changes on physical parameters of lake ecosystems investigated.

Water quality recovery

Where data were reported during disposal, high turbidity levels were observed from tailings input (Benson) (Rescan 1991) but not from waste rock input (Brucejack) (Price 2005). Unsuccessful attempts to mitigate the problem at Benson Lake included flocculent addition and tailings input at increased depths, although water clarity recovered to pre-dumping conditions within 10 months after disposal ceased (Hallam *et al.* 1974).

Cases of elevated (relative to background or reference) and/or above guideline levels of metals in the water column were found at some point in all lakes except for Kootenay, Summit (no data) and Red Indian lakes. Analyses of inflow/outflow metal concentrations at Brucejack (Price 2005), Mandy (Hamilton and Fraser 1978, Rescan 1990b, Rescan 1990d), Buttle (Pedersen 1983) and Benson (Rescan 1991) concluded that the major if not total metal sources were land-based waste rather than submerged waste.

Metal fluxes from tailings into the overlying water column were observed at two of the three tested lakes: Buttle (zinc, copper, lead) and Mandy (copper and lead). Conservative calculations predictedthe annual metal loadings over the entire lake water volume from these fluxes would not significantly affect the water quality of the overlying water(Rescan 1995, Rescan 1990c, Rescan 1990d). Evidence of metal fluxes from tailings into water have been found at sites other than our 10 focal lakes, such as the fluxes of arsenic, silver, copper, zinc, lead, cadmium, nickel, antimony, thorium and uranium noted in a pond in Cobalt, Ontario (Kwong *et al*. 2010). Quantification of these fluxes should be undertaken.

Fluxes were not investigated at Thompson Lake, but the submerged tailings were concluded to be a likely source of water contamination as total arsenic, mercury and zinc concentrations above CEQG were only observed close to tailings in the lake (Moore 1981). In Garrow Lake, tailings were deposited directly into the hypersaline lower water layer. However, metal monitoring was conducted only in surface water and concentrations of lead and zinc increased over permitted levels due to metal contribution from the lower layer during partial mixing in the fall (Dickman 1991) and to a tailings pipe break in 1985 (Donald 2005).

CEQG exceedances in water due to tailings were still present during the most recent site studies at two lakes. Exceedances were observed at Thompson Lake (arsenic, mercury, zinc) 32 years after mine closure (Moore 1981) and at Garrow Lake (zinc) 19 years after the tailings pipe break contaminated surface waters (Donald 2005).

Sediment quality recovery

Metal levels in sediment were often elevated in comparison to background and/or above CEQG levels. Solid phase heavy metal concentrations in sediments were analysed in seven lakes: Benson (two studies), Buttle (two), Giauque (four), Kootenay (prior to remediation via shallow sediment removal), Mandy (two), Red Indian (two) and Thompson (two, one only analysing mercury). No data were found for Brucejack, Garrow or Summit. Six of the seven sampled locations showed heavy metal enriched sediments, most with CEQG exceedances, during the latest study conducted at each site.

Significant amounts of metals were found in surface sediments even after many years of natural sediment deposition at: Mandy Lake 46 years after deposition ceased (Rescan 1990d), Giauque Lake 33 years post-deposition (Gartner Lee 2007), Buttle Lake 11 years post-deposition (Rescan 1995) and Benson Lake 19 years post-deposition (Rescan 1992). Bioturbation by benthos, slumping of deposits and wave action are potential explanations for these long-term impacts.

Heavy metals above guidelines in sediments are cause for concern as they may affect benthic populations, an integral part of aquatic food webs. An example of substantial contaminated sediment impact is the mercury contamination of fish in Giauque Lake. Underwater tailings deposition is considered the primary cause of mercury in Giauque Lake fish and sediment has been identified as the likely contamination pathway (Gartner Lee 2007).

Efforts to remediate Kootenay Lake sediments were prompted by observations of ecologically non-functional sediments in Bluebell Bay, moderately impacted sediments and metals contamination of invertebrates in Galena Bay and wave action dispersal of tailings in shallow areas. Tailings were excavated 2m and 0.5m below water level at Galena Bay and Bluebell Bay respectively. Bluebell Bay's beach and littoral area were reconstructed to prevent erosion and re-contamination (Donald *et al.* 2001). No follow-up monitoring data were found regarding the subsequent state of littoral productivity and invertebrate contamination in these areas.

Predictive tools for sediment metal toxicity and bioavailability are still limited and require further research and validation. Prediction methods depend on whether sediments are oxic or anoxic, a characteristic which may change throughout the lake bottom and seasons (Vigneault and Gopalapillai 2009). The studies researched do not contain sufficient spatial and temporal resolution to take these factors into account.

Benthic life recovery

Of the 10 lakes analysed for this paper, records of benthic invertebrate sampling were found for seven. No data were found for Garrow (paper unavailable), Summit and Brucejack lakes. Three of the other seven locations each had only one study examining benthic life (Buttle, Mandy and Thompson). Research at Mandy and Thompson were conducted decades after disposal ceased. The findings of these studies are summarised below:

- During tailings disposal and in the year after disposal ceased, Benson Lake had no benthos present. By 17 years after waste disposal, benthic community structure and density were similar to those of uncontaminated lakes with similar characteristics (Rescan 1991).
- One year after dumping ceased in Buttle Lake, deformities in the heavy metal tolerant species were observed. This may have impaired fitness but no further benthos studies were conducted. Metal tolerant species were present and abundance and diversity was lower closer to the discharge site (Roch *et al.*1985).
- Sampling of Mandy Lake 46 years after tailings disposal ceased did not find any negative effects on benthic life (Rescan 1990b).
- Decreases of benthic algae diversity and density correlated with decreasing distance from submerged tailings in Thompson Lake 29 years after tailings disposal ended (Moore 1981).
- Studies showed suppression of density and diversity closer to the tailings site in Giauque Lake (Moore *et al.*1978 and NSMHL *et al.*1999). Subsequent studies in 2000, 2005 and 2007 reported recovered populations with no differences between tailings and non-tailings sites within the lake (Gartner Lee 2007, NSMHL and Gartner Lee 2002). Invertebrates were tested for mercury and arsenic but detection levels and low sample masses limited conclusions. Clams at two of three sampling locations were found to contain arsenic levels higher than the control (NSMA 1998).
- Approximately 25 years after mining ceased, Kootenay Lake analyses showed elevated metals in Galena Bay invertebrates, and presumably no benthic life in Bluebell Bay, where sediments were labelled 'ecologically non-functional' (Donald *et al.* 2001).
- Absence of benthic life was noted during tailings deposition (1961) in part of Red Indian Lake, but by the next sampling (1974), benthic life showed no negative effects (Morry and Cole 1977).

In summary, over the seven locations for which we found data, six exhibited negative impacts to benthos diversity, abundance and/or community structure due to tailings deposition. Over time, recovery of investigated parameters was documented at three locations (Benson, Giauque and Red Indian) in comparison to non-contaminated parts of the same lake or to similar but uncontaminated lakes. No data were found for Kootenay Lake after remediation was completed. Negative impacts were found in single studies done at Buttle (diversity and abundance - one year post tailings) (Roch *et al.*1985) and Thompson (diversity and density - 29 years post tailings) (Moore 1981). No further data were found to verify if recovery ever occurred. Little can be concluded regarding metal accumulation in benthos, as benthic tissue metal concentrations were tested at only two lakes (noted above), and without food web analyses.

Zooplankton recovery

Zooplankton data were located for five of the 10 lakes. Zooplankton sampling over more than one time period occurred only at Buttle Lake (spanning 1984 - 1986) and Red Indian Lake. At Buttle Lake, diversity decreased and species composition turned towards metal tolerant species (Deniseger *et al.*1986). Elevated metal concentrations were detected in Buttle Lake zooplankton tissue in the only study to analyse this parameter at any of the 10 lakes (Roch *et al.* 1985). The zooplankton population crashed to negligible levels in 1984-1985, possibly influenced by an algal bloom enabled by metal contamination (Deniseger *et al*. 1986). By 1986 species composition and diversity had recovered to pre-mine impact levels (van Dyk 1987, Deniseger *et al.*1990). At Red Indian Lake, a shift towards smaller zooplankton was observed. The shift was explained as a top-down effect from increased fish feeding on larger members of the zooplankton community due to a decrease in benthos, their usual food source (Morry and Cole 1977).

No impacts on zooplankton were observed at three of the lakes (Giauque, Benson and Mandy). These studies looked at abundance and species composition at Giauque 10 years post tailings disposal (Moore *et al.*1978), community structure and density at Benson 17 years post-disposal (Rescan 1991), density and species composition in Red Indian eight years post-disposal (Morry and Cole 1977) and diversity at Mandy 46 years post-disposal (Rescan 1990b).

Phytoplankton recovery

Phytoplankton studies for five of the lakes were found. Sampling occurred over more than one time period at Buttle Lake (spanning 1981-1986) and Garrow Lake (spanning 1980-1987). At Buttle Lake the community shifted to metal tolerant species and density and diversity decreased (Munteau and Austin 1981, Roch *et al.* 1985, Deniseger *et al.* 1986). By 1986, density was noted to be within the range expected for similar lakes and species composition and diversity were improving but had not returned to pre-impact levels (van Dyk 1987, Deniseger *et al.*1990). No further studies were found to verify if full recovery occurred. At Garrow Lake, tailings discharge at the same depth as the anaerobic phototrophic bacteria habitat significantly reduced populations of these major primary producers in the lake (Dickman 1991). This would conceivably have significant impacts on the entire food web, but no follow-up reports have been located.

Studies showed no impact on abundance and composition of phytoplankton at Giauque 10 years after deposition ended (Moore *et al.* 1978); nor on structure and density of phytoplankton communities at Benson 17 years post-disposal (Rescan 1991); nor on density and distribution at Mandy 46 years post-disposal (Rescan 1990b). No information regarding effects in years previous to these studies was located.

Fish recovery

Studies of tailings effects on fish were limited in number and in scope. One study was found for each of Red Indian, Mandy and Thompson lakes. Three studies were located for fish in Benson, numerous fish studies were conducted for Buttle (spanning 1960-1986) and Giauque Lake (spanning 1978-2006). Fish-related parameters investigated varied among the studies. Despite high surface water zinc levels and significant changes in the food web of Garrow Lake, no studies of Garrow sculpin health were located.

Most studies did not include fish population estimates, habitat use or productivity. Fish population changes were studied only at Red Indian and Buttle lakes. Results from population representative sampling conducted at Red Indian Lake were compared to data obtained during tailings disposal, when populations were seen to decrease. The study found no negative effects on fish populations eight years after dumping ceased (Morry and Cole 1977). Baseline fish data prior to mine operation and tailings disposal at Buttle Lake were found only in the form of angling success rates (no species composition or overall population estimates). From 1964 to 1980, significant decreases in catch success rates were experienced and inferred to be due to heavy metals in the lake water (Hirst 1991). Population and species composition estimates were produced for Buttle Lake in 1982 and 1988. Both samples failed to catch any stickleback or prickly sculpin, which are known natives in Buttle Lake, although pre-disturbance species proportions are not known (Roch *et al.*1985). Fish numbers in 1988 were high, but species composition varied notably from 1982. Cutthroat trout made up 24% of the catch in 1982, but were not caught in 1988, while Dolly Varden increases made up the difference. Comparisons between 1982 and 1988 are confounded by the fact that in 1988 sampling was limited to the area near the stream inlet where tailings were submerged, whereas sampling in 1982 was more representative of the entire lake (Hirst 1991).

Of the five lakes where data on contaminants in fish muscle were obtained (Mandy, Benson, Buttle, Giauque and Thompson), Mandy was the only lake where elevated metals were not observed. Muscle metal concentrations were tested in three of five Mandy Lake fish species and were found to be within Canadian background concentrations (Rescan 1990b).

Results from Benson Lake were mixed. One study showed no significant difference between Benson fish and control fish (Kussat *et al.* 1972). A more recent study showed copper and cadmium body burdens of Benson fish to be higher than control fish. However, sample sizes in both studies were small (two or three fish per lake) reducing confidence in the results. Metal levels were within Canadian background. In both cases sampling was done for only two of four species in the lake (Rescan 1991).

Zinc, copper and lead concentrations were significantly greater in Buttle Lake fish than control fish between 1979 and 1981, but zinc and copper levels fell within control levels in 1983 to 1986. Insufficient data prevented conclusions regarding lead in 1983-1986. Three of the five species present in Buttle Lake were analysed (Deniseger *et al.* 1990).

In Giauque and Thompson lakes, fish mercury levels remained elevated for many years after tailings disposal, prompting human consumption advisories to be put in place (Gartner Lee 2007, Moore and Sutherland 1980). As stated earlier, the tailings deposited into Giauque Lake are considered the main source of metal and mercury contamination (Gartner Lee 2007). Today, there is no advisory for Thompson Lake, but no further details have been located.

Fish liver metal concentrations were reported for only three lakes: Benson, Buttle and Mandy. Benson rainbow trout exhibited possible biomagnification of arsenic, cadmium, copper and cobalt. Human consumption guidelines at sampling time existed only for arsenic, and fish were below the guideline (Rescan 1991). No further study of this suspected biomagnification was found. In the most recent samples at Buttle Lake, copper and cadmium liver levels in rainbow trout were significantly greater than control. Three of five Buttle Lake species were tested (Deniseger *et al.* 1990). Pike liver levels in Mandy Lake were within Canadian background levels and the four other lake species were not tested (Rescan 1990b).

It is a concern that not all species in each lake were sampled in the studies, as interspecies variations in response to metal pollution are too large to allow generalisations from single species data (Deniseger *et al.* 1990). Chronic exposure effects, fish population, fitness or behavioural changes were also not well studied. One study looked at fish size and condition factors, and found Benson Lake fish had better results than control lake fish, but small sample size makes this inconclusive (Rescan 1991). Two studies noted signs of slowing fish growth (Benson and Buttle lakes) (Hallam *et al.*1974, Roch *et al.* 1985). The following statement made regarding Buttle Lake can be applied to all the lakes in question: "Very little work has been done in this study to assess sublethal effects on behavior, growth of wild fish or success of reproduction and development, because of the expertise required and the difficulties of assessing these effects in the natural environment" (Roch *et al.*1985).

Aquatic macrophyte recovery

Studies of two lakes noted revegetation of tailings with emergent and floating plant species (Benson and Mandy) (Rescan 1991, Rescan 1990b). The recovery of aquatic plant communities is important given their role in habitat creation and food webs. They are also of interest because they can play a role in metal cycling. Metals taken up from sediments by plants may be made available to biota following plant consumption or plant death and decomposition. Root respiration by-products may include bioavailable metal compounds and oxygen supplied to sediments through roots may facilitate metal uptake.

Metals in aquatic plants were analysed at Benson Lake and Mandy Lake. Metal accumulation was noted in tops and roots of horsetail (*Equisetum* sp.) and pondweed(*Potamogeton* sp.) of Benson Lake (arsenic and copper) (Rescan 1991) and Mandy Lake pondweed (arsenic, cadmium, copper, lead, mercury, nickel and zinc) and cattails (*Typha* sp.) (arsenic, copper and zinc) (Rescan 1990b). Due to these findings, it was recommended that tailings deposition be limited to deeper portions of a water body. Despite the significance of macrophyte communities, no extensive study of these issues has been found.

Sustainability

A successfully recovered water body should not require long-term intervention to maintain water quality or aquatic organism populations. Kootenay Lake's littoral remediation (previously discussed) was the only case of an intervention taking place in one of the lakes following tailings deposition.

All the water bodies examined appear to be self-sustaining with regard to their post-disposal community structure. The lack of biotic monitoring data, especially population level analysis and chronic toxicity tests make it impossible to be conclusive about this.

Stability and resilience

Healthy ecosystems exhibit a certain degree of stability and ability to recover from disturbances. This resilience and stability cannot be easily measured or predicted, however evidence of major swings in community structure and population levels relative to control lakes would indicate ongoing stress potentially from tailings disposal.

While there are not enough data to comprehensively assess this aspect of aquatic ecosystem health, one interesting example of the fragility of a recovering water body was discussed in the literature. When heavy metal loadings to Buttle Lake decreased, ecosystem health did not improve at first, but declined. The initial metal pollution had caused changes in the algae species present, which coupled with nutrient changes unrelated to mining activity, allowed one diatom to dominate the phytoplankton community once metal concentrations began to decrease. Only 18 phytoplankton species were found in 1984, compared to 46 species found the previous year. The diatom bloom may have contributed to the concurrent steep decline of the zooplankton population, an important source of fish food in Buttle Lake (Deniseger *et al.* 1986). The zooplankton population eventually recovered to pre-disturbance levels (Deniseger *et al.*1990). The last phytoplankton studies observed recovered density (van Dyk 1987) and *improving* species composition and diversity (Deniseger *et al.*1990), but no further studies verified if the phytoplankton community fully recovered. This example illustrates that ecosystem recovery is not simply a linear reversion to its original state (Deniseger *et al.*1990). Many unforeseen factors influence recovery and results are difficult to predict.

Contaminant fate and transport

If a lake ecosystem is said to be healthy or recovered it should not harm the surrounding environment through contribution of contaminants. Potential contaminant pathways from subaqueous tailings include seepage into groundwater, resuspension of sediments, geochemical fluxes into the water column, uptake by plants rooted in the sediment, and uptake by benthos. Studies identified that geochemical reactions such as precipitation of iron oxides, manganese oxides or sulfides can remove dissolved metals from the water column and prevent effluxes from tailings. However, remobilization of metals also occurs in certain conditions, as observed in the seasonal cycling of arsenic released to lake water during reducing conditions of winter (Rescan 1996). While lake surface inflows and outflows were sometimes characterised, no mention was ever made of testing for lake seepage into groundwater. Groundwater was analysed at two lakes due to concerns about land-based tailings. Environmental Impact Statement documents for Kemess North, Prosperity and Long Harbour Hydrometallurgical projects all describe risks of groundwater contamination from tailings disposal into natural water bodies (Hart 2011).

The two lakes where macrophyte data were available showed elevated metals in plant tissues. No risk analysis for wildlife consuming these plants has been done. Due to the dearth of research, the contaminant risks for groundwater or wildlife in the areas surrounding the tailings receiving waters are largely unknown.

Social and economic values

The technical studies read for this paper did not include substantial information on potential socio-economic impacts related to lake changes. Issues of concern include impacts to First Nations culture, hunting, fishing and health, commercial and sports fisheries, water related recreation and tourism, clean water resources, wildlife habitat and health and aesthetic values. Fishing resources were the most investigated (see fish section).

Despite past tailings deposition, Buttle, Kootenay and Red Indian lakes are presently recreational and tourist destinations for sport fishing and other water activities. Conversely, mercury contamination has brought an end to the use of Giauque Lake and another downstream from it for commercial, sport and subsistence fishing. Currently, an advisory limits consumption of four species present in Giauque Lake (NT 2007).

A Human Health Risk Assessment for Giauque Lake predicted no health risks from cobalt, lead, manganese, nickel or zinc to First Nations people consuming fish from the lake. However, non-cancer health risks due to mercury contamination were not ruled out, and increased cancer risks due to arsenic contamination were predicted (Gartner Lee 2007). In its report on the North Slave Area, Northwest Territory fish stocks, the Department of Fisheries and Oceans noted that Thompson Lake fish were contaminated above human consumption guidelines in 1978, and that occasional sports fishing may occur in the lake (Stewart 1997). Currently, there is no fish consumption advisory for Thompson Lake.

Acknowledged socio-economic factors linked to Buttle Lake, located in Strathcona Provincial Park, included the downstream domestic water collection for the town of Campbell River, and the use of the Campbell River for Quinsam River Hatchery juvenile salmon habitat and fishing grounds (Deniseger *et al.* 1986). No problems from contamination were described regarding these two specific resource uses or the tourism that takes place. The fact that the tailings disposal was limited to the South Basin of Buttle Lake, which is approximately 10% of the entire lake volume and is partially isolated by a natural sill, may have helped minimise downstream impacts (Roch *et al* 1985).

Garrow Lake literature also indicated some assessment of socio-economic factors. An analysis of hunting and fishing usage of Little Cornwallis Island (the location of Garrow Lake) was conducted and reported in the 1980 Potential Socio-Economic Impacts of Polaris Mine Project report by Outcrop Ltd. It concluded that the Resolute Inuit would suffer little impact from the mine as the area was not important hunting ground (Donald 2005). The Teck Cominco Remediation plan for Garrow Lake stated they would conduct studies to see if the fourhorn sculpin had been affected by tailings deposition. The remediation plan's goal was to "return the lake to its once pristine condition" (Donald 2003 pers comm as cited by COSEWIC 2003). Yet zinc concentrations were greatly over CEQG in 2004 (Donald 2005). Water quality monitoring was to be ongoing until 2011 but data were not available to the authors.

The important genetic and scientific research value of the fish and zooplankton community in the hyper-saline environment of Garrow Lake could be lost. This community has developed over the last 3,000 years and is unique to Garrow Lake (COSEWIC 2003). Surface water metal contamination and dramatic changes in the food chain have been observed since tailings deposition. This could mean a significant loss for the scientific community studying zoogeography and natural selection (Dickman 1995).

Many isolated lakes may contain uniquely structured biotic communities and genetic diversity, even when species lists appear relatively similar to other lakes. Evaluating the uniqueness of lake ecosystems proposed for use as tailings impoundments would require much more rigorous investigation than was found in most of the studies located in the course of our research.

We also acknowledge that further concerns regarding the impacts of subaqueous disposal are held by many whose spiritual or philosophical beliefs affirm the intrinsic value of nature and may place a special importance to some or all aquatic ecosystems. This aspect was not addressed in the technical literature reviewed for this paper but is an issue deserving of greater discussion and understanding.

Research gaps and uncertainty

The Rawson Academy review of Mine Environment Neutral Drainage (MEND) work identified an important research gap in that little sampling had been done on shallow areas exposed to wind, wave and plant root influence, despite being continually noted as potential areas of greater tailings effects (Rescan 1995). From our review of the literature this is still the case.

A review of MEND studies from 1993-1995 noted a number of areas requiring more study (Sly 1996). Our research found that many of the gaps identified then still exist today including: effects on ecosystems during subaqueous disposal, influence of high spatial and temporal variability of sediment conditions on tailings reactivity and toxicity and possible effects of lime in tailings on nutrient levels and thus ecosystem productivity. Despite being flagged as research gaps in other reports, we also found no follow up studies on the contribution of bioavailable metals by littoral vegetation or metal biomagnification.

Interspecies and inter-metals variability in metal uptake for fish, plants and other biota make prediction of tailings effects difficult. Variations in aquatic sites including but not limited to climate, species and genetic diversity, food chain characteristics, natural productivity, historical use and nearby development all contribute to uncertainty regarding effects and recovery. It is conceivable that the uniqueness of each aquatic ecosystem may confound the capacity to predict the outcomes of tailings disposal in lakes.

Conclusion

A clear picture of whole ecosystem recovery is not available for any of the lakes, as not all the same parameters were consistently monitored over time. Little knowledge of pre-mining ecosystem conditions was found, which is not surprising considering the historical nature of the tailings disposal researched. This means that the true extent of ecosystem effects, changes and recovery are not measurable. Three lakes (Benson, Buttle and Garrow) were studied during tailings deposition, which clarifies some general stressors on a system during this time, and provides an impacted state against which recovery can be held.

The data gaps identified can provide guidance for future studies designed to assess recovery. In addition, any future regulatory approval for reclassifying natural water bodies as TIAs should require mine companies to collect comprehensive baseline information to act as a reference during disposal and post-closure ecological assessments. Without this information the degree of recovery a lake may achieve cannot be accurately assessed, as has been noted in the studies examined in this paper.

Generalising across the studies for the 10 water bodies, water quality parameters consistently recovered to acceptable conditions at eight of 10 sites. Metal contaminated sediments remained a long-term issue at all lakes, even where thick layers of natural sediments overlay the tailings. Benthic communities usually recovered diversity, density and species composition but lack of studies preclude confirmation of this for all lakes, and limit conclusions regarding benthos metal body burden. Zooplankton communities at five lakes were examined and showed eventual recovery. Phytoplankton communities at four lakes were examined and showed full recovery in all except one case, where partial recovery was observed but no follow up study was done. Little work was done regarding fish community parameters, with no effects observed on fish numbers at two lakes and possible species composition change observed at one. Metals in fish muscle were found to be within background levels in three of five lakes with data. In the other two, long-term contamination of fish with mercury and arsenic posed human health risks. From limited sampling of liver tissue there is some evidence of metal bioaccumulation occurring in two of three lakes with data. Aquatic plants were shown to accumulate metals at the two lakes where this was studied. Lack of study precludes conclusions about contaminant transport via groundwater and plants. Post-disposal ecosystems did not require long-term interventions. Evidence of the non-linear nature of recovery leaves more questions than answers about ecosystem resilience in the face of pollution-induced stress. Socio-economic impacts were felt in a number of ways and require more consideration.

The studies reviewed in this paper support the idea that lakes can achieve a degree of recovery after tailings disposal. However, a clear definitive picture of the extent of damage and recovery is not available due to research gaps and uncertainty. There are also indications that in some cases ongoing long-term negative effects to the lake ecosystem and even downstream ecosystems continue to occur. While the results described in these studies point to the potential for some recovery, many questions still remain.

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Acronyms

Canadian Environmental Quality Guidelines (CEQG)