Mercury Loss from Gold Rush Era Placer Mines in the Fraser Basin

by

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Declaration of Committee

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Abstract

Gold-rush era mercury loss at mine sites in the Fraser Basin was investigated. 109 soil and sediment samples were collected from suspected hotspots on 15 legacy placer mine sites and tested for total mercury. 89% of sites that had clearly discernable signs of mining had at least one test sample that exceeded all control samples taken during the study, suggesting that mercury use was widespread during B.C.'s Fraser and Cariboo gold rushes. An estimated 17,768 to 247,665 kg was lost in the Fraser Basin between 1858 and 1910, calculated by relating mercury loss to different records of gold extraction. Historical records show that 26,749 kg of mercury was shipped to B.C. from California between 1860 and 1883, and mercury imports into Canada between 1882 and 1899 exceeded expected mercury needs for gold amalgamation practices.

Keywords: Mercury, methylmercury, placer mining, gold-rush, gold mining, ASGM, amalgamation, mercury imports, contaminated sites, British Columbia environmental history, Barkerville, Quesnel, Fraser River.

Dedication

Dedicated to those who eat what the lands and waters provide.

Also dedicated to my dad, who taught me to fish, who shared wonder in the earth, trees and sky, and who patiently answered what must have been rather annoying strings of “but why” questions.

Acknowledgements

This project was supported by many people. I returned to university with 4 and 6-year-old children in tow and could have not done this project without Tyler Ammerlaan, whom in addition to taking on extra parenting responsibilities, also provided invaluable support as an unpaid and intrepid research assistant. My kids have also gamely put up with being deposited at grandparents and dragged along on working camping trips.

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Thank you to the UniverCity community and University Highlands Elementary for being a wonderful nest for our 20 months in the big city. And also, Hillary Atleo, for keeping me sane!

I am also grateful for the millennia of stewardship of the WSÁNEĆ people, on whose land I live, work, and raise my family as an uninvited settler. I also want to acknowledge that field work for this project was conducted on sites in S'ólh Téméxw (Stó:lō), Nłeʔkepmx Tmíxʷ (Nlaka'pamux), Tsilhqot'in Nen, Sɬáɬimc Tmicw (St'at'imc), Secwepemcúl'ecw (Secwépemc), and Dakeł Keyoh (ᑕᗷᒡ ᗰᑎᐦ).

Finally, I would like to thank my parents, who always encouraged curiosity and the big questions.

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List of Acronyms

AEPHIN	Alberta Environmental & Public Health Information Network
AMAP	Arctic Monitoring and Assessment Programme
ANOVA	Analysis of Variance
ASGM	Artisanal and small-scale gold mining
BCMOE	British Columbia Ministry of Environment
CVAAS	Cold Vapor-Atomic Absorption Spectrophotometry
FLNRO	British Columbia Ministry of Forests, Lands, Natural Resources Operations
MECP	Ontario Ministry of the Environment, Conservation and Parks
PCB	Polychorinated biphenyl
SALM	Strong Acid Leachable Metals
SD	Standard Deviation
UNEP	United Nations Environmental Programme
USEPA	United States Environmental Protection Agency

Glossary

Alluvial Ore	Also known as “pay dirt,” alluvial ore refers to soil or sediment moved by water that may carry gold in desirable quantities.
Amalgamation	The process of combining mercury with another metal, where positively charges ions form a crystal lattice structure.
Artisanal and small-scale gold mining (ASGM)	ASGM includes both gold placer mining and other small scale gold mining methods.
Au	Symbol for gold.
Hg	Symbol for mercury.
Flask of mercury	“Flasks” were the standard unit of measurement for mercury, and weighed 34.5kg, with a volume of about 2.5 liters.
Placer Mining	Mining of gold or other minerals moved by water. In this paper, the term placer mining is used exclusively to describe placer gold mining. In British Columbia, jade mining is sometimes also referred to as placer mining.
ppm and ppb	Studies report total mercury in soil, sediment, fish and hair in parts per million (ppm) and its equivalents: mg/kg and µg/g; and parts per billion (ppb) and its equivalents, ng/g and µg/kg. For simplicity, most values in this project have been converted to ppm or mg/kg.
Quicksilver	Quicksilver is an antiquated synonym for liquid mercury.
Tailings	Tailings refers to the material that remains after minerals have been extracted. In placer mining, this material is in the form of cobbles, gravel, sand, silt and clay.
tHg	Symbol for total mercury.

Preface / Self Location

My parents often recount stories of the summer I was three. They were both on a four-month break from university, my mother in the third year of a law degree, my father in a teaching degree. We moved from our townhouse in University of Alberta family housing to our homestead near Joussard, a four-hour drive north.

My father's family has been in that area for generations. Following the Louis Riel rebellion, my Dane-Zaa and Métis grandmother Olive Dumas, and my Métis great-grandfather, Gregoire Jobin, moved to Big Prairie, near Grouard, across Lesser Slave Lake from Joussard. My grandmother, Helen Jobin, attended residential school in Grouard, and raised my father and his twelve siblings in Peace River and McLennan. My mother, who is Estonian and Scottish, moved to Alberta in her early 20s from Ottawa.

The land around Joussard is a network of rivers and big lakes, with farms interspersed by stands of trembling aspen and muskeg. Knowing my parents were raising three kids and expecting a fourth on a meagre income, a friend invited my dad to go fishing at the start of the summer, and sent him home late that day with hundreds of jackfish (which they caught using probably illegal fish traps, but that's another story). My family refers to that summer as "the summer of jackfish and pigweed." Throughout that summer, our family ate one or two meals of jackfish almost every day.

At the time, my mother was pregnant with my younger sister. Fish advisories for mercury usually provide separate, and much lower, limits for fish consumption by pregnant women because consuming mercury contaminated fish exposes women, and their fetuses, to the highly toxic form of mercury called methylmercury. Children exposed to methylmercury in the womb and early childhood have shown significant declines in cognitive performance, along with other issues. At today's average mercury concentrations for jackfish in Lesser Slave Lake (0.33 ppm), our consumption of these fish would have well exceeded the recommended maximum methylmercury consumption rate for children and women of childbearing age.

My siblings and I do not show any obvious signs of fetal or early childhood methylmercury exposure, but the effects can be subtle. So while we are all functional members of society, perhaps without that exposure we would be smarter, better coordinated, or healthier.

My parents, my sister and I have all moved to British Columbia (B.C.), and while we now eat more settler and conventional diets, I feel fiercely protective of the right and ability of Indigenous people, and all people, to eat the food the land provides. I also believe that information on the safety of our food sources should be widely available.

Chapter 1. Introduction

Mercury is a well-known contaminant that can cause severe ecological and human health issues at low concentrations (Driscoll et al., 2013). It is persistent, bioaccumulative, and capable of long distant transport in the atmosphere (AMAP/UNEP, 2015). It also forms an amalgam with gold and has been used in placer mining to increase gold yields for millennia (Lacerda & Salomons, 2012).

In this case study, I sampled a subset of gold-rush era (1858-1910) placer mine sites to assess the prevalence of mercury use during the gold rush period in the Fraser Basin, a region where mercury was not locally mined. This work may be applicable to similar mine structures found in other regions throughout the world where mercury was not locally mined and will assist in understanding the spatial and temporal fluxes of mercury in the Fraser River, the Fraser delta, and the Georgia Strait.

Placer mining has been practiced more or less continually for over 2000 years, and mercury amalgamation techniques have an equally long history (Brooks, 2012, pg 19; Nriagu, 1994, p. 168). In a 1905 review of the historical practice of placer mining, Bowie (1905) notes placer mining activity in 27 countries and across every continent except Antarctica (p. 15-43). Mercury amalgamation techniques are still in use today in more than 70 countries, and are a major source of atmospheric mercury (AMAP/UNEP, 2015; Telmer & Veiga, 2009, p. 131). International efforts to phase out the use of mercury in artisanal mining, which includes placer mining, are currently underway (United Nations, 2017).

Colonial use of mercury amalgamation techniques in the Americas began in Mexico the mid 1500s (TePaske, 2010, p. 72, Nriagu, 1994, p. 172). The practice eventually spread to California, where mercury was mined on the western side of the Central Valley and used in gold mining to the north and east of the valley (C. Alpers et al., 2005, p. 2). Between 1848 and 1968, placer miners in California lost approximately 4.5 million kg of mercury to the environment (Churchill, 2000, p. 38). Mercury contamination persists at Californian mine sites and is mobilized during storm events (Fleck et al., 2010) converting to methylmercury which biomagnifies, resulting in increased mercury concentrations in fish (Alpers et al., 2016; Keeble-Toll, 2016).

At the start of B.C.'s Fraser gold rush in 1858, 20 to 30 thousand miners from California travelled to Victoria and on to Fraser (Haggen, 1924), a population that was by some estimates one-sixth of the total number of voters residing in California at the time (Bowie, 1905). While many of these miners soon left the region, strong connections between British Columbia and Californian mining cultures remained (Marshall, 2000), and mining practices prevalent in California at that time were transplanted to British Columbia (Kennedy, 2009; Nriagu, 1994, p. 175).

Despite the strong connections between British Columbian and Californian mining cultures, and the well-known presence of gold-rush era mercury contamination in California, few efforts have been made in B.C. to understand if miners used mercury, what quantities were used, and whether mercury persists in the ecosystem.

While it has been over 100 years since the gold rushes in British Columbia, and one might expect any environmental effects from mercury would have passed, a number of factors make this issue ripe for investigation and policy consideration. First, climate change is increasing wildfires, which are linked to high rates of erosion and increased peak waterflows (Doerr & Shakesby, 2006), which could facilitate the erosion of gold-rush era mine sites (Nepal, 2013). River temperatures are also increasing (Déry et al., 2012), which could increase the conversion of elemental mercury to the more toxic, and bioaccumulative, methylmercury. (Ullrich et al., 2001). Further, the price of gold is at historically high levels (La Monica, 2020) which will stimulate the modern placer mining industry. Modern miners frequently operate in the same areas as historical miners and disturb or even remine gold-rush sites. As discussed in Section 4.2, B.C. does not have a contaminant testing program in the Fraser or other watersheds (Cohen, 2012, p. 322), so mercury concentrations could rise in lakes, rivers and fish tissue without triggering a policy response.

1.1. Health and Ecosystem Effects of Mercury

Mercury is present in lakes and rivers through human activities, geologic weathering, and atmospheric deposition (Eagles-Smith, Ackerman, et al., 2016, p. 1171). Elemental mercury can be converted to methylmercury by anoxic, sulfur reducing bacteria, and is taken up by aquatic life through diet (Klapstein & O'Driscoll, 2018, p. 14; Ullrich et al., 2001). Methylmercury bioconcentrates, so even low background

concentrations in the environment can result in high methylmercury loads, especially in predatory fish (Reed C. Harris et al., 2007; Morel et al., 1998, p. 544). The primary route of human exposure is through fish consumption. At high doses, such as those experienced in Minamata, Japan, hair mercury levels of 300 to 700 ppm were accompanied by a host of problems ranging from neurological issues such as reduced vision and poor coordination, to diabetes, cardiovascular issues, and death (Tchounwou et al., 2003, p. 156). In the early 1970s, some members of Grassy Narrows First Nations in Ontario had hair mercury levels as high as 96 ppm, but these results were not reported to the Grassy Narrows First Nation for three years, and health testing for effects was neglected (Lee 1973, cited in D'Itri & D'Itry, 1978, p.9).

There are conflicting studies on the effects of low-dose methylmercury exposure. Grandjean et al. (1997) found neurological issues in children exposed to low doses of mercury in the Faroe Islands, while a similar study conducted by Myers et al., (2003) in the Seychelle Islands found no association with low dose mercury exposure and neurological issues in children. A potential explanation for these different results is that fish consumption has benefits that counter the effects of low-level methylmercury exposure (Karagas et al., 2012, p. 799). This is supported by studies where the effects of fish consumption were controlled and researchers found that children exposed to low doses of methylmercury as fetuses had higher incidence of adverse neurodevelopment issues such as cognitive decline and Attention Deficit Hyperactivity Behaviour (Karagas et al., 2012, p. 802). Elemental mercury is also poisonous, with effects including loose teeth, tremors, cognitive impairment, and death (D'Itri & D'Itri, 1978, p. 3).

Mercury also harms the health and reproduction of non-human animals, especially high tropic-level predators, causing similar symptoms to those found in humans, including: neurological impairment, changes in reproduction, behavioral changes, and death (Scheuhammer et al., 2007, p. 12). For example, decreased reproductive success has been found in fish at mercury concentrations in water that are normally encountered in Canada (Crump & Trudeau, 2009, p. 898, Scheuhammer et al., 2007, p. 13). Within B.C., animals that are at risk for high concentrations of methylmercury are piscivorous (fish-eating) and include pike, lake trout, mink, seals, bald eagles, common loons, osprey, and kingfishers (Scheuhammer et al., 2007, p. 12).

Mercury was recognized as poisonous by the Incas, Mayans and Romans (Brooks, 2012, p. 23). In his account of the Inca empire, Garcilaso de la Vega, a *mestizos* born of Inca and Spanish nobility (De La Vega, 2006, p.xiv), wrote in 1604 that the Incas had mined mercury prior to the arrival of the Spanish, but "they felt that it was dangerous to the lives of those who mined and handled it, since they noticed that it caused them to tremble and lose their senses," so the Incas prohibited the mining and use of mercury and their word for mercury passed out of their language (De La Vega, 2006, p. 79). This is one of the first policy responses to the toxic effects of mercury. In contrast, Western science was slow to recognize the health effects of mercury: elemental mercury was first recognized as poisonous in 1860 (Wedeen, 1989), while fatal methylmercury poisoning was described in 1865 (Grandjean et al., 2010). Due to the ability of mercury vapor to circulate throughout the earth's atmosphere, an international treaty to control mercury emissions, the Minamata Convention, was signed in 2013 (United Nations, 2017). Canada ratified this treaty in 2017 (Environment and Climate Change Canada, 2017).

1.2. Historical Documentation of Mercury Use in B.C.

In his summary of historical placer mining methods, Galois (1970) noted that mercury may have been used by placer miners in B.C. during the gold rushes to aid in the collection of fine gold (p. 53). Placer mining techniques included hand panning, which was the simplest form of mining and used chiefly to prospect; rocker boxes, which were usually operated by one or two people, and were useful in situations with limited water availability; and some form of sluice box which was used for all larger scale forms of placer mining, including ground sluicing and hydraulic mining (Galois, 1970, p. 53). Sluice boxes were rectangular boxes with ridges, or riffles, along the bottom. They were tilted slightly, and a slurry of water and gold-bearing sediment (sometimes called "pay dirt" or "alluvial ore") was added. The turbulent action of the water and higher density of the gold caused the gold to collect in the riffles (Galois, 1970, p. 48-50). Descriptions of hydraulic mining practices used in California at the time report the practice of pouring several 34.5 kg flasks of mercury directly into sluice boxes (Bowie, 1905, p. 244). Mercury also may have been used to coat gold pans (Galois, 1970, p. 53).

Direct references to the use of mercury in B.C. from archival documents include:

- The 1874 Annual Report of the Minister of Mines, which states that “On the bars near the mouths of rivers [gold] is found in a fine impalpable dust known as “flour gold” and can only be collected by the aid of quicksilver” (British Columbia, 1875, p. 4).

- The 1897 Annual Report of the Minister of Mines, which states that the Cariboo Hydraulic Mining Company (later called Bullion Pit) used “about one flask [of mercury] per day[1], in Pit No. 1, when working with a full head of water” for a total loss of 23 flasks (793.5 kg) of mercury that year (British Columbia, 1898, p. 480). This Annual Report also contains reference to the use of quicksilver in dredging operations near Boston Bar (p. 616).

- The 1902 Annual Report of the Minister of Mines, which states in regard to the Thibert Creek Mining Company, working a creek which flows into Dease Lake, that “The loss of quicksilver in sluices and undercurrents amounted to 8 per cent. of the total amount used.” (British Columbia, 1903, p. 988). The entry for this mine also includes the cost of a “Retort” at $362.99. Retorts were used to recover mercury when gold amalgam was heated.

- Other references to the use of mercury or quicksilver can be found in the Annual Reports of the Minister of Mines for the following years: 1876 (p. 422); 1877 (p. 395 and 397); 1883 (p. 1071); 1886 (p. 201); 1894 (p.730); 1896 (p. 8, 84, 571, and 573); 1899 (p 618-619,); and 1903 (p.68 and 90).

- The *San Francisco Newsletter* reported in 1858 that at “Hill’s Bar, three men anxiously awaited quicksilver in order to accumulate $10 to $12 dollars a day” (“Letters of a Sullivan County ‘Forty-Niner,” as cited in Marshall, 2000, p. 102). Hills Bar is located in the Fraser Canyon, between Yale and Emory Creek.

[1] “Flasks” were the standard unit of measurement for mercury, and weighed 34.5kg, with a volume of about 2.5 liters.

1.3. Study Overview

As described above, while there is historical evidence that mercury was used during the gold rushes in British Columbia, no work to date has sought to understand how widespread the use of mercury was in B.C., nor has research attempted to calculate or otherwise tabulate the total amount of mercury lost to the environment during this period. The objectives for this project are to: (1) measure mercury concentrations at potential hotspots at a selection of gold-rush era mine sites for total mercury to predict the prevalence of mercury amalgamation practices during the gold-rush period; and, (2) use a combination of research on mercury imports and mining methods to estimate how much mercury was lost by gold-rush era mines in the Fraser Basin. Chapter 2 describes the field work and results from the 15 placer mine sites where I sampled soil and sediment for total mercury concentrations. Chapter 3 reviews literature on how much mercury gold-rush era miners may have lost per unit of gold produced and develops an estimate for the amount of mercury that was lost to the environment from placer mining during the gold-rush. Chapter 4 discusses the potential impacts of mercury contamination from the mine sites, and reviews B.C.'s record on mercury monitoring.

Chapter 2. Mine Site Testing

Research investigating mercury in tailings or sediment at gold-rush era mine sites in B.C. is limited. Veiga and Meech (1995) tested 14 samples in the Port Douglas area where gold-rush era placer mining may have occurred and found a range of 0.49 to 29.5 ppm[2] total mercury. However, Viega and Meech (1995) note that the area was influenced by hot springs which may have been responsible for these high mercury concentrations, a speculation supported by their tests of nearby sites without mining influence, which ranged from 0.77 to 57.2 ppm total mercury (n=8).

Andrews (1989) surveyed the soil, sediment, water and biota at Wells, B.C., a site which was influenced by both gold-rush era placer mining and gold mining between the 1930 and 1960 (Andrews, 1989, p. 7). Andrews tested six soil samples for total mercury and found 0.05 and 0.06 ppm total mercury at the beach site on Jack of Clubs Lake, while samples from the "Ball Diamond" site were below the detection limit of 0.05 ppm. Nevertheless, they tested fish in Jack of Clubs Lake for mercury and found that in the lake trout (n=5, length range 39.4 – 48 cm), mercury content ranged from 0.24 – 0.84 ppm wet weight (p. 30). Other researchers in B.C. have not included mercury in analysis of sites that may have been influenced by gold rush era mining (see Clark et al., 2014; Smith & Wilford, 2013).

Downstream from the areas where gold was mined, there is some evidence of elevated mercury in sediment cores that correlate to the gold rush; Johannessen et al., (2005) noted there was likely a pulse of mercury into Strait of Georgia sediments around 1900 and suggested that this was an effect of placer mining in the Fraser watershed (p. 4363). In cores from the Fraser delta, Hales (2000) found elevated concentrations of mercury (0.100 – 0.320 ppm relative to background concentrations of 0.050 to 0.060 ppm) in sediment deposited during the late 1800s and early 1900s, which she also attributed to gold rush-era placer mining (p. 123, 124).

Natural Resources Canada has conducted extensive soil and lake sediment sampling (Arp et al., 2016, p. 85; Geological Survey of Canada, 2019). Arp et al (2016)

[2] Studies report total mercury in soil, sediment, fish and hair in parts per million (ppm) and its equivalents: mg/kg and µg/g; and parts per billion (ppb) and its equivalents, ng/g and µg/kg. For simplicity, most values in this project have been converted to ppm or mg/kg.

reported total mean mercury in sediments from this dataset for 542 upland lakes and 153 lowland lakes in British Columbia and the Yukon. These lakes had mean total mercury in sediment of 0.1035 and 0.0814 mg/kg respectively (p. 85). They note total mercury concentrations as high as 10 mg/kg in some areas with mining operations including Pinchi Lake and Myra Falls, however, they do not mention if any sediment connected to gold-rush era sites was sampled (pp. 103-104).

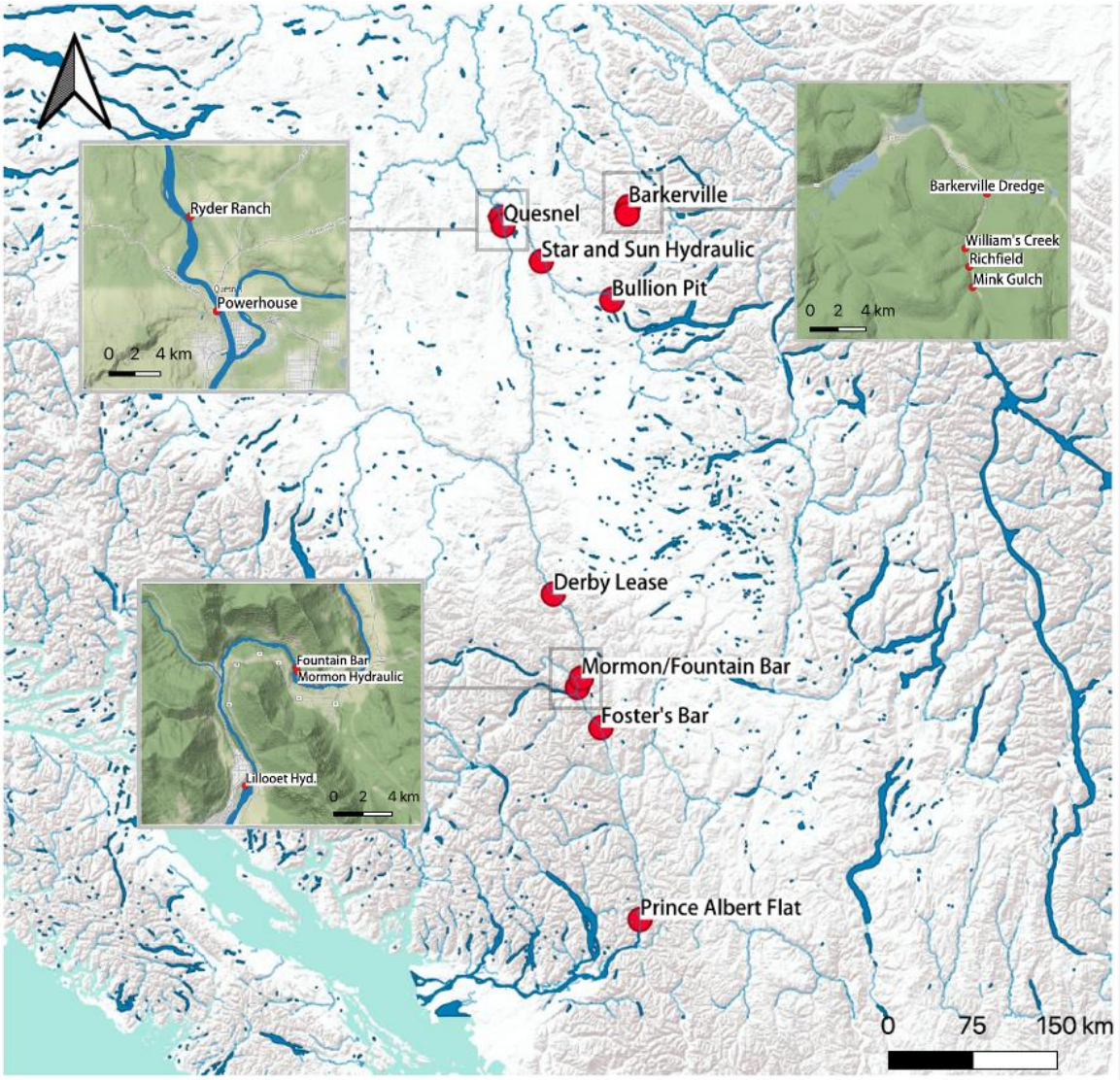

Figure 2.1 Study area and mine sites tested.

In contrast to the limited work on mercury from gold-rush era mine sites, there has been significant effort mapping the locations of mine sites along the main stem of the Fraser and the Quesnel Rivers (Kennedy, 2009; Nelson & Kennedy, 2012), and modelling sediment transport (Ferguson et al., 2015; Nelson & Church, 2012; Nelson, 2011, 2017). These works have laid the groundwork for this current study, which combines the research on mine site locations and methodologies with field testing for mercury to determine whether mercury was commonly used in gold-rush era mining. For this study, I tested a subgroup of 15 mine sites spread through the Fraser basin. Figure 2.1, shows the locations of the mines tested.

2.1. Methods

2.1.1. Mine site selection

During the gold rushes, miners first arrived in the Hope to Lytton area in 1858 and worked their way upriver in search of the source of gold. Some remained behind, working and re-working sites into the early 1900s (Kennedy, 2009, p. 45). To explore regional and time period differences between sites, I divided the research area into five subregions: Hope to Foster's Bar, Fraser Canyon, Quesnel, Quesnel River, and Barkerville. To identify mine sites in all regions except Barkerville, I relied on the map "Fraser River Gold Mines and Their Place Names: A Map from Hope to Quesnel Forks," created by Andrew Nelson, Michael Kennedy, and Eric Leinberger (2012). For the Barkerville sites, locations sampled were in an area of obvious and well-known historical workings. Regions, mine site names, locations and descriptions are reported in Table 2.1.

Field data collection was conducted in June 2019, September 2019, and July 2020. Potential sites were sometimes inaccessible (see Figure 2.2). I had also planned to sample sites near Horsefly, B.C. but was unable to access any mine sites in the area due to unseasonable high water during a July 2020 visit to the area.

Mine site selection was not random. Derby Lease / Bumgardner's Claim was chosen because I had a contact able to provide an introduction to the landowner. The remaining sites were located on public land and had reasonable road access, which was so limiting that, for the Quesnel and Quesnel River areas, I believe the sites tested are a

near-complete inventory of accessible mines on public land. For the remaining regions, sites were prioritized based on ease of road and foot access. While there is a possibility that that mercury use is correlated with proximity to modern land-based transportation infrastructure, this is not likely as transportation for much of the study area was water-based during the gold-rushes. For these reasons, despite the non-randomness of mine site selection, I believe that the sites chosen are a fair representation of placer mines in the Fraser Basin, with the exception of the Bullion Pit and Bullion Pit at Quesnel River sites.

Table 2.1 Mine site locations and descriptions

Site Name	Location	Dates Mined	Mining Method	Site Description	Date Sampled
Hope to Foster's Bar: *Prince Albert Flat*	49.51627 121.4159	1858 -	Sluice	Rows of cobbles perpendicular to river, possible hydraulic teardrop shaped excavations	July 2020
Foster's Bar	50.5037 121.72851	1858 -	Sluice	No discernable mine site structure	June 2019
Fraser Canyon: *Lillooet Hydraulic*	50.70803, 121.91713	1890 – 1904	Hydraulic and Sluice	Stacked cobbles, teardrop shaped hydraulic excavation	July 2020
Fountain Bar Sluice	50.75415 121.88584	1861-	Sluice	Possible ground sluice run, miners' cabin	June 2019
Mormon Bar Hydraulic	50.75265 121.88511	1958	Hydraulic	Hydraulic excavation, abandoned wood structure	June 2019
Derby Lease / Bumgardner's Claim	51.17716 122.10923	1899 – 1904 / 1882 -	Sluice, Hydraulic, Modern	Hand stacked cobbles undercut by hydraulic mining from lower bench and modern reworking of site. Disorganized mounds of cobbles on lower bench.	July 2020
Quesnel: *Powerhouse*	52.99012 122.51071	1880 -	Sluice	Distinct rows of cobbles perpendicular to river	Sep 2019
Ryder Ranch	53.02975 122.52944	1880s?	Sluice, Rocker Box	Ditch that may have been a ground sluice	July 2019
Quesnel River: *Star and Sun Hydraulic*	52.81682, 122.20495	1895	Hydraulic	Banks that may have been hydraulic mined, no discernable sluice runs or tailing piles, recent road cuts through site.	Sep 2019
Bullion Pit	52.62851, 121.64213	1890 -	Hydraulic	Hydraulic mine pit extending approx. 1.5 km, 125 m deep	July 2019

BP @ Quesnel River	52.63236, 121.64102	1890 -	Unknown‡	Unidentified mound 2 m high, perhaps tailings pile, area of sediment aggradation from Quesnel River.	July 2019
Barkerville: *Mink Gulch Hydraulic*	53.04393, 121.51794	1861 - / 1931 - 1945	Various methods, Hydraulic	Hydraulic mine pit, tailings piles, cobbles	Sep 2019
Richfield	53.05191, 121.52014	1861 -	Various methods,	Ditches or sluice runs, piles of cobbles	Sep 2019
William's Creek	53.05912, 121.52265	1861-	Various methods,	Ditches or sluice runs, piles of cobbles	Sep 2019
Barkerville Dredge	53.08031, - 121.50917	1861 -	Dredge / Modern Mining	Area with mixed cobbles and sand, modern mining tailings.	Sep 2019

For regions "Hope to Foster's Bar," "Fraser Canyon," "Quesnel," and "Quesnel River," names, dates mined, and mining methods are from (Kennedy, 2009; A. Nelson et al., 2011, p. 60). For "Barkerville" region and the "Mormon Bar Hydraulic" site, the names are from local landmarks and dates mined from MINFILE records.

Unique among other mines included in this study, historical documents indicate mercury use at Bullion Pit (see Section 1.2), which was also the largest hydraulic mine in B.C. (Mulvihill et al., 2005, p. 207). Additionally, the Bullion Pit at Quesnel River site is located 75 meters downstream of the confluence of the Quesnel River and a creek draining the main Bullion Pit mine. This site is a vegetated flat area with mature trees, about one meter above the Quesnel River high water mark and may have been deposited during a period of altered river morphology and flow caused by a sediment slug from the Bullion Pit mine. While there were some landforms found that suggest mining activity, specifically a 2 meter mound of earth, Nelson et al., (2011) did not note a second mine in the vicinity of Bullion Pit. Thus, while the sites Bullion Pit and Bullion Pit at Quesnel river are interesting and locally relevant, they will not be included in estimations of the prevalence of mercury amalgamation practices in the Fraser Basin because they (1) have historical documentation indicating mercury use, and (2) are possibly are the same mine site.

Figure 2.2 Sign encountered while attempting to access mine site near Hope, B.C.

2.1.2. Sampling and testing

Were this study unconstrained by funding and time, I would have collected a minimum of 15 test samples at each mine site and an equal number of control samples at each site. Additionally, samples would have been sieved on site, a grain-size analysis performed on each sample, and different size fractions would have been analyzed separately. This additional work would have aided future work predicting the mobility of mercury (see, for example, Veiga & Baker, 2004, p. 19). However, in order to maximise the number of sites sampled with the available funding and time, I developed a rapid site assessment which focussed on-site sampling effort in suspected mercury hotspots, such as areas where sluices may have been run and where they likely discharged (Alpers et al., 2005), tailings piles (Fleck et al., 2010) and pits and mounds of suspected rocker box sites. I collected between three and eight test samples per site, and one to three control

samples per site, depending on the size of the site and the number of unique features. In total, 109 soil or sediment samples were collected from 15 mine sites. Of these, 85 samples were test samples from mine sites and 24 samples were control samples. Control samples were pooled by region, and regional control sample data from British Columbia Ministry of Environment and Climate Change Strategy (2017a) was added to the study controls for statistical analysis.

Potential locations for sluices were identified through inspection of the mine site, following descriptions of common mine site elements provided by Michael Kennedy (pers comm.) and Nelson and Church (2012). I did not pool samples within sites, a methodology that combines small samples in a single sampling container for analysis. While pooling samples allows for increased sampling locations within a mine site which increases the likelihood that mercury hotspots will be found, this methodology also dilutes the highest samples, reducing the opportunity to learn which areas within a site are most likely to be contaminated.

Figure 2.3 Sampling location of suspected sluice run at Lillooet Hydraulic mine site

Control sample sites were chosen to be as reflective of the mined area as possible. In areas where an escarpment was present due to hydraulic mining, control samples were taken from the escarpment wall, with a small hole excavated 10-30 cm in from the surface of the escarpment. At sites without a clear escarpment, control samples were taken 10 meters or more inland from any signs of mining. At the Barkerville sites, mining activity was widespread, so control samples were taken in an escarpment at Mink Gulch and in an unmined area about 1km from the nearest known mined sites.

To collect samples, a hole was dug between 10 and 45 cm deep using a spade or trowel, which was rinsed with fresh water between sampling locations. Once the hole was near the desired depth, a layer 2 cm deep was removed by hand using a fresh nitrile glove to ensure there was no cross contamination between sampling locations carried by the shovel or trowel. Samples were collected in precleaned 120 ml glass jars with Teflon lined lids provided by ALS Laboratories, and kept in a cooler with ice packs or a refrigerator until sent to the lab. Samples were held for a maximum of 3 days before transfer to the lab.

All samples were processed at ALS laboratories in Burnaby, B.C. After drying, samples were sieved using a 2 mm screen, digested with nitric and hydrochloric acid, and analysed for total mercury using Cold Vapor-Atomic Absorption Spectrophotometry (CVAAS) analysis. This analysis uses EPA 200.2 methodology for preparation (Martin et al., 1994), and a modification of EPA 1631 methodology for analysis (EPA, 2002), and is compliant with B.C.'s standard methodology for metals in soil and sediment, the Strong Acid Leachable Metals (SALM) in Soil methodology. Results were reported in mg/kg dry weight and had a detection limit of 0.0050 mg/kg.

2.1.3. Data Analysis

Analysis of variance of the total mercury concentrations in soil and sediment samples were conducted with RStudio (R Core Team, 2019) using the "car" package (Fox & Weisberg, 2019) and "userfriendlyscience" package (Peters, 2018). The "ggplot2" package was used for visualization (Wickham, 2016).

To test if samples taken within a single mine site had a mean total mercury (tHg) concentration significantly higher than that in pooled control samples for that region, sites were first grouped by region, for example, the “Quesnel River” region included the “Star and Sun Hydraulic,” “Bullion Pit,” and “Bullion Pit at Quesnel River” sites. Regional divisions are shown in Table 2.1 and 2.2. Control samples from all the sites within a single region were pooled with the nearest regional samples in the B.C. Background Concentrations in Soil Database “BCMOE control samples” (British Columbia Ministry of Environment and Climate Change Strategy, 2017b), and these were treated in analysis as a single regional “control” site. Group sizes (i.e., the number of samples taken at each site) were not equal. Total mercury concentrations from mine sites samples and control samples were natural log transformed.

Second, preliminary analysis of total mercury concentrations in soil and sediment samplers was performed to identify the most appropriate analysis of variance test. The Levene test was used to test the null hypothesis that samples have equal variances. I centered the Levene test on the median of natural log-transformed total mercury concentrations because their distribution was asymmetrical for some of the regions (Carroll & Schneider, 1985). The Shapiro test was used to test the null hypothesis that total mercury concentrations in samples are lognormally distributed. The conclusions of these tests are reported in Table 2.2.

Table 2.2 also shows the analysis of variance test used for each region. The standard ANOVA was used to compare means for sites within the regions “Hope to Fraser’s Bar,” “Quesnel,” and “Barkerville,” because the Levene test found that mercury concentrations in samples in these regions had equal variances (Blanca et al., 2017). For the “Quesnel River” region, sample data was normal and heteroscedastic, so a Welch’s ANOVA was chosen (Lix et al., 1996). For the “Fraser Canyon” region, data was neither normal nor homoscedastic. There is no ideal analysis of variance test for non-normal, non-homoscedastic data (Lix et al., 1996; Liu, 2015, p. 3). I ran an ANOVA, Kruskal-Wallis and Welch’s Test on the “Fraser Canyon” sites, and of these three tests, the ANOVA and Kruskall Wallis found a significant difference ($p < 0.05$) between the mean tHg concentration in pooled control samples and the mean tHg concentration from Derby’s Lease, Lillooet Hydraulic, and Fountain Bar Sluice. In contrast, the Welch’s ANOVA and the Games-Howell post hoc only showed a signficant difference between mean tHg concentrations of the control samples and Lillooet Hydraulic samples. As the

Welch's ANOVA is preferred for heteroscedastic variances, and reported the highest p-values, suggesting this test was the most conservative, the results from the Welch's ANOVA are reported in Table 2.3 and referenced in the discussion.

Table 2.2 Levene test for homsedacity and Shapiro test for lognormality of total mercury concentration samples in regional groups

Region	Levene test (variances are equal if p> 0.05)	Shapiro test (distribution is lognormal if p > 0.05)	Test and Post-Hoc Tests Used
Hope to Foster's Bar	0.2939 pass (homoscedastic)	0.001508 fail (not lognormal)	Anova, Tukey
Fraser Canyon	0.002277 fail (not homoscedastic)	3.771e-06 fail (not lognormal)	Welch's Test, Games Howell
Quesnel	0.6704 pass (homoscedastic)	0.2363 pass (lognormal)	Anova, Tukey
Quesnel River	0.025 fail (not homoscedastic)	0.4779 pass (lognormal)	Welch's Test, Games Howell
Barkerville	0.1789 pass (homoscedastic)	0.1812 pass (lognormal)	Anova, Tukey

Results from statistical test for homoscedacity and normality, and the analysis chosen to determine the significance of differences between mercury concentrations at mine sites versus control samples within regions. Levene Test is centered on median because some datasets had asymmetrical distribution.

2.2. Results and discussion

Total mercury concentration in test samples ranged from 0.0060 mg/kg to 1.16 mg/kg, with a mean of 0.1916 mg/kg (standard deviation (s) =0.2645 mg/kg, n=85). Total mercury (tHg) concentrations in control samples ranged from 0.0076 to 0.0966 mg/kg, with a mean concentration of 0.0415 mg/kg tHg (s=0.0234 mg/kg, n=24). Concentration of total mercury in BCMOE control samples ranged from 0.0130 to 0.107 mg/kg tHg, with a mean of 0.0424 mg/kg tHg (s=0.0275 mg/kg, n=32).

There were no statistically significant differences between mean tHg concentrations of control samples, both for those collected during this study and BCMOE control samples, with the exception of the Barkerville control samples (mean = 0.0136 mg/kg tHg, s = 0.0045 mg/kg tHg, n = 4), which had a mean tHg concentration significantly lower than the Quesnel control samples (mean = 0.0565 mg/kg tHg, s =

0.0123 mg/kg tHg, n = 4, p = 0.016) and MOE William's Lake control samples (mean = 0.0594 mg/kg tHg, s = 0.0314 mg/kg tHg, n = 8, p = 0.0051). Figure 2.4(a) and 2.4(b) show total mercury in control samples, grouped by region.

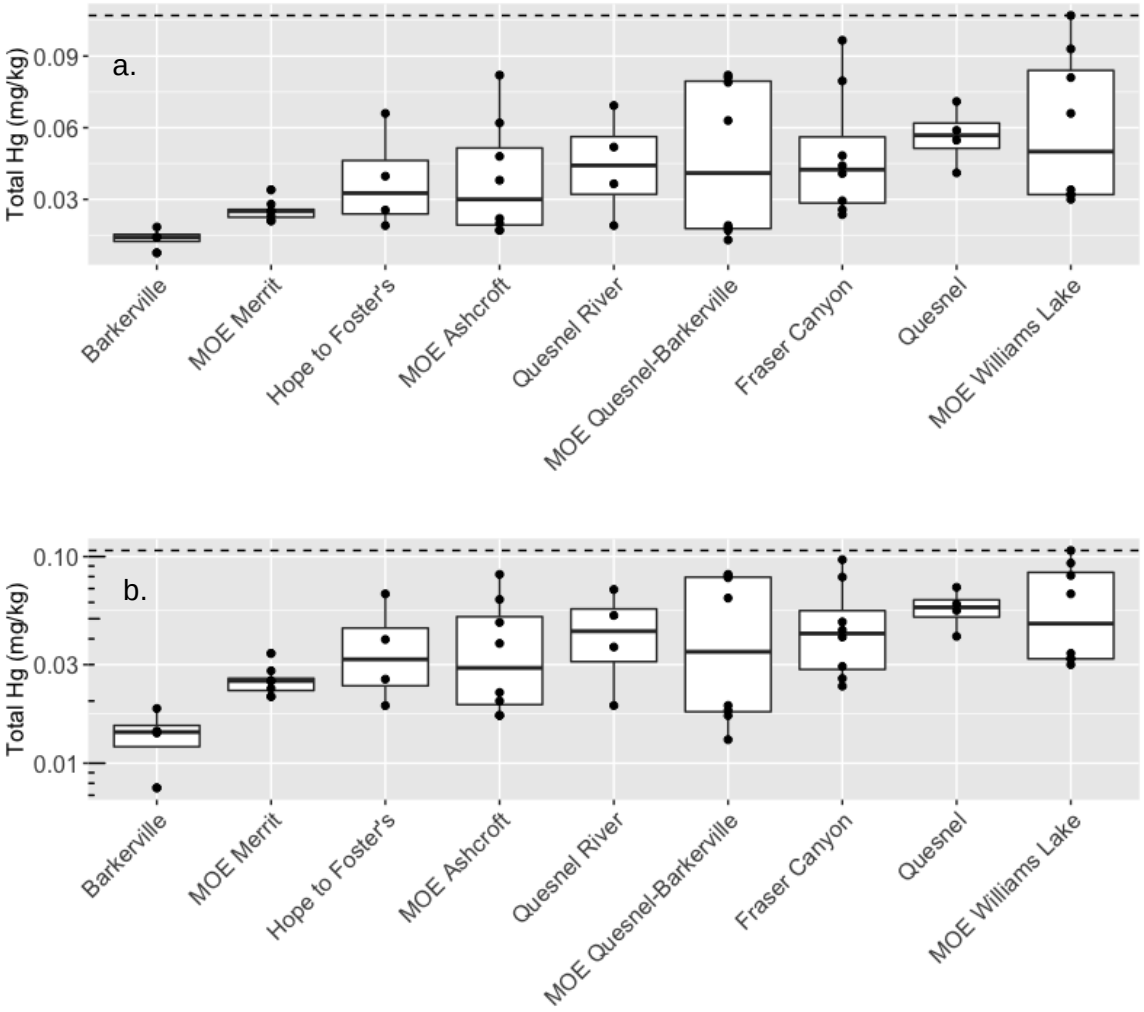

Figure 2.4 (a) Total mercury in mg/kg in control samples, grouped by regions (b) Natural log of total mercury in mg/kg of control samples, grouped by regions

"Fraser Canyon" had 10 samples, all the MOE regions had 8 samples, and the remaining regions (Barkerville, Hope to Foster's Bar, Quesnel River, and Quesnel) had four samples. The dotted line shows 0.107 mg/kg total mercury, the highest control sample. Box plots are ordered by mean of tHg concentration of region. Median is middle line of boxplot, box extends to the "hinge", defined as the median, or natural log median, of the upper and lower half of the data, and whiskers extend to 1.5 times the interquartile range of the hinge. Individual sample tHg concentrations are plotted as points.

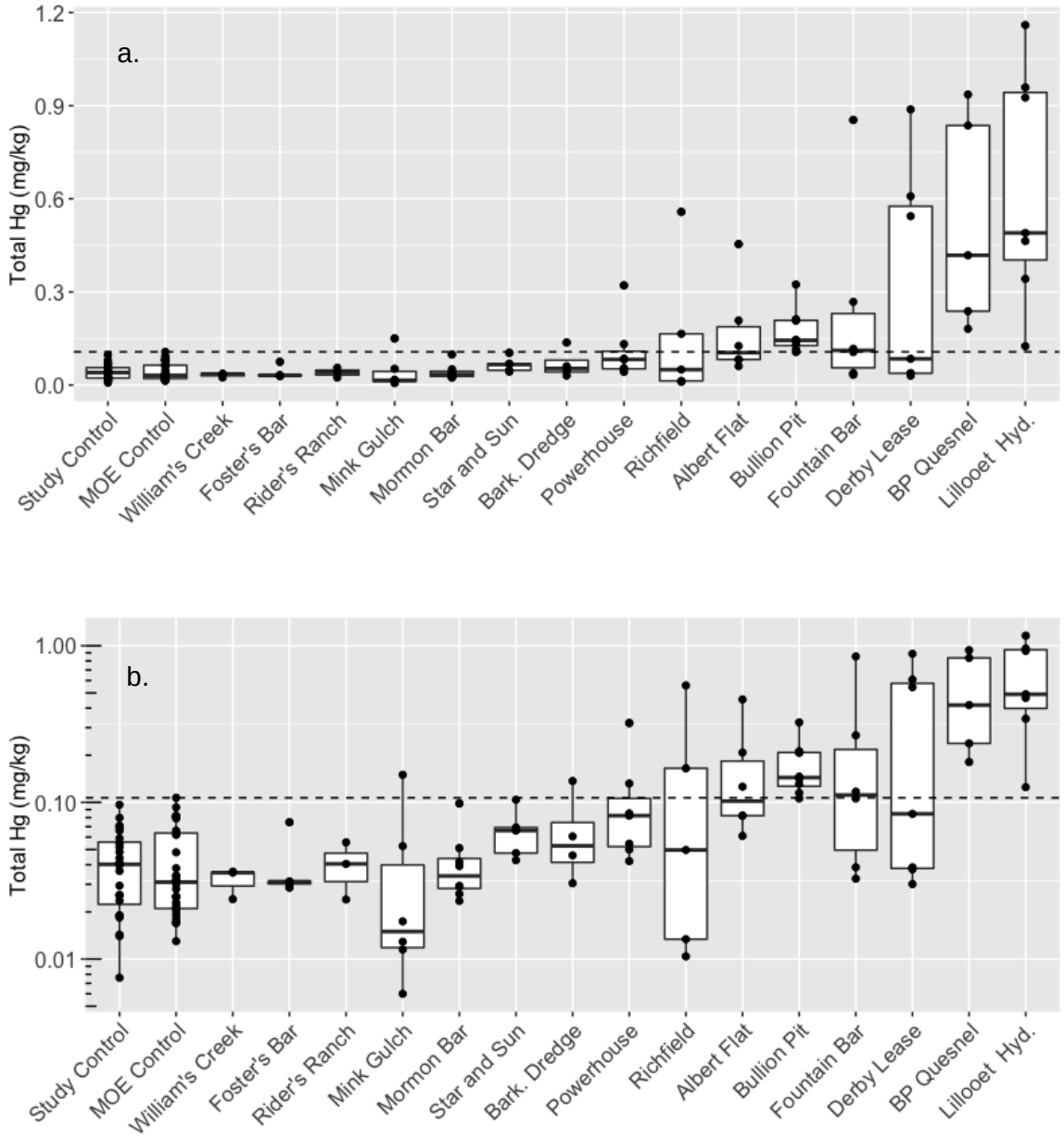

Figure 2.5 a) Total mercury concentration in mg/kg by mine sites (b) Log base 10 plot of total mercury concentration in mg/kg by mine sites

Sample sizes are reported in Table 2.3. The dotted line shows 0.107 mg/kg tHg, the highest control sample. Boxplots constructed using methodology described in Figure 2.4.

Table 2.3 and Figure 2.5(a) and (b) summarise the results of the tHg mine site sampling survey. In total, of the 85 samples collected on mine sites, 40% of samples were higher than 0.107 mg/kg, the highest control sample.

To evaluate how commonly mercury was used during the gold rushes, and whether mercury contamination persists at gold rush era sites, I will consider the following two indicators of potential mercury use at a mine site: (1) mean tHg at individual mine sites that are significantly higher than mean tHg at control sites; and, (2) one or more samples from a mine site have tHg concentrations that exceed the highest control sample, which was 0.107 mg/kg tHg. Additionally, there are multiple ways to frame what proportion of gold rush era mine sites show indications of mercury use:

a) Include all mine sites sampled in this study (n=15), which is problematic because it includes Mormon Bar Hydraulic which was mined in the 1950s, and because it includes Bullion Pit and Bullion Pit at Quesnel River which are connected sites with documented evidence of mercury use (see Section 2.1.1).

b) Include only gold rush representative mine sites, by excluding Mormon Bar Hydraulic, Bullion Pit, and Bullion Pit at Quesnel River (n=12).

c) Include only gold-rush representative mine sites with obvious signs of mining, such as cobble piles, parallel rows of cobbles, and hydraulic escarpments. This analysis excludes Bullion Pit, Bullion Pit at Quesnel River, Mormon Bar Hydraulic, Foster's Bar, Ryder Ranch, and Star and Sun Hydraulic (n=9).

Table 2.4 organizes these options into a matrix. For comparison of mean tHg concentrations, 4 of the 15 sites sampled, or 27%, had mean tHg concentrations that were significantly higher than control samples ($p < 0.05$). These are reported in Table 2.3 and include Prince Albert Flat in the Hope to Foster's Bar region, Lillooet Hydraulic in the Fraser Canyon region, and Bullion Pit and Bullion Pit at Quesnel River, in the Quesnel River region. Of the "gold rush representative sites," 2 of 12 sites, or 17% had mean tHg concentrations significantly higher than control samples. These include Prince Albert Flat, and Lillooet Hydraulic. Finally, constraining analysis to sites that had obvious signs of gold-rush era mining, 2 of the 9 sites, or 22%, had mean tHg concentrations that were significantly higher than control samples ($p < 0.05$).

Table 2.3 Sample size, mean, standard deviation, highest sample, and p-value for tHg concentrations of soil and sediment samples

Site Name	sample size	arithmetic mean (mg/kg tHg)	standard deviation (mg/kg tHg)	highest sample (mg/kg tHg)	p-value mine site vs regional control
Controls					
Study Controls	24	0.0415	0.0234	0.0966	
MOE Controls	32	0.0424	0.0275	0.107	
Hope to Foster's Bar:					
Prince Albert Flat	6	0.169	0.149	0.4540	0.0000033
Foster's Bar	5	0.0392	0.0199	0.0747	0.698
Hope to Foster's Bar Control	20	0.0329	0.0181	0.08201	
Barkerville:					
Mink Gulch Hydraulic	6	0.0417	0.0556	0.15	0.999
Richfield	5	0.1592	0.2316	0.558	0.587
William's Creek	3	0.0319	0.0067	0.0361	0.998
Barkerville Dredge	4	0.0685	0.0473	0.137	0.645
Barkerville Control	12	0.0355	0.0306	0.082	
Fraser Canyon:					
Lillooet Hydraulic	8	0.638	0.3789	1.16	.00019
Fountain Bar Sluice	6	0.236	0.3144	0.854	.195
Mormon Bar Hydraulic	8	0.0423	0.0245	0.0985	.934
Derby Lease / Bumgardner's Claim	7	0.3188	0.3544	0.888	.190
Fraser Canyon Control	24	0.0373	0.0221	0.0966	
Quesnel:					
Powerhouse	7	0.1096	0.0980	0.321	0.17
Ryder Ranch	3	0.0400	0.0158	0.0556	0.63
Quesnel Control	12	0.0498	0.0271	0.082	
Quesnel River:					
Star and Sun Hydraulic	5	0.0659	0.0242	0.104	0.313
Bullion Pit	8	0.1729	0.0725	0.324	0.00318
BP @ Quesnel River	5	0.5218	0.3456	0.936	<0 .00001
Quesnel River Control	20	0.0512	0.0295	0.107	

Studies of mercury remaining at gold-rush era mine sites in California found mercury in hotspots, rather than evenly distributed across a mine site (Alpers et al., 2005; Fleck et al., 2010). Assuming that mercury found on mine sites was introduced by miners, outliers and above-baseline results are potential indicators of gold-rush era

mercury use at mine sites. The proportion of mine sites with one or more samples with a mercury concentration greater than 0.107 mg/kg tHg for all sites in this study is 10 out of 15, or 66%. For gold-rush representative sites, 8 of the 12, or 66%, of mine sites had at least one sample above the baseline tHg concentration. Finally, for mine sites with obvious signs of mining, 8/9, or 89% of sites, had one or more sample with a mercury concentration exceeding 0.107 mg/kg.

Table 2.4 Matrix summarizing proportion of mine sites with indications of mercury use

	Proportion of sites where mean [tHg] of site samples > mean [tHg] of control samples ($p < 0.05$)	**Proportion of sites with one or more sample > 0.107 mg/kg tHg**
All sites (n=15)	4/15 or 27%	10/15 or 66%
Gold-rush representative sites (n=12)	2/12 or 17%	8/12 or 75%
Gold-rush representative sites with obvious signs of mining (n=9)	2/9 or 22%	8/9 or 89%

Notably, no sites from either the Barkerville region or the Quesnel region had a significantly higher mean total mercury concentration than the regional control samples. Further, the William's Creek site, located in the Barkerville area, was the only site in this study with cobbles present but tHg concentrations that did not exceed control samples. While these results may indicate lower mercury use in the Barkerville and Quesnel regions, more work is required to reach this conclusion for the following reasons:

(1) The Barkerville sites were all clustered along a six km stretch of William's Creek. It is possible that mercury hotspots at the Barkerville sites are present but were missed during the field sampling, particularly because a flume was constructed along William's Creek to collect tailings and processing water from claims along the creek, in order to collect any gold that had escaped the individual claim's sluices (British Columbia, 1875, p. 7). If mercury was used, it is likely that this flume would have collected mercury along with the gold. Another possibility is that mercury contamination at the Barkerville sites have been cleaned up. However, there was no indication of mercury clean-up efforts in a search of the Barkerville archives for the word "mercury."

(2) The Quesnel region had only two sites: Powerhouse, which showed clear signs of mining activity in the form of parallel rows of cobbles, and had a test sample with a mercury concentration of 0.321mg/kg tHg suggesting mercury had been used at the site; and Ryder Ranch, which had no clear cobbles rows or piles to orient sampling effort, so I am unsure that any hotspots were sampled at this site.

Future work in Barkerville area should plot and sample the course of the flume and its discharge point. Further, more sites should be sampled in the Barkerville and Quesnel regions to understand if these results indicate there was less mercury use in the Barkerville and Quesnel regions or time periods, or if these results are an artifact of limited sampling.

In contrast, for the Fraser Canyon region, 3 of the 4 sites had samples with tHg concentrations exceeding baseline concentrations, with one site, Lillooet Hydraulic, having a significantly higher mean tHg concentration. Similarly, for Hope to Foster's Bar, 1 of the 2 sites sampled had significantly higher mean tHg concentrations in test samples than control samples, and both sites in this region had samples with tHg concentrations exceeding baseline concentrations.

2.2.1. Soil & Sediment Quality Guidelines

While some of the soil and sediment samples were well above control samples collected in this study and regional control samples collected by others (British Columbia Ministry of Environment and Climate Change Strategy, 2017b; Siegel et al., 1985), these concentrations would not trigger classification as contaminated sites under B.C.'s Contaminated Sites Regulation. Schedule 3.1, Matrix 20 stipulates that for the protection of human health, mercury concentrations in soils should not exceed 10 mg/kg of total mercury in agricultural lands and low-density residential areas, 25 mg/kg in urban parks and high-density residential areas, 75 mg/kg for commercial lands and 2000 mg/kg for industrial lands (Contaminated Sites Regulation, Schedule 3.1, Matrix 20). The exposure pathway that these limits were modelled on was the direct ingestion of soil. In contrast, the Canadian Soil Quality Guidelines for the Protection of Human Health suggests a limit of 6.6 mg/kg for agricultural and residential lands, and 24 mg/kg for commercial land,

also modelled on soil ingestion, and 50 mg/kg for industrial lands, modelled on off-site migration (Canadian Council of Ministers of the Environment, 1999).

Because marine environments are more likely to result in mercury methylation and uptake by aquatic life than terrestrial environments, sediment quality guidelines are lower than soil quality guidelines. The Canadian Sediment Quality Guidelines for the Protection of Aquatic Life (Canadian Council of Ministers of the Environment, 1999) sets an interim sediment quality guideline of 0.17 mg/kg for freshwater environments, and 0.13 for marine and estuarian environments; and a probable effect level of 0.486 and 0.70 respectively. There is some disagreement whether these levels are adequately protective. In a review of studies of sediment toxicity, Macdonald et al (2000) proposed a sediment quality guideline of 0.18 mg/kg Hg as protective for benthic invertebrates, and a level of 1.06 mg/kg, above which harmful effects are likely. In cross referencing these recommendations with field studies, however, Macdonald found that sediment with less than 0.18 mg/kg Hg were toxic to benthic invertebrates in 23 of 35 samples analysed, suggesting that even 0.18 mg/kg may not be sufficiently protective. All sediment samples with Hg concentrations above 1.06 mg/kg were found to be toxic in all samples. Notably, the assessment of toxicity for these studies was based on the health of invertebrates living in the sediment, and as shown for PCBs, “safe” concentrations of biomagnifying contaminants in sediment may result in detrimental concentrations in upper trophic levels (Arblaster et al., 2015).

Placer mine sites are often closely associated with water, both because water was used to process materials, and because placer mining targets gold moved by water, and therefore focusses on current or ancient stream and riverbeds. Most samples collected during this study were soil samples, collected above the high-water line of nearby streams or rivers (mean = 0.2153 tHg mg/kg, s = 0.2752 tHg mg/kg, n=76).

Eleven sediment samples were collected below the high-water line in the Fraser, from Foster’s Bar, Fountain Bar, Mormon Bar, and Rider’s Ranch (mean = 0.03480 tHg mg/kg, s = 0.0083 tHg mg/kg, n=11). These samples are notably low in tHg concentration and relatively consistent, despite Foster’s Bar and Ryder’s Ranch being over 300km apart. The Fraser is likely diluting any added mercury with its high sediment load, as suggested by Johannessen et al., (2005) and evidenced by low and consistent concentrations found in samples from this study taken high on the Fraser’s littoral zone.

Sediment samples were also collected in shallow ponds on the Bullion Pit site (mean = 0.2123 tHg mg/kg, s=0.1091 tHg mg/kg, n=3). A further two sediment samples were collected along the Quesnel River: one at the Bullion Pit at Quesnel River site, which had a tHg concentration of 0.418 mg/kg, and the other at the Star and Sun site which had tHg concentration of 0.0661mg/kg. Two sediment samples were taken along Williams Creek near Barkerville: at the William's Creek site, the sediment sample had a mercury concentration of 0.0356 mg/kg, and at the Barkerville Dredge site, the sediment sample had a total mercury concentration of 0.0607 mg/kg. Thus, of the sediment samples collected during this study, only the samples at the Bullion Pit site and Bullion Pit at Quesnel River site exceeded The Canadian Sediment Quality Guidelines for the Protection of Aquatic Life of 0.17 mg/kg tHg for freshwater environments (Canadian Council of Ministers of the Environment, 1999).

2.2.2. Limitations and caveats

Mine sites are complex and may have been remined several times over the course of the past 160 years. Kennedy (2009, p. 60) noted that different types of mining frequently overlaid one another at mine sites. His work notes that this occurs at the "Lillooet Hydraulic" site. Additionally, I observed layered methodologies at "Derby Lease", where a bench with hand stacked cobbles, likely from sluicing, was undercut by a hydraulic mining operation from a lower bench and overturned by a modern mining operation on the upper bench. Sites in the Barkerville region also appeared influenced by different mining methods. Some mining methods, for example, using mercury to coat a gold pan, could result in elevated mercury concentrations without disturbing older mine-site structures. Thus, while this study found that mercury was present at a majority of mine sites, it is not possible with the current data to make conclusions about mercury use by time period and mining method.

A second potential issue is that mercury and gold form an amalgam, and it is possible that naturally occurring mercury and gold would concentrate in the same places along a river. Thus, there is a possibility that mercury found in this study co-occurred with gold and was present prior to mining, then was redistributed through mining effort. To reduce this possibility, I usually took samples from benches and scarp walls directly adjacent to the mine sites, and none of these control samples showed elevated mercury concentrations. Of course, if mercury and gold were co-occurring, and mining stopped

when gold was no longer encountered, this could explain the lower mercury concentrations in the control samples. However, no samples from the “Mormon Bar” site, which was mined in the 1950s, had mercury concentrations above control samples. While certainly not conclusive, this supports the hypothesis that miners introduced the mercury. Further research could include testing for gold concentrations in samples, which would help ensure control samples were representative of the alluvial ore targeted by the miners.

2.2.3. Conclusions for mine site sampling

There is no official estimate of the total number of placer mines worked during the gold-rush era in the British Columbia, however, Nelson and Kennedy (2012) identified a total of 457 gold rush era placer mines along the Fraser and Quesnel rivers. In the Fraser basin, gold-rush era mines are found along the Fraser, Quesnel, Thompson, Horsefly, and Bridge Rivers, (Nelson & Kennedy, 2012) and within in the Cariboo region, mines were located on the Lowhee, Keithley, Antler, Williams, and Lightning creeks, and tributaries to these creeks (Hagen, 1924, p. 11). On William’s Creek alone, 111 claims were recorded (Haggen, 1924, p. 13-15). There was also significant placer mining effort in the Cariboo, Cassiar, Similkameen and Atlin areas, and placer work scattered throughout B.C., including on the Columbia River, the Skeena River, the Thompson River, the Peace River, and the Leech River and China Creek on Vancouver Island (British Columbia, 1875, pp. 7–13; Carmichael & Moore, 1930), suggesting that the total number of historic placer mines in B.C. may be in the thousands.

My research suggests that for gold-rush era mine sites where there are obvious mining-created landforms, such as sluice runs, cobble piles, tailings piles, and parallel rows of cobbles, it is likely that at least some soil samples from such a site will exceed baseline tHg concentrations. This further suggests that mercury amalgamation techniques were widely adopted by miners during the gold rushes in the Fraser Basin, and that there may be thousands of gold-rush era mine sites in British Columbia with some level of mercury contamination.

Chapter 3. Estimated Mercury Loss

3.1. Introduction

The field study described in Chapter 2 found that mercury was likely used in a majority of gold mining operations during the Fraser and Cariboo gold rushes in British Columbia. An obvious question that follows is “how much mercury did gold rush era miners use?” Within this chapter, I will discuss methods used to estimate mercury loss by gold miners across regions and time periods and apply them to B.C. to develop an estimate of mercury loss for the period 1858 to 1910.

3.2. Overview of methods to determine mercury loss

Mercury is still used in artisanal and small-scale gold mining (ASGM), which includes placer mining, in an estimated 70 countries worldwide (Telmer & Veiga, 2009, p. 131). Due to health risks from local use of mercury, and methylmercury bioaccumulation associated with the atmospheric deposition of mercury, there is growing interest and awareness of the contribution of ASGM to global atmospheric mercury. In 1988, Pfeiffer & Lacerda (1988) estimated that ASGM contributed 6% of global anthropogenic mercury emissions. By 2003, that estimate had climbed to 20% (Lacerda, 2003), and in 2015, the accepted figure was that ASGM accounted for 46% of total anthropogenic global mercury emissions (AMAP/UNEP, 2015). This latter estimate was for an “intentional use and product waste” category, which is mostly comprised of ASGM in Southeast Asia, Central and South America, and Sub-Saharan Africa (AMAP/UNEP, 2015).

The ASGM sector is primarily made up of individuals and small operators who often work within an informal or illegal economy (Veiga, 1997). The informal nature of this economy means that the sector’s contribution to global anthropogenic atmospheric mercury is difficult to directly quantify (Veiga, 1997). Gold extraction, however, is easier to track, so equations have been developed to relate mercury loss to gold extraction (see, for example, Pfeiffer & Lacerda, 1988). Versions of these equations are called mercury use factors (Ganesan, 2000), mercury loss ratios (Veiga, 1997), and mercury emission factors (Lacerda, 2003). These were generally built by observing mercury

amalgamation techniques and noting the mercury losses to the atmosphere and terrestrial environments at different stages.

Mercury use factors vary between 0.1 and 10 units of mercury lost per unit of gold extracted (Hg/Au), with a mercury use factor of 0.1 Hg/Au reported in Poconé mining district in Brazil, and between 2 and 10 Hg/Au for Pará State mining in Brazil (Pfeiffer et al., 1993). Veiga (1997) notes that if mercury is used to amalgamate alluvial ore, the mercury use factor can be as high as 3 Hg/Au. In contrast, if mercury is used to process concentrates, an intermediate product consisting of fine gold mixed with other heavy metals, about 1 kg mercury is used per 100 kg concentrate, and between 74% and 94% of mercury is retained (Veiga, 1997). Pfeiffer et al (1989) calculated the total mercury loss in this case as 1.32 Hg/Au. Lacerda (2003) states that 1.3 Hg/Au is the most widely accepted contemporary mercury use factor (p. 309).

Mercury is lost to the environment through two routes. First, mercury is lost to processing water and tailings during the initial processing of alluvial ore. Chapter 2 of this project tested mine sites for traces mercury lost in this way. Mercury leaked from sluice boxes, and the turbulent action of water and alluvial ore caused mercury to be discharged along with water and tailings. The second route of mercury loss is to the atmosphere. To separate gold and mercury, miners heat the gold amalgam which converts mercury to vapour. Loss of mercury to the atmosphere is highly influenced by the use of a retort, a device that captures mercury vapour and cools it, allowing the recovery of mercury for future re-use. At some Brazil mines where retorts were used, the mercury loss factor ranged from 0.1 - 1.1 Hg/Au, while mines that did not employ retorts reportedly had mercury use factors of 2 – 10 Hg/Au (Pfeiffer et al., 1993, p. 28). Pfeiffer et al. (1989) estimated that in Brazilian mines, 70% of mercury is lost to the atmosphere, and 30% lost is in tailings. By 1993, Pfeiffer et al. had refined their estimates of mercury loss in Brazil to 65%-83% loss to the atmosphere, versus 17% to 35% lost to tailings. Veiga (1997) estimated that if a retort is not used when processing concentrates, 70% of mercury is lost as vapour to the atmosphere, versus 20% in tailings and 10% in final gold processing (p.25).

In his review of gold extraction and mercury loss by artisanal miners in fifteen countries, Veiga (1997) noted that favored methodologies and associated rates of mercury loss varied both temporally and spatially. In the 1970s, for example, Brazilian

miners used mercury to amalgamate whole ore, and by the 1990s were using mercury primarily to process concentrates. In contrast, Mexican miners reportedly favored a cyanide gold-leaching process which had very low mercury use (Veiga, 1997).

In this case, we are focussed on historical (1858 – 1910) mercury use factors in British Columbia. There is less literature on historical mercury loss, however, Churchill, (2000) reviewed historical data and narratives on mercury use and gold extraction for mining in California, producing estimates of mercury loss for time periods spanning 1848 – 1976, summarised in Table 3.1. His estimates combine mercury losses from different placer mining methodologies, but he notes in discussion that hydraulic mining mercury use factors were roughly between 3.6 to 4.9 Hg/Au, while other forms of placer mining were more economical, ranging from 0.4 to 1.0 Hg/Au.

Table 3.1 Mercury Use Factors calculated from Churchill 2000

Period	Mercury Use Factor
1848-1858	0.9
1859-1884	4.9
1885-1899	3.6
1900-1934	0.6
1935-1968	0.4
Hydraulic Mining, lower bound	3.6
Hydraulic Mining, upper bound	4.9
Other placer mining, lower bound	0.4
Other placer mining, upper bound	1.0

Mercury Use Factors calculated from Churchill 2000, Table 1, and discussion in text. Mercury use factor originally reported as oz gold recovered per pound mercury lost.

3.3. Method for estimating mercury loss during B.C.'s gold rushes

Following on the work of Churchill and others, the following equation can be used to estimate mercury loss in B.C. during the gold rush era:

$$H = \frac{g}{p} 0.033103(u_1 m_1 + u_2 m_2) \qquad (1)$$

Where

H = mercury use (kg)

g = gold extraction ($)

p = price of gold ($/oz)

0.033103 is a conversion factor to change troy oz. gold to kg gold

u_1 = mercury use factor for hydraulic mining (kg Hg / kg Au)

m_1 = percentage of gold from hydraulic mining

u_2 = mercury use factor for other methods of placer mining (kg Hg / kg Au)

m_2 = percentage of gold from other methods of placer mining

Gold extraction

Gold extraction from different areas and time periods is included in the British Columbia Annual Reports of the Minister of Mines and various other sources (Haggen, 1924; Holland, 1950). This information is incomplete and includes data manipulations made during the period the information was recorded: between 1858 and 1874, the only available records for gold production are based on the amount of gold shipped from Victoria (Holland, 1950, p. 8; Nelson, 2017). Official figures for gold production in British Columbia, reported in Ministry of Mines documents for this period are 1/3 higher than amounts recorded by banks in Victoria, to account for gold leaving the province through unofficial channels (Holland, 1950, p.8). With the inception of the B.C. Ministry of Mines in 1874, regional Gold Commissioners reported on local gold production, improving accuracy and regional definition, and record keepers at the time added 1/5 to the known amount of gold exported from the province to account for unrecorded gold exports (Holland, 1950, p. 8). As an aside, manipulations of placer gold extraction records in B.C. are not limited to 1800s and early 1900s; between 1999 and 2017, figures tabulating placer gold extraction in B.C. published by the Ministry of Energy, Mines and Petroleum Resources are based on the estimate that placer gold extraction totalled 1% of the total gold extraction in the province (BC EMPR, 2017, line 165).

While official records of gold extraction for Fraser Basin regions do not include the period 1860 – 1874, Haggen (1924) collected regional data for the Cariboo region, and his “estimates based on the best information that can be obtained,” conclude that over $74 million in gold was extracted from that area between 1858 and 1923 (p. 63). Assuming a gold price of $17/oz, the total gold extraction from the Cariboo region was

145,524 kg. In contrast, the total gold extraction **for B.C.** between 1858 and 1923, reported by Holland (1950) and based on local gold prices received at the time adds up to **138,998 kg**. As the Cariboo region is wholly located in B.C., the fact that Haggen's Cariboo gold extraction estimate is higher than the total estimate for gold extraction for the province over the same period illustrates some of the uncertainties with using historical documents to estimate gold extraction and mercury use.

Price of Gold

Gold extraction was recorded in dollars, and the Canadian dollar was based on the gold standard between 1854 and 1914, meaning the price of gold was stable during this period (Powell, 2005, p. 33). However, miners received different prices per ounce of gold based on purity. Holland (1950) reports that prior to 1931, the value of an ounce of placer gold in British Columbia ranged from $13.85 to $20.67. Based on a review of gold purity across placer mines and regions in B.C., Holland considers $17/oz representative of the average value of an ounce of crude placer gold (Holland, 1950, p. 8), and I will use this $17 figure in the calculations.

Mercury Use Factors

There are three alternatives for arriving at mercury use factors for B.C. during the gold-rush period: (1) use records of mercury loss at individual mine sites in B.C.; (2) base mercury use factors on Californian mercury use factors for similar mining methodologies and time periods; and, (3) calculate mercury loss based on the assumption that mercury imported into the province was used and lost during gold mining. The following pages outline mercury use factors from these three sources, arriving at a range for mercury use factors that are applicable to B.C.

(1) The 1897 Annual Report of the Minister of Mines states that The Cariboo Consolidated Hydraulic Mining Company, operating the site later known as "Bullion Pit," near the town of Likely, British Columbia, included "mercury, loss for the season, 23 flasks," in their expenses for that year (British Columbia, 1898, p. 480) equivalent to 792.88 kg of mercury. Their gold extraction that year was 8078.1 oz gold, equivalent to 267.41 kg (British Columbia, 1898, p. 480). This results in a mercury use factor of 2.97 Hg/Au. This is the only mine in the Annual Reports of the Minister of Mines that reports mercury loss and gold production, allowing the calculation of a mercury use factor.

(2) As discussed in section 3.2, Churchill (2000) reported ranges of mercury use factors for mining methods and time periods in California, summarised in table 3.1. Due to the close connections between these jurisdictions, Californian mining practices would have had influence on mining in B.C. and thus these mercury use factors would have some applicability. However, in California, mercury was locally mined and therefore more readily available.

Bullion Pit can be used to fit Californian mercury use to B.C. circumstances. The Bullion Pit mercury use factor is similar to, but lower than, Churchill's estimates of a mercury use factor of 3.6 Hg/Au for both that time period and that mining method in California, suggesting that mercury use in B.C. in hydraulic mining may have been lower than in California. However, we do not know if Bullion Pit was average in its mercury use, or exceptionally efficient or wasteful. To account for this, I will assume that the range of between high levels and low levels of mercury loss from hydraulic mines in the same era in California, discussed by Churchill (2000) applies to B.C. The lower bound of mercury use for hydraulic mining in California is 3.6 Hg/Au, and the higher bound for mercury use is 4.9 Hg/Au, the range between these two values is 1.3 Hg/Au. Assuming this range of 1.3 Hg/Au for California represents the possible range in B.C., then if Bullion Pit was an uncommonly economical mine and had a mercury use of 3.0 Hg/Au, the highest mercury use value for hydraulic mines in the province would be 4.3 Hg/Au. If Bullion Pit, instead, had a more liberal use of mercury than other hydraulic mines, this would give us a lower bound of 1.7 Hg/Au.

(3) The third method of deriving a mercury use factor for B.C. divides the total amount of mercury imported and produced in B.C. by the total gold extracted. This is based on the assumption that most of the mercury imported into the province was used in gold mining. I did not, as part of this work, investigate the use of mercury in other industries in B.C. during the mid 1800s to early 1900s, however, across the world mercury was used in silver mining, gilding of buildings, mold-inhibition in paint, mirror backing, felting, and the pigment vermillion in the 19th century (Brooks, 2012, p. 20). In the 20th century, mercury was used in ammunition, turf fungicides, fungicidal seed treatments, anti-mildew and anti-fouling paints, and dental fillings; as well as in chloro-alkali plants and pulp mills, and in the production of scientific instruments (Fimreite, 1970). Horowitz et al., (2014), in an analysis of mercury use worldwide, found that gold and silver mining were responsible for almost all global mercury consumption up to

1900. As discussed below, mercury imports and gold extraction do appear linked from 1860 to 1883, after which mercury imports to Canada were higher than expected needs for gold production.

Table 3.4 shows mercury exported by sea to B.C. from San Francisco between 1860 and 1883 (Hanks, 1884, p. 343); and mercury imported into Canada between 1882 and 1899 (Ingall et al., 1899, p. 80). There was also limited local production of mercury from mines near Kamloops Lake, these produced 100 flasks of mercury in 1895 (British Columbia, 1896 p. 697). Mercury production from the Kamloops Lake mines in other years is not mentioned in Annual Reports of the Minister of Mines. It is important to recognize that the export-by-sea dataset from San Francisco does not necessarily present the total amount of mercury available for mining in the province for the period 1860 to 1883. Official traffic to the Fraser moved through Victoria, however, the ports of Whatcom, Port Townsend, and Sehome also serviced the Fraser gold rush (Marshall 2000, p.5). Further, in 1869, a transcontinental railroad was built in the United States, and by 1886 the Canadian Pacific Railway had opened a route to eastern Canada, both which would have increased access to mercury mines in Europe. Also, mercury available for exportation from California was likely limited, as Californian mines were unable to meet domestic mercury consumption requirements between 1870 and 1893, during which period the United Stated imported an average of 75 tonnes per year (Nriagu 1994, p. 177).

Table 3.2 Datasets on mercury imported and produced in B.C. and Canada, 1858 – 1899

Year	Flasks shipped to BC by sea from California	Mercury Shipped to BC from San Francisco (kg)	Mercury Imported to Canada (kg)	Mercury extracted in British Columbia (kg)
1858				
1859				
1860	326	11237		
1861	116	3999		
1862	5	172		
1863	42	1448		
1864	21	724		
1865	24	827		
1866	6	207		
1867	20	689		

Year	Flasks shipped to BC by sea from California	Mercury Shipped to BC from San Francisco (kg)	Mercury Imported to Canada (kg)	Mercury extracted in British Columbia (kg)
1868	20	689		
1869	4	138		
1870	9	310		
1871	6	207		
1872	2	69		
1873	9	310		
1874	2	69		
1875	17	586		
1876	36	1241		
1877	16	552		
1878	25	862		
1879	10	345		
1880	14	483		
1881	14	483		
1882	21	724	1108	
1883	11	379	3361	
1884			2653	
1885			6573	
1886			6040	
1887			8350	
1888			12679	
1889			10402	
1890			7218	
1891			13506	
1892			14033	
1893			23003	
1894			16744	
1895			28909	3447
1896			35334	
1897			34500	
1898			27107	
1899			46729	
Total	**776**	**26749**	**298246**	**3447**

Mercury imported to B.C. by sea from San Francisco, 1860 to 1883, from (Hanks, 1884, p. 343); Mercury imported to Canada 1882 to 1899 from (Ingall et al., 1899, p. 80); Mercury extracted in Canada from (British Columbia, 1896 p. 697).

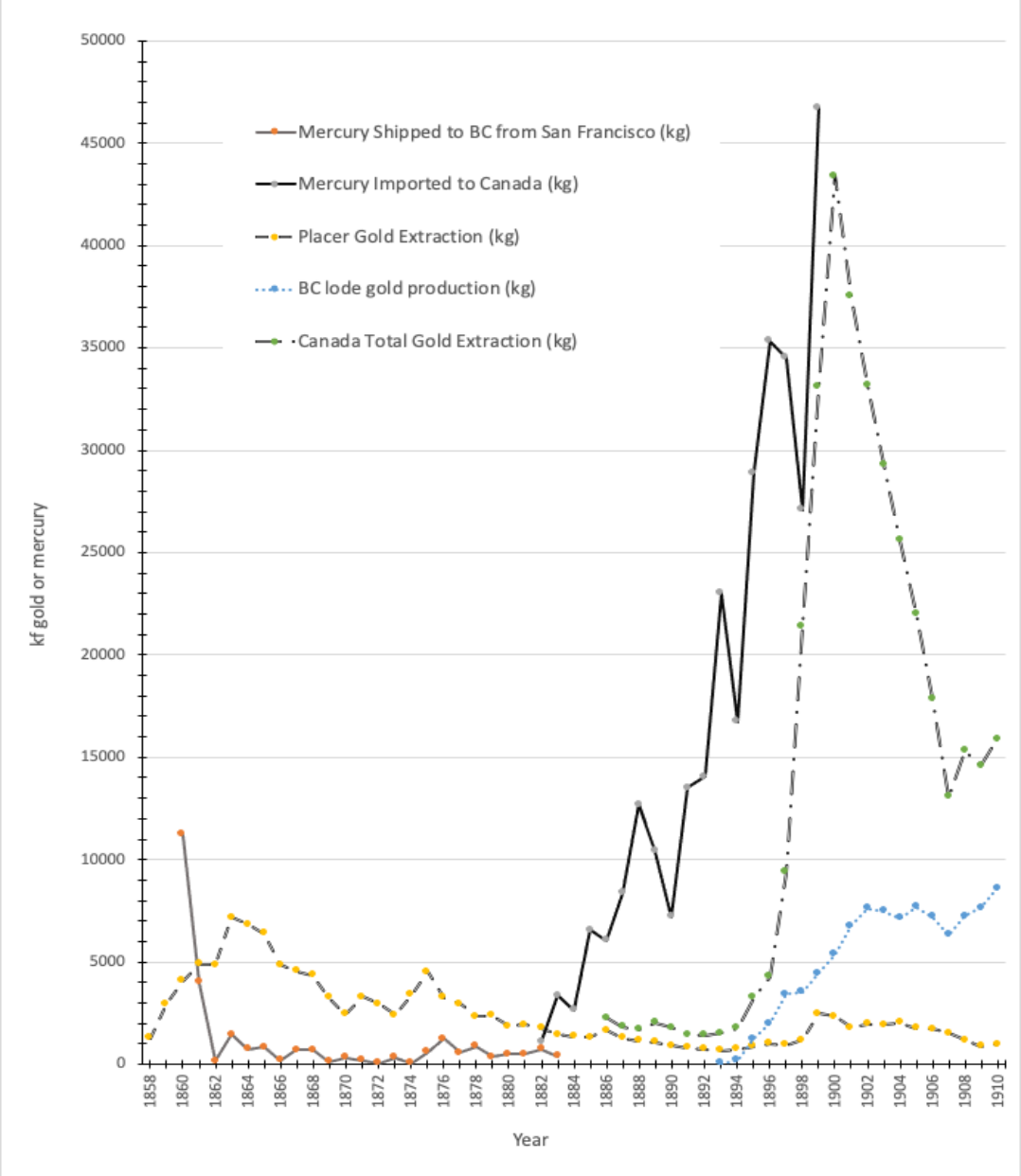

Figure 3.1 B.C. and Canada Gold Extraction and Mercury Imports, 1858 - 1910
Mercury exported by sea from San Francisco to B.C. for the period 1860 to 1883 (Hanks, 1884, p. 343); mercury imported to Canada from 1882 to 1899 (Ingall et al., 1899, p. 80); gold extraction by placer and lode mines in B.C. from 1858-1910 (Holland, 1950, p. 9); and Canadian gold extraction from 1886 to 1910 (Historical Statistics of Canada, n.d.).

Figure 3.1 shows mercury imports graphed alongside gold extraction for B.C. and Canada. For the first twenty-five years of the gold extraction in B.C. (1858 to 1882), gold extraction was much higher than the mercury entering the province from San Francisco. Beginning in the 1890s, both gold extraction and mercury imports began rising

exponentially. Trends over time, however, can be misleading, as unrelated activities can both concurrently rise or fall over time without having any real correlation. To understand if trends are related, year-over-year graphs are more useful. Year-over-year graphs are created by subtracting the previous year's value from the current year's value and graphing the resulting yearly change. Figure 3.2 shows the year-over-year change in BC and Canadian gold extraction, and mercury imported into Canada, for the time period 1881 to 1900. It is apparent in Figure 3.2 that while gold extraction and mercury use both increased in volatility over time, there is no clear relationship between the amount of mercury imported into Canada, and the gold extraction in the country. This suggests that there were other major users of mercury in Canada at the time that influenced the amount of mercury entering the country, or that mercury availability changed

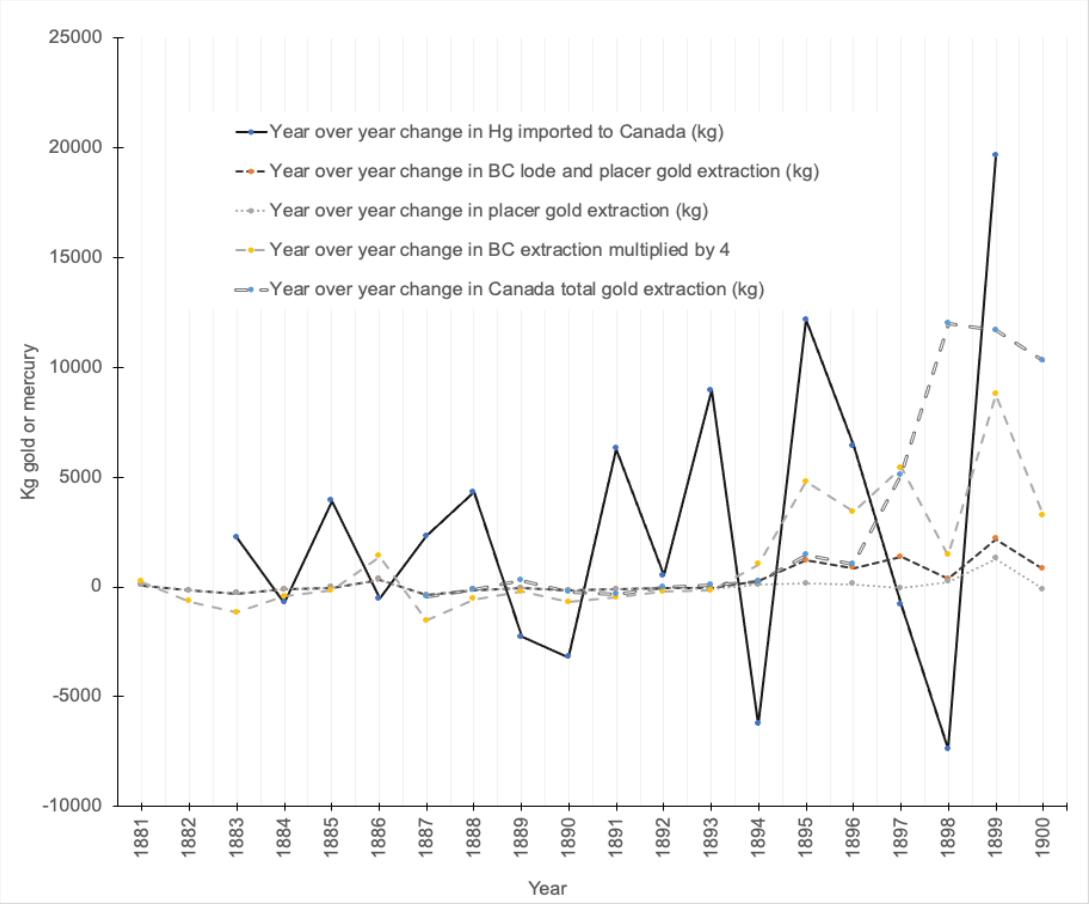

Figure 3.2 Gold extraction and mercury imports in Canada and B.C. 1881 – 1900

Mercury imported to Canada from 1882 to 1899 (Ingall et al., 1899, p. 80); gold extraction by placer and lode mines in B.C. from 1858-1910 ((British Columbia, 1911, p. 10); Canadian gold extraction from 1886 to 1910 (Historical Statistics of Canada, n.d.). The series "Year-over-year gold extraction in B.C. multiplied by 4" was calculated from the series "Year-over-year change in B.C. lode and placer gold extraction," as the expected mercury use if a mercury use factor of 4 was occurring.

substantially between years, and that changes in the amount of mercury imported each year based more on supply than demand.

In contrast, Figure 3.3, shows the year-over-year change in placer gold extraction and mercury exported to B.C. from San Francisco between 1860 and 1885. Between the start of the gold rush in 1860 and 1872, gold extraction and mercury imports appear to be almost inversely related, where a year-over-year increase of mercury imports coincides with a year-over-year decrease in gold extraction. Conversely, beginning in 1873, gold extraction and mercury imports become closely linked. Perhaps prior to 1873, delays in ordering and receiving mercury meant that orders were based on the previous-years gold extraction, while after 1873, communication and transportation became

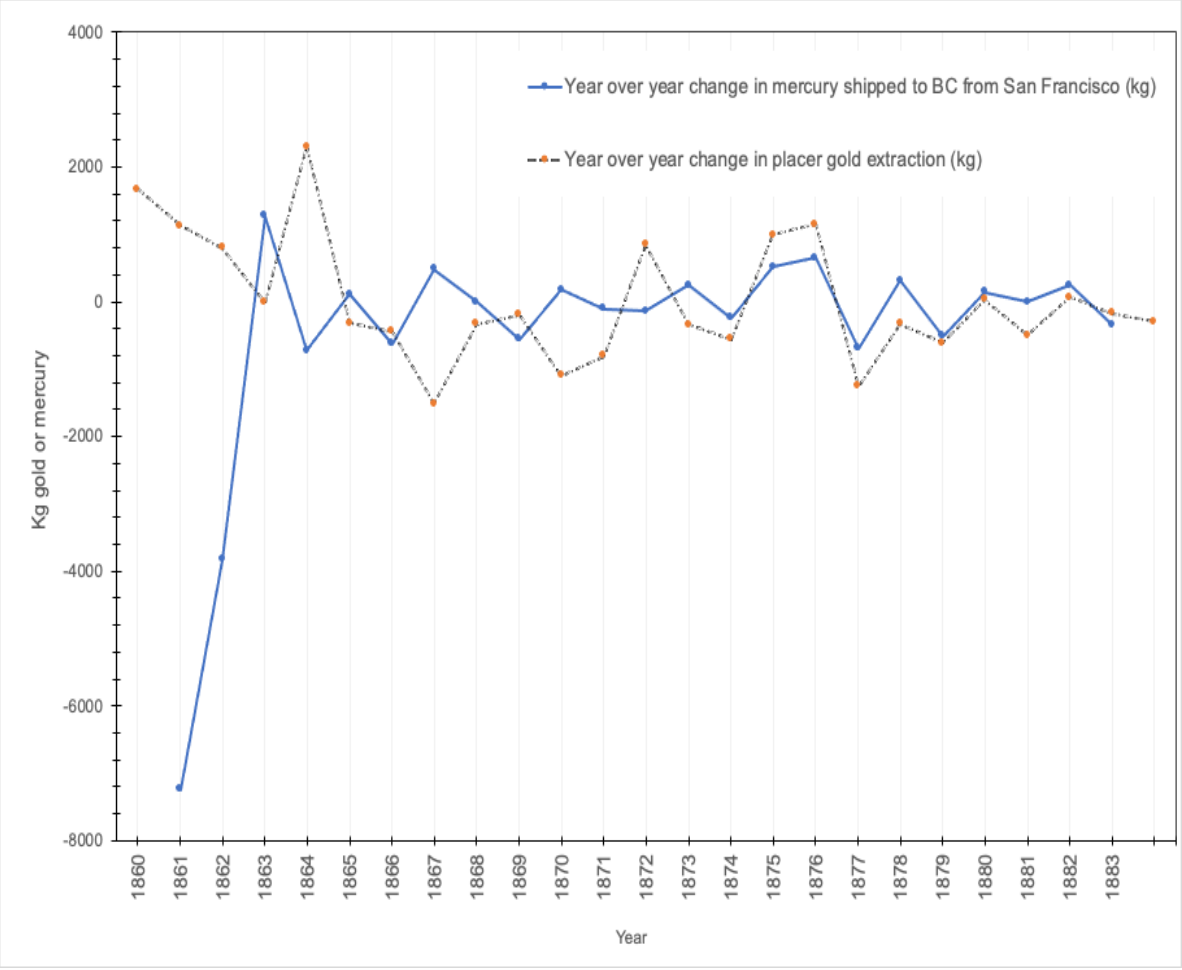

Figure 3.3 Year-over-year change in gold extraction and mercury imports from San Francisco, by sea, 1860 - 1883

Mercury exported by sea from San Francisco to B.C. for the period 1860 to 1883 (Hanks, 1884, p. 343); gold extraction by mines in B.C. from 1858-1910 (Holland, 1950, p. 9). Year-over-year figure is calculated by subtracting the previous year's gold extraction from the current year.

faster, and mercury was ordered and arrived in the same season. Alternatively, as methods and gold characteristics changed over the course of the gold rush, it is possible that the amount of mercury available exerted significant influence on the amount of gold miners were able to retain, which would also explain this in-sink relationship.

To summarise, Table 3.4 shows that there was at least 26,749 kg shipped to B.C. from California between 1860 and 1880, and 298,246 kg of mercury imported into Canada between 1882 and 1899. Figure 3.3 shows that mercury imports from California were closely linked to placer mining activity, suggesting that these mercury imports were, indeed, used in placer mining activity in the province. Figure 3.2 suggests that later mercury imports into Canada were not closely linked to mining activity, however, there was far more mercury imported during this period than gold extracted, so mercury was available in quantities sufficient to support high rates of mercury use during mining.

The following mercury use factors can be derived from mercury imports and gold extraction in B.C.: from 1860 to 1880, placer gold production in B.C. was 87,181 kg (Holland, 1950) and total mercury from San Francisco by sea was 26,749 kg, (Hanks, 1884, p. 343) which provides mercury use factor of 0.31 for the years 1858-1882. A mercury use factor of 0.31 Hg/Au fits with other available information: Churchill estimated a mercury use factor of 0.4 to 1.0 Hg/Au for non-hydraulic placer mining methods during this time period (Churchill, 2000, p. 38), and non-hydraulic methods were dominant in B.C. during the period 1858-1882 (Nelson, 2017). However, as discussed above, there existed other routes through which mercury may have entered the province, therefore I will use the range 0.31 – 1.0 Hg/Au as a mercury use factor range for non-hydraulic mining methods. Mercury would have been much more widely available by 1890s when the trans-Canada railroad was completed, which coincides with increased hydraulic placer mining activity noted by Nelson (2011). While there remains uncertainty in these estimates, calculations this paper will therefore use a range of **1.7 to 4.3 Hg/Au** for hydraulic mining, and a range of **0.31 to 1.0 Hg/Au** for other methods of placer mining.

Mining method prevalence

Andrew Nelson's 2017 article "Gold in the documents: estimating placer mining excavation volumes in the Fraser Basin, British Columbia, using historical sources" contains compilations of historical data that summarises gold extraction and mining

methods in the Fraser basin (p. 96-98). Additionally, ongoing research by Andrew Nelson has provided estimates for mining methodologies over time at various locations in the Fraser Basin (Nelson et al., 2011; Nelson, 2017, p. 103). Nelson (2017) estimates for prevalence of different mining methodologies over regions and times is used in this paper's calculations of mercury loss.

3.4. Results and Discussion

The following mercury losses were calculated using versions of equation (1).

3.4.1. Bullion Pit Calculated Mercury Loss

Bullion Pit lost an estimated 6677.5 kg of mercury to the environment over 10 years of operation from 1895 to 1904. To calculate this, I applied the mercury use factor for 1897, 2.97 Hg/Au, to the ten-year record of gold extraction reported in Haggen (1924). Annual and total estimated mercury loss for Bullion Pit is shown in Table 3.3.

Table 3.3 Gold extraction and estimated mercury loss from Bullion Pit / The Cariboo Hydraulic Mining Company

Year	Gold extraction ($)	Total Hg Loss (kg)
1895	42000	240.91
1896	127000	728.48
1897	*138520*	*794.56*
1898	105141	603.09
1899	92769	532.13
1900	350086	2008.11
1901	142273	816.09
1902	61395	352.16
1903	44944	257.80
1904	60000	344.16
Totals	**1164128**	**6677.50**

Gold extraction from Haggen (1924) p. 56-7. Price of gold used for calculations was $17.14 / oz, as reported by mine, and mercury loss ratio was calculated from gold production and mercury loss reported by mine for the year 1897. (British Columbia, 1898).

As discussed in Section 3.2, mercury is lost to tailings and processing water during the mining process, and to the atmosphere during gold purification. Applying Pfeiffer et al., (1993), range of 17% to 35% loss to tailings to the Bullion Pit mine is imperfect but suggests that between 1135 kg and 2337 kg of mercury may have been lost to tailings at the Bullion Pit site between 1895 and 1904, while a further 4340kg to

5542kg may have been lost to the atmosphere over that same period. Notably, these figures apply 1990s rates of mercury loss to 1890s mining practices and should therefore be considered a rough estimate.

3.4.2. Cariboo Region Calculated Mercury Loss

Table 3.3 shows a rough estimate of total mercury loss for the Cariboo region of between 86,990 kg and 247,665 kg. This was calculated using equation (1) with inputs from Hagan (1924) Cariboo gold extraction estimates from 1860 to 1924 and Nelson (2011) estimates of mining method prevalence in each area. Notably, the upper bound is likely an overestimate, as the datasets on mercury exported to B.C. from San Francisco and imported to Canada for the period 1860 and 1899 total 323,891 kg. Although it is possible that two thirds of this mercury was bound for the Cariboo, there was significant gold mining occurring elsewhere in the province and the country in the late 1800s, and potentially other industrial uses of mercury, as discussed in Section 3.3. Applying Pfeiffer et al., (1993), range of 17% to 35% loss to tailings results in an estimate of 14,788 kg to 86,682 kg mercury loss to tailings and processing water in the Cariboo.

Table 3.4 Estimated mercury use for Cariboo region Fraser and Quesnel Rivers and tributaries, 1858 – 1923, data from Hagan (1924)

Location	Estimated Gold Extraction ($)	Portion hydraulic	Portion other methods	Lower bound Hg loss estimate (kg)	Upper bound Hg loss estimate (kg)
Fraser River in Cariboo:					
Fraser River at Quesnel	1,000,000	0.5	0.5	1,947	5,160
Fraser River, sundry bars in Cariboo	1,000,000	0.2	0.8	1,129	3,232
Subtotal				3,077	8,393
Quesnel River & tributaries					
N. Fork Quesnel	1,025,000	0.6	0.4	2,275	5,948
Spanish Creek	500,000	1	0	1,655	4,187
Golden River Quesnel	222,648	0	1	130	434
South Fork -Sundry Claims	1,000,000	0.6	0.4	2,220	5,803
Roses Gulch	80,000	1	0	265	670
Chinese Farm	70,000	1	0	232	586
Chinese Pit, Bullion	900,000	1	0	2,979	7,536

Consolidated Cariboo (Bullion)	1,214,128	1	0	4,019	10,166
Quesnel River Campan Creek	1,250,000	1	0	4,138	10,466
Quesnel River, Sundry Claims	3,000,000	0.6	0.4	6,660	17,408
Subtotal	9,261,776			24,573	63,203
Other Cariboo Locations					
Lightning Creek	8,000,000	0.5	0.5	15,578	41,281
Tributaries of Willow River	8,000,000	0.5	0.5	15,578	41,281
Antler Creek	6,000,000	0	1	3,505	11,683
Williams Creek and tributaries	26,000,000	0	1	15,188	50,628
Cunningham Creek	2,250,000	0	1	1,314	4,381
Harvey Creek	2,750,000	0	1	1,606	5,355
Keithly Creek	5,000,000	0	1	2,921	9,736
Cedar Creek total	289,000	0	1	169	563
Horsefly = Wards Horsefly	1,500,000	0	1	876	2,921
Horsefly Hydraulic	166,004	1	0	550	1,390
Horsefly Sundry Claims	2,500,000	0	1	1,460	4,868
Moorehead	1,000,000	0	1	584	1,947
Seven Mile	17,064	0	1	10	33
Subtotal				59,340	176,069
Total Potential Mercury Loss Estimate for Cariboo				86,990	247,665

Estimated gold extraction from Haggen, (1924), p. 63); placer mining method for "Fraser River at Quesnel," "Quesnel River and tributaries," "Lightning Creek," and "Tributaries of Willow River" from (Nelson, 2011, p. 38). Placer mining methods for other locations are not known, so are assigned to the more conservative "other methods" category. Hydraulic mining methods uses mercury use factors of 1.7 (lower bound) and 4.3 (upper bound). Other placer mining methods uses mercury use factors of 0.3 (lower bound) and 1.0(upper bound).

3.4.3. Fraser Basin Calculated Mercury Loss

Nelson (2017) compiled gold extraction and mining techniques for Fraser Basin regions across the decades 1858 – 1910 (p. 97-98; p103). Nelson's work provides sufficient inputs to estimate mercury loss in the Fraser Basin from 1858 – 1910, using equation (1). As an example, Table 3.5 shows inputs and results for Yale District. In total, an estimated 2561 kg to 7412 kg mercury was lost through placer gold mining in the Yale district between 1858 and 1909.

Table 3.5 Estimated mercury use for Yale District by decade, 1858 – 1909, data from Nelson (2017)

Year	Gold extraction ($)	Proportion Hydraulic	Mercury loss lower Estimate (kg)	Mercury loss upper Estimate (kg)
1858-1859	1,059,097	0	619	2062
1860s	557,135	0.05	401	1264
1970s	59,114	0.05	43	134
1880s	148,200	0.6	329	860
1890s	337,148	0.9	1024	2606
1900-1909	249,182	0	146	485
Total	**2,409,876**		**2561**	**7412**

Data for gold extraction and hydraulic portion of mining method from Nelson (2017). Hydraulic mining methods uses mercury use factors of 1.7 (lower bound) and 4.3 (upper bound). Other placer mining methods uses mercury use factors of 0.3 (lower bound) and 1.0(upper bound). Note that there is limited data between 1861 and 1873.

Table 3.6 shows the results of applying equation (1) to Fraser Basin mining methods and extraction estimates provided by Nelson (2017). Between 1858 and 1909, an estimated 17,768 kg to 48,113 kg of mercury was lost in the Fraser River and tributaries. Applying Pfeiffer et al., (1993), range of 17% to 35% loss to tailings results in an estimate of 3020 kg to 16,839 kg mercury lost to tailings and processing water in the Fraser Basin from 1858 to 1909.

In contrast, working with Hagan (1924) numbers produced a much higher estimate of between 86,990 kg and 247,665 kg total mercury loss. There are a number of potential reasons that may account for these discrepancies. First, Hagan attempted to "fill in the blanks" and extrapolated data for the period 1860-1874, for which no regional data in B.C. was recorded. Second, Hagan's dataset extends to 1924, so covers a larger time period. Third, Hagan's dataset was not temporally resolved, however, practices and mercury use shifted over time, which may cause under or over-estimates.

Table 3.6 Estimated mercury use for Fraser River and tributaries, 1858 – 1909, data from Nelson (2017)

Area	Year	Total
Fraser River in Yale District	Gold Extraction ($)	2,409,876
	Mercury loss lower estimate (kg)	2,561
	Mercury loss upper estimate (kg)	7,412
Fraser River in Lillooet District	Gold Extraction ($)	3,137,164
	Mercury loss lower estimate (kg)	3,473

	Mercury loss upper estimate (kg)	9,975
Fraser River Above and Below Quesnel	Gold Extraction ($)	630,731
	Mercury loss lower estimate (kg)	1,452
	Mercury loss upper estimate (kg)	3,782
Quesnel River and Tributaries, including Quesnel Mouth, Keithly, Upper and Lower Quesnel, North and South Fork	Gold Extraction ($)	4,513,832
	Mercury loss lower estimate (kg)	9,881
	Mercury loss upper estimate (kg)	25,865
Quesnel District, including Swift and Cottonwood Rivers	Gold Extraction ($)	235,170
	Mercury loss lower estimate (kg)	401
	Mercury loss upper estimate (kg)	1,080
TOTAL	Gold Extraction ($)	10,926,773
	Mercury loss lower estimate (kg)	17,768
	Mercury loss upper estimate (kg)	48,113

Data for gold extraction and hydraulic portion of mining method (not shown) from Nelson (2017). Hydraulic mining methods uses mercury use factors of 1.7 (lower bound) and 4.3 (upper bound). Other placer mining methods uses mercury use factors of 0.3 (lower bound) and 1.0(upper bound). Note that there is limited data between 1861 and 1873.

This chapter estimated mercury loss from gold-rush era mine sites in the Fraser Basin using different records of gold extraction. The Bullion Pit mine on the Quesnel River lost and estimated 6677.5 kg of mercury to the environment during its operation between 1895 to 1904. Hagan's 1924 estimate of gold extraction in the Cariboo region resulted in an estimated mercury loss of between 86,990 kg and 247,665 kg, while Nelson's 2011 dataset resulted in an estimated loss of 17,768 kg to 48,113 kg mercury to the atmosphere, Fraser River, and tributaries.

Chapter 4. Discussion and Recommendations

Within this chapter I first discuss the potential impacts of mercury from gold-rush era placer mine sites on their surrounding environment, concluding that ecosystems near these mine sites should be monitored for mercury uptake. In Section 4.2, I cover mercury monitoring in B.C. in general, comparing mercury monitoring and public dissemination of information in B.C. to selected provinces, showing that B.C. lags behind other provinces in this regard. Finally, I outline opportunities for further research, and recommendations for policy responses to gold-rush era placer mine sites.

4.1. Discussion of potential impacts

This section outlines the potential impact that mercury from gold rush era mines may be having on ecosystems in British Columbia. As discussed in Section 2.2.1, total mercury concentrations found in soil samples collected from mine sites in this study were well below levels that would trigger classification of the sites as “contaminated” under the B.C. Contaminated Sites Regulation, Schedule 3.1, Matrix 20. The mercury concentrations cited in the regulation, however, are modelled on soil ingestion by humans, and therefore are not suitable to account for environmental effects that may be caused by mercury bioaccumulation and biomagnification. This is illustrated by studies that have shown that mercury levels rise in fish and other species with very low mercury inputs (see, for example, Harris et al. 2007).

Research on watersheds that host gold mine sites where mercury was or is used in other parts of the world have found that for small and medium sized watersheds: mercury loads may exceed atmospheric loading (Domagalski et al., 2016, p. 638); there is a steep gradient of mercury concentration from the site of deposition, suggesting that mercury has limited mobility (Lacerda & Salomons, 2012, p. 52); and, inorganic mercury sources appear to have little influence on methylmercury concentrations in local biota, although mercury contamination from mines have local impacts (Eagles-Smith, Wiener, et al., 2016).

Methylmercury is the primary route through which mercury impacts both environmental and human health. The formation of methylmercury is a complex process

that is not fully understood. In a seminal article, Ullrich et al., (2001) reviewed the factors that increase the production of methylmercury and found that influencing factors include:

- The presence of sulfate-reducing bacteria;
- Anoxic conditions, which increases methylation;
- Temperature, with increased temperature correlating with increased methylation;
- Reduced pH, which may increase methylation although the nature of this effect is uncertain;
- The form of mercury present (valence states, inorganic and organic molecules), which makes mercury more or less biologically available;
- Higher organic matter, which increases methylation; and,
- The presence of sulfides, which may increase methylation at low concentrations and inhibits it at high concentrations.

More recent work has indicated that while sulfate-reducing bacteria is usually responsible for mercury methylation in aquatic environments, other organisms may take that role in some systems (Paranjape & Hall, 2017). Further, the presence of iron and manganese oxides have been found to increase methylation, while light can both reduce the bioavailability of mercury, and stimulate the production of organic matter, both which affect methylation (Paranjape & Hall, 2017, p. 98).

In a review of mercury concentrations and ecological responses in western North America, Eagles-Smith et al (2016) provides a summary of mercury bioaccumulation according to risk factors. Eagles-Smith's review found that the key factors that influence the formation of methylmercury included land use, biogeochemistry, and habitat type, while methylmercury bioaccumulation is influenced by the productivity of the area, habitat use, and food web structure. Finally, they found that the key factors influencing whether accumulated methylmercury had toxic effects were species sensitivity, environmental stressors, and the effects of other metals and contaminants, especially selenium (Eagles-Smith, Wiener, et al., 2016).

Thus, the effect mercury from a mine site may have on the local environment will be determined by a host of environmental variables that influence methylmercury's formation, bioaccumulation, and effect on species. Research suggests sites adjacent to

waterbodies that have high organic matter and anoxic conditions may be more prone to mercury methylation, therefore these areas should be prioritized for further investigation. Methylmercury concentrations may also be high due the atmospheric deposition of mercury. Section 4.2 discusses monitoring ecosystems for methylmercury accumulation, which is arguably the best way to assess if an ecosystem has undesirable concentrations of mercury.

Another effect of mercury contaminated sites is their influence on atmospheric mercury. Soil bound mercury can convert to gaseous mercury, especially in the presence of sunlight and moisture, an effect that is strongest in the first 1-3 cm of soil depth (Mazur et al., 2015). Studies have found that the background mercury degassing rate for non-contaminated soils between 1.0 and 9.5 µg m^{-2} $year^{-1}$, a rate of 9.5 – 56.0 µg m^{-2} $year^{-1}$ for mineralized areas, and a rate of 180 µg m^{-2} $year^{-1}$ for tailings from the 1800s (Summarised in Lacerda & Salomons, 2012, p. 34). Thus, mercury is likely off-gassing from these gold mine sites in B.C. at above background rates, which would have some influence on local and global atmospheric mercury. While the contribution from B.C. gold rush era placer mines may be relatively small, Chapter 2 of the *Canadian Mercury Science Assessment* notes that legacy mercury emissions may account for up to 60% of total atmospheric mercury emissions, and their relative importance will increase as current sources of mercury emissions are controlled (Kos et al., 2016, p. 46).

4.2. Mercury monitoring in B.C.

The primary goal of public policy for mercury contaminated sites should be to reduce or eliminate risks to human and ecosystem health. The most straightforward method for accomplishing this is to monitor ecological receptors, such as fish, for total mercury concentrations, which will allow identification of problem areas and prioritization of remediation efforts. Remediation may require removing or sequestering mercury when local conditions indicate there is a problem.

For humans, Health Canada considers a maternal blood concentration of 8 µg/L mercury (2.0 ppm hair mercury) to be safe for fetuses (Legrand et al., 2010, p. 29). In contrast, the United States' Environmental Protection Agency (USEPA) cites 5.8 µg/L (1.5 ppm hair mercury) as a safe level for women of childbearing age (Mahaffey et al., 2009). However, there is some evidence that, because fetal mercury concentrations are

higher than maternal mercury concentrations, the even more conservative concentration of 3.5 µg/L (0.9 ppm hair mercury) should be used (Mahaffey et al., 2009).

In a survey of blood mercury concentrations in women throughout the United States between 1999 and 2004, Mahaffey et al, (2009) found that in the western United States, 5% of women had blood mercury concentrations in excess of the USEPA 5.8 µg/L reference. This number increased to 8.1% in coastal areas and was correlated with above-average fish consumption. Similarly, a 2019 wide-ranging health assessment in British Columbia found that of a population of 102 coastal First Nations women of childbearing age, 2.9% had hair mercury concentrations above 2.0 ppm, with no individuals having a hair mercury concentration above 6.0 ppm. In test groups from the Boreal Cordillera (n=22) and Montane Cordillera (n=47), no women had a hair mercury concentration higher than 2.0 ppm (Chan et al., 2019, p. 248). In contrast, a 1970 to 1992 survey of Indigenous people self-identified as high fish consumers in northern Canada found that 13.1% of Indigenous women of childbearing age had mercury concentrations in hair that exceeded 10 ppm (Wheatley & Paradis, 1995, p. 10). Thus, it appears that while some individuals have borderline mercury concentrations, there is not currently a major risk to First Nations women and their fetuses in B.C. However, the Wheatly & Paradis (1995) study showed that for Indigenous people eating traditional diets in areas with high levels of mercury in the ecosystem, some individuals may have mercury concentrations that put them at higher risk for mercury-related health issues.

To protect the health of Canadians, Health Canada, (2007) limits commercially sold fish to less than 0.5 ppm mercury, with three exempted species: shark, swordfish and fresh/frozen tuna. The general public is advised to limit their consumption of these three fish to one 150g meal per week, while pregnant women are advised to limit their consumption to one meal per month (p. 6). These limits are based on using 10 ppm hair mercury as a No Observed Adverse Effect Level, and an uncertainty factor of 5. The hair mercury level was converted to blood mercury concentration using a ratio of 250, and the amount of fish consumption required to reach the resulting blood mercury concentration of 8 µg/L was calculated. This resulted in a provisional Tolerable Daily Intake of 0.2 µg/kg-day. (Legrand et al., 2010). Thus, limits are based on total mercury consumption, and a single meal of 0.5 ppm fish would have a similar risk to two meals of 0.25 ppm fish.

Notably, these limits are based on surveys of fish consumption within the general population (Health Canada, 2007, p. 17), and do not consider diets based primarily on fish, which for some Indigenous people is as high as 226 kg/year, or 620 grams per day (Harper & Harris, 2008). At these high consumption rates, a safe concentration of mercury in fish would be 0.05 ppm or less, while fish with 0.1 ppm mercury would support a consumption of 100 – 454 grams per day (Harper & Harris, 2008, p. 64).

B.C. does not routinely monitor total mercury, methylmercury, or any other contaminants in fish, a defect noted by Justice Cohen during the Cohen Commission (Cohen, 2012, p. 322). The province claims that concentrations of mercury in fish are generally low, and that routine monitoring is unnecessary (FLNRO, 2019, p. 81).

B.C. currently has four fish consumption advisories for the province, issued because fish were found with concentrations higher than 0.5 ppm mercury. These advisories are for smallmouth bass from lakes on Vancouver Island and the Gulf Islands, lake trout and bull trout from the Williston Reservoir, lake trout from Pinchi Lake, and lake trout from Jack of Clubs lake (FLNRO, 2019). The latter three advisories have been in place for at least 25 years (Azimuth Consulting Group, 2019, p. 1), and are at sites where mercury contamination would be expected: Jack of Clubs lake is a few kilometers downstream of the Barkerville mining area, and had a gold mine immediately adjacent to the lake which operated from 1933 to 1966 (Azcue et al., 1995, p. 96). Pinchi Lake had an adjacent mercury mine which operated from 1940-1944 and from 1968-1975 (Crowley et al., 2018, p. 65). The Williston reservoir was originally part of the Peace River and was flooded by the Bennet Dam in 1968. Reservoirs are well known for high methylmercury concentrations in resident fish (see, for example, Mailman et al., 2006). Incidentally, there was also significant placer gold mining on the Manson and Germansen Creeks (British Columbia, 1875, p. 8) which were tributaries to the Peace River and later became tributaries to the Williston Reservoir.

A 2019 assessment of the fish consumption advisory on the Williston Reservoir noted that average concentrations of mercury in bull trout found in the study five times lower than 1980-2000 concentrations and are now near the concentrations of reference lakes used in the studies. However, mercury concentrations for specific species and size classes were *high* across Williston Reservoir *and all* the reference lakes, and the study authors reach the conclusion that “some form of mercury consumption guidance may be

warranted for large bull trout and lake trout, but the guidance should not be limited to fish from Williston Reservoir" (Azimuth Consulting Group, 2019, p V). Further, the study found that, according to Health Canada guidelines, women of childbearing age should not eat more than two meals per week of the larger lake trout or bull trout from any of the lakes in the study, which include Thutade Lake, Fraser Lake, Kootenay Lake, Takatoot Lake, Kloch Lake, Tezzeron Lake, and Thompson River (p.17). Other publicly available mercury testing data for B.C. is scarce, however there is an Environment Canada dataset collected between 2008 and 2014 as part of nation-wide program to monitor atmospheric mercury deposition. The two B.C. lakes in the study are Salisbury Lake which is north of Mission, and Frederick Lake, which is adjacent to the Huu-ay-aht First Nation reserve and near Bamfield, on Vancouver Island. Neither lake has known sources of mercury contamination in their watersheds. For Frederick Lake (n=80), there were a total of 39 Cutthroat Trout collected over 25cm, and these had mean mercury concentration of 0.65 ppm, and at least one fish each year had a mercury concentration greater than 1 ppm. For Salisbury Lake (n=36), the mean mercury concentrations of rainbow trout over 25 cm were 0.17 ppm.

The mercury concentrations reported by Azimuth Consulting Group and Environment Canada are found throughout western North America: a review of mercury concentrations in fish in watersheds across western North America found that 30% of sampled fish had mercury concentrations higher than 0.3 mg/kg wet weight (Eagles-Smith, Ackerman, et al., 2016, p. 1171). Similarly, in a review mercury concentrations in marine fish along the Pacific coast of North America, more than half of sites had a species of fish with an average mercury concentration higher than 0.30 mg/kg, and concentrations were relatively high in Puget Sound and the Californian Coast (Davis et al., 2016, p. 1146). The Davis et al. study was based on publicly available datasets and noted that they were unable to locate any such dataset for coastal British Columbia (p. 1153).

Importantly, any advice to reduce fish consumption must be balanced with the health and cultural benefits of traditional diets (Chan et al., 2019, p. 127). Consumption of fish is linked to better cardiovascular health (Kris-Etherton Penny M. et al., 2002), and better cognition in infants, with the best outcomes from women who ate higher amounts of low mercury fish (Oken Emily et al., 2005).

Mercury concentrations in salmon are relatively low. Commercial sockeye salmon between 2000-2010 had a mean mercury concentration of 0.034 ppm, while Atlantic salmon was 0.027 ppm. In contrast, commercially sold halibut, lingcod and rockfish had mean values of 0.257 ppm, 0.230 ppm and 0.192 ppm respectively (Kodama, 2011, p. 9). Thus, pregnant women would exceed Health Canada recommendations if they ate two or three meals per month halibut, lingcod, or rockfish from B.C.'s coast, or large predatory fish from B.C.'s lakes, and the general public should arguably not be eating more than two or three meals per week from these sources. Commonly, halibut of 10 to 15 kgs are targeted, so a single fish could provide eighty or more 150g "meals" for a household. Having easily available data on mercury, refined by water body and fish species, would empower people to make educated decisions on which fish species to choose, and how much to eat.

This idea is not radical. Alberta maintains a highly detailed and user friendly database on mercury concentrations of fish throughout the province (*AEPHIN Mercury in Fish Testing*, n.d.), and has developed an app called "Should I Eat This Fish" to assist consumers in making educated choices. Saskatchewan publishes and periodically updates a report that has fish consumption guidance for hundreds of lakes in the province (Government of Saskatchewan, 2015). Ontario maintains an online database of mercury in fish at over 2400 locations (Ontario MECP, 2017).

With the crashing of the sockeye salmon stocks, an important source of healthy, low mercury fish, consumption patterns among the Indigenous and settler populations in B.C. may shift to include more lake trout, bull trout, pike, halibut, lingcod and rockfish. B.C. is at an inflection point and should both monitor mercury and work hard to protect salmon, an incredibly valuable and important resource. In the words of Jun Ui, "Our largest task is to prevent the onset of disease before the discovery of typical victims." (Ui, 1975, as cited in (D'ltri & D'ltri, 1978, p.13). A provincial testing regime in British Columbia that monitored upper trophic levels for mercury, PCBs and other contaminants of concern, as called for in the Cohen Commission, would be a positive and proactive step towards ensuring the health of humans and ecosystems in the province.

4.2.1. Further Research

Further research questions and improved methodologies include:

1. Test biological receptors in downstream ecosystems for mercury.

2. Increase access to mine sites by using water-based transportation.

3. Test samples for gold as well as mercury to ensure that control samples are representative of material targeted by miners.

4. Conduct grain-size analysis, and test mercury concentrations at various grain sized, to assist in characterization of mercury mobility.

5. Locate and map the gold-rush era mine sites in other regions in B.C.

6. Test mine sites in other regions (for example, the Atlin region) for mercury hotspots.

7. Conduct further research into historical mercury imports and production, and build an understanding of what portion of these imports were lost to the environment due to mining

8. Further and more extensive sampling of mine sites could help determine:

   - the three-dimensional extent of mercury contaminated soil within a mine site;
   - if mercury at individual sites is entering the ecosystem, or if it is sequestered on the mine site;
   - the potential for erosion, both currently and with changing climatic conditions; and,
   - if correlations exist between mercury contamination, mining methods, time period of mining, and structures within a mine site, which would require testing a larger group of mine sites across regions.

4.3. Recommendations

Monitor mercury concentrations in fish

The monitoring of mercury contamination in B.C.'s food fisheries is in state of dire neglect. Lakes in B.C. are not routinely monitored for mercury concentrations in fish, and this issue has been ignored by government, non-governmental organizations and academics, while First Nations generally focus on mercury concentrations in their local areas. There has been no province-wide call for adequate monitoring. In contrast, Alberta, Ontario, and Saskatchewan frequently test fish for mercury concentrations, and maintain comprehensive, easy to access databases where First Nations, recreationists,

commercial fishers, and sustenance harvesters can quickly and easily access information on mercury concentrations. B.C. should follow suit.

Consider inclusion of legacy placer mine sites in "Crown Contaminated Sites Program"

B.C. has created the "Crown Contaminated Sites Program" which manages contaminated sites that have reverted to provincial responsibility. The program spent $60 million between 2014 and 2019 on 87 orphaned mine sites, none of which are legacy placer mines. (Forests, Lands, Natural Resource Operations and Rural Development, 2018; Legislative Assembly of British Columbia, 2019). There are over 1000 other sites of interest (MiningWatch Canada, 2017). I have not found legacy placer mines on either the provincial or federal registries of contaminated sites, so it appears that these sites are not currently being considered for remediation. Mine sites that meet the risk factors outlined in Section 4.1 should be assessed to determine their effect on local ecosystems, if any.

Ban use of mercury in current placer mining in Canada

This research considered gold-rush era placer mining; however, B.C. does not ban mercury use in modern day placer mining. Rather, tailings may only be deposited if mercury was not used in processing (Placer Mining Waste Control Regulation, 1989). Commonly, fine gold collects with other heavy minerals, resulting in "black sand." In other jurisdictions, miners use mercury to process this black sand. Such use should be explicitly prohibited by B.C.'s laws.

Moratorium on all current placer mining activity that overlaps legacy placer mines

While further work is required to investigate the severity of mercury contamination from legacy placer mines, a cautionary approach would call for the halt of any re-mining of legacy placer mines, which is currently a common practice. This would prevent mercury sequestered on a site from being mobilized by mining activity and entering the ecosystem.

Prioritize remediation high risk sites

The province should focus on sites with a high potential for erosion, especially those near lakes or dammed areas that are at higher risk for mercury methylation.

Create a fund to remediate legacy placer mine sites

B.C. has a B.C.'s Orphan Site Restoration Levy, which requires permit holders for oil and gas sites to pay a levy for the restoration of orphaned sites that is based on the total liability of the permit holder (*Oil and Gas Activities Act*, SBC 2008, c36, S. 47). A similar program could be created where current placer miners pay into a reclamation fund for remediating legacy placer mines.

Backstop current placer miners to remove mercury

Mercury can be removed from soil or sediment, along with gold, using the same low-tech sluice boxes that placer miners have been using for hundreds of years (Fleck et al., 2010). To encourage remediation of legacy placer mines, the province could develop protocols for safely removing mercury and encourage the re-mining of legacy placer mines, perhaps by backstopping the operations so that placer miners retain any profits they make from gold production, but would not lose money if their efforts only resulted in the removal of mercury. Such a program would have to be done in close consultation with First Nations and environmental professionals to ensure that re-disturbing mine-sites did not cause more harm than benefit to sensitive riparian habitat.

4.4. Conclusion

This study investigated gold-rush era mercury contamination at mine sites in the Fraser Basin, and found some samples that had concentrations of mercury above background concentrations, but below national soil contamination guidelines. These results suggest that mercury use was widespread during British Columbia's Fraser and Cariboo gold rushes. This study also used the historical record to estimate the total amount of mercury that may have been lost to the environment in the Fraser Basin. Using one set of gold extraction data for the Cariboo resulted in a mercury loss estimate of 86,990 kg to 247,665 kg for mines operating in the Cariboo from 1860 to 1924. A different gold extraction dataset for the Fraser Basin from 1858 to 1909 resulted in a mercury loss estimate of 17,768 kg to 48,113 kg. Mercury import data showed that 26,749 kg mercury was shipped to B.C. from California between 1860 and 1883, and this appears linked to mining activity. Mercury imports into Canada between 1882 and 1899 exceeded expected requirements for mercury amalgamation practices. Mercury in fish tissue is not routinely monitored in B.C., and this study further illustrates that this basic public and environmental health monitoring measure should be implemented in this province.

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Appendix A Mine test sample descriptions and results

Sample ID	Sample Type	Total Hg (mg/kg)	Longitude	Latitude	Depth (cm)	Sediment Description	Sample Location Description
BB 01	Test	0.544	-122.111642	51.176431	30	sand and gravel	slope with random piles of cobble about 1.5-3 meters across, sampled depression between cobble piles
BB 02	Test	0.03	-122.107279	51.176307	30	sand and gravel	top of tailings mound, possible end of sluice run
BB 03	Test	0.0845	-122.108025	51.176423	30	sand and cobbles	area of cobbles, possible sluice run path
BB 04	Test	0.0385	-122.109204	51.175974	30	fine sand and silt	flat are between 3 mounds, possibly bulldozed
BB 05	Test	0.888	-122.111138	51.176668	30	sand and gravel	top of probably hydraulic tailings pile
BB 06	Test	0.608	-122.111572	51.177571	30	silt and clay	middle of modern mine settling pond
BB 07	Test	0.0374	-122.1129	51.177607	30	fine sand and silt	between cobble piles, top of hydraulic slope
BBC 01	Control	0.0236	-122.111838	51.178645	30	sand	unmined sand bank adjacent to mine site
BBC 02	Control	0.0294	-122.113263	51.178271	30	sand and gravel	unmined rock and cobble bank adjacent to mine site
BBC 03	Control	0.0483	-122.106992	51.176874	15	fine sand and silt	side of compact sand outcropping
BD 01	Test	0.0459	-121.508663	53.080462	30	coarse sand and gravel	vegetated gravel bar 50 cm above water level
BD 02	Test	0.0607	-121.508663	53.080462	5	sand	on river's edge, beside BD 01 gravel bar
BD 03	Test	0.137	-121.508663	53.080462	30	sand and gravel	riverbank tailings pile, recently worked
BD 04	Test	0.0305	-121.509177	53.080314	30	sand, silt and gravel	90 m from Williams Creek, in recently worked tailings
BP 01	Control	0.0693	-121.637588	52.626071	10	sand and gravel	north-east side of canyon,

BP 02	Test	0.142	-121.637314	52.625468	0	sand and gravel	tailings pile, possibly side of sluice run, middle of canyon
BP 03	Test	0.212	-121.637314	52.625468	35	sand and gravel	between tailings piles, possibly a sluice run, recent machine tracks, approx. 8-11 years ago, estimated using tree rings
BP 04	Test	0.131	-121.637964	52.625913	10	sand and silt	possible sluice run discharge center of flat, mossy area
BP 05	Test	0.115	-121.637964	52.625913	45	sand and silt	possible sluice run discharge center of flat, mossy area
BP 06	Test	0.146	-121.638097	52.626031	45	sand and gravel	downstream end of flat, mossy area, 125 cm below mossy surface, 45 cm below recently excavated surface
BP 07	Test	0.207	-121.63969	52.627176	5	silt and clay	downstream of previous samples, mud shelf above wet, swampy area
BP 08	Test	0.106	-121.63969	52.627176	10	silt and clay	same as BP 07
BP 10	Test	0.324	-121.643509	52.629830	10	silt and clay	combo sample from stream bed
BQ 01	Test	0.418	-121.64106	52.632585	30	sand	small beach 30 m downstream of outlet of canyon mouth, 2 m from Quesnel River
BQ 02	Test	0.836	-121.64106	52.632585	40	silt and clay	inland of BQ 01 approx. 5 meters, in between abandoned road and riverbank fortification
BQ 03	Test	0.238	-121.64106	52.632585	10	clay	same hole as BQ 02, clay layer near surface
BQ 04	Test	0.936	-121.64106	52.632585	55	silt and clay	same hole as BQ 02, odd sulfur/metallic smell
BQ 06	Test	0.181	-121.641246	52.631905	5	silt and clay	conglomerated sample from 4 places along mine blow out
EC 1	Test	0.0611	-121.415986	49.51473	30	sand	possible rocker box mound

EC 2	Test	0.0824	-121.416136	49.514539	20	sand, silt and clay	possible rocker box depression
EC 3	Test	0.126	-121.414965	49.51394	30	sand, silt and gravel	tailings pile at end of sluice run
EC 4	Test	0.454	-121.415221	49.514066	25	sand and silt	depression in sluice run, west of EC 03
EC 5	Test	0.208	-121.41452	49.514148	30	sand, silt and gravel	bottom of tailings pile at high water line
EC 6	Test	0.0822	-121.415047	49.514128	40	sand and gravel	top of cobble pile beside sluice run, under cobbles
ECC 1	Control	0.0397	-121.423753	49.516656	30	sand and silt	North side of logging road in undisturbed forest uphill of mine site
ECC 2	Control	0.066	-121.423727	49.516529	30	sand and silt	South side of logging road in undisturbed forest uphill of mine site
ECC 3	Control	0.0255	-121.443017	49.561288	30	sand and gravel	bank below hydro lines near Yale
FB 01	Control	0.019	-121.730767	50.507991	35	sand	30 meters upslope from possible sluice, no visible signs of mining at sample location
FB 02	Test	0.0747			30	sand	strange rock ring arrangement, possibly a burn pit, north of mined area indicated by Kennedy
FB 03	Test	0.0313	-121.731856	50.507083	5	sand	possible sluice run or path, 1 m lower than observed highwater tree line, between boulders
FB 04	Test	0.0312	-121.727959	50.503064	5	clay and sand	bottom of possible sluice run at intersection of feature and river's high water, from under multiple cobbles, clay at surface under cobles
FB 05	Test	0.03	-121.727959	50.503064	35	sand	upper end of possible sluice run below high-water line

FB 06	Test	0.0286			35	sand	bottom of possible sluice run, sample from hole dug under large cobble
LL 01	Control	0.0796	-121.919903	50.705871	30	sand and gravel	unmined scree slope on side of possible sluice run
LL 02	Test	0.342			25	sand and gravel	combined sample from 3 sites in sluice run, 10 m inland of sluice tailings pile
LL03	Test	3.82			40	sand and gravel	top of tailings pile at end of sluice run
LL04	Test	0.464			35	sand and gravel	side of tailings pile, just above river high water mark
MG 01	Test	0.15	-121.517829	53.043858	20	coarse sand and gravel	bottom of possible sluice run, possibly reworked
MG 02	Test	0.0174	-121.517504	53.044166	30	coarse sand and gravel	possible tailings pile below assumed sluice run
MG 03	Test	0.0129	-121.519365	53.04332	30	silt, sand and gravel	top of gulch, in large tailings pile on north side of creek
MG 04	Test	0.006	-121.518392	53.043994	30	coarse sand and gravel	beside coble pile on north slope, possible end of sluice run
MG 05	Test	0.0526	-121.516581	53.04419	30	clay, silt, sand and gravel	top of tailings pile near confluence of creek draining mink gulch and William's creek.
MG 06	Test	0.0115	-121.516581	53.04419	5	sand and gravel	under cobbles where creek meets gulch
MGC 01	Control	0.0076	-121.518194	53.043226	30	silt, clay and gravel	south slope of mink gulch hill side, scree slope, 8m down from original grade
MGC 02	Control	0.0143	-121.518082	53.043265	30	coarse sand and gravel	same slope as MGC 1, 0.5m below original grade
MGC 03	Control	0.0184	-121.519253	53.043212	30	coarse sand and gravel	mid height on scree slope on north side of gulch, 25m below original grade

MGC 04	Control	0.014	-121.51424	53.07641	5	sand and gravel	in a possible diversion ditch, taken from creek bed, behind Government Hill campground. formerly coded BCC 01
MH 01	Control	0.0257	-121.884598	50.752584	30	sand and gravel	5 meters from top north edge of hydraulic face
MH 02	Test	0.0417	-121.884853	50.75213	10	silt and clay	flat area below hydraulic face appears to be ephemeral water pooling. Surface dry and caking
MH 03	Test	0.0293	-121.885190	50.752384	0	sand and silt	under top of broken ramp
MH 04	Test	0.0511	-121.885190	51.752384	30	sand and silt	deeper in same hole as MH 03
MH 05	Test	0.0235	-121.885484	50.752175	10	sand and gravel	under boulder, possible ground sluice
MH 06	Test	0.0985	-121.885484	50.752175	25	sand and gravel	deeper in same hole as MH 06
MH 07	Test	0.0392	-121.886046	50.75154	10	silt and clay	drying pool below highwater, below mine site
MH 08	Test	0.0261	-121.886046	50.75154	30	silt and clay	drying pool below highwater, below mine site
MH 09	Test	0.029	-121.885818	50.751509	10	silt and clay	drying pool below highwater, below mine site
MS 01	Control	0.0441	-121.885694	50.755795	40	sand and gravel	uphill of cabins, 10 m uphill of sluice run
MS 02	Test	0.106	-121.885908	50.755815	10	sand and gravel	under cobbles of sluice run
MS 03	Test	0.117	-121.885908	50.755815	35	sand and gravel	under cobbles of sluice run, same hole as MS 02
MS 04	Test	0.268	-121.886185	50.7558	40	sand and gravel	assumed end of sluice run
MS 05	Test	0.854	-121.885808	50.755767	30	sand and gravel	under miner's cabin floor
MS 06	Test	0.0326	-121.886486	50.755712	30	sand	where sluice meets river

MS 07	Test	0.0385	-121.886486	50.755712	10	sand	under rock, where sluice meets river
OB 01	Test	0.926	-121.915619	50.709062	30	sand and gravel	top of tailings pile at bottom of possible sluice run
OB 02	Test	0.49	-121.915514	50.708956	30	sand and gravel	side of tailings pile, just above high-water mark
OB 03	Test	0.125	-121.915897	50.708714	40	sand and gravel	top of tailings pile, one pile south of OB 2
OB 04	Test	1.16	-121.916348	50.70893	30	sand, silt and gravel	bottom of hydraulic trench, same line as OB 3
OB 05	Test	0.959	-121.916945	50.708885	30	sand, silt and clay with gravel	confluence of two trenches lined with large, hand-stacked boulders
OBC 01	Control	0.0966	-121.916809	50.7101	30	sand, silt and gravel	5 meters uphill of bank above Old Bridge Rd. and mine site
OBC 02	Control	0.0408	-121.916938	50.709863	30	sand and silt	in road cut on west side of Old Bridge Rd
PH 01	Test	0.0422	-122.511092	52.990307	30	sand and silt	knoll at inland side of mined area, possibly un-mined
PH 02	Test	0.0823	-122.51089	52.99006	30	coarse sand	bottom of assumed sluice run, between two rows of cobbles
PH 03	Test	0.132	-122.51089	52.99006	40	fine sand	deeper in same hole as PH 02
PH 04	Test	0.321	-122.51096	52.99015	10	silt and clay	two rows north of PH 02, under big cobbles
PH 05	Test	0.05	-122.51041	52.99015	30	sand and silt	towards river in same row as PH 02 & 03,
PH 06	Test	0.0545	-122.51041	52.99026	15	sand and gravel	where sluice meets riverbank, sample taken in unworked sediment with visible stratification below worked sediment
PH 07	Test	0.0851	-122.51041	52.99026	15	clay and silt	30 m above PH 06 in the cobbles from the sluice run. Sample taken from clay and silt around boulders.

PHC 01	Control	0.071	-122.511196	52.990223	30	sand and organic matter	15 meters inland of mined rows of cobbles
PHC 02	Control	0.0589	-122.511144	52.990308	30	sand and organic matter	15 meters inland of mined site, 6 m south of PHC 01
PHC 03	Control	0.0548	-122.511798	52.990071	30	sand, organic matter and gravel	50 meters inland of mine site
RF 01	Test	0.0134	-121.520149	53.051917	20	coarse sand and gravel	upstream of possible sluice run, just below old Richfield townsite. Underneath cobbles at high water mark
RF 02	Test	0.0104	-121.520149	53.051917	20	coarse sand and gravel	ledge 3 m from creek, 1/2 meter above water
RF 03	Test	0.165	-121.520496	53.051962	30	sand, silt and clay with gravel	tailings pile at end of possible sluice run
RF 04	Test	0.0497	-121.520496	53.051962	30	sand, silt and clay	bottom of possible sluice run
RF 05	Test	0.558	-121.520496	53.051962	30	sand, silt and clay	tailings pile beside possible sluice run
RR 01	Test	0.0556	-122.529404	53.030344	5	silt and clay	shore of pond, beside water's edge,
RR 02	Test	0.024	-122.529591	53.030176	30	sand and gravel	top of possible tailings ridge
RR 03	Test	0.0405	-122.529812	53.029667	15	silt and clay	inside of river influenced bar, below the pond sampled by RR 01, erosion layer of clay
RR 04	Control	0.0411	-122.527406	53.029446	15	sand and gravel	top of river slope, just below bench with houses
SS 01	Test	0.104	-122.202962	52.816344	30	sand, silt and clay	bottom of possible hydraulic hill, possible sluice run
SS 02	Test	0.0691	-122.202712	52.816466	30	sand and silt	mound approximately 8 x 15m, on river side of mined area

SS 03	Test	0.0428	-122.20508	52.816851	30	sand and silt	below hydraulic workings, possible sluice run. Slight mounding between sample site and river
SS 04	Test	0.0475	-122.204952	52.816828	30	sand and silt	at edge of steep bank eroding into the river
SS 05	Test	0.0661	-122.203873	52.81662	15	coarse sand and gravel	below hydraulic working, at water line of river, beneath cobbles
SSC 01	Control	0.0365	-122.203039	52.816166	30	sand, silt and clay with gravel	top of bench, just inland of mined bank
SSC 02	Control	0.0519	-122.207667	52.817501	30	sand and gravel	down river of mine site, between main road and steep banks down to river
SSC 03	Control	0.019	-122.207216	52.81675	30	coarse sand, fine sand and gravel	south side of Quesnel Hydraulic Rd.
WC 01	Test	0.0356	-121.522814	53.05918	20	coarse sand and gravel	within riverbed, below cobble piles

Appendix B

Selected Maps of Mine Sites Sampled

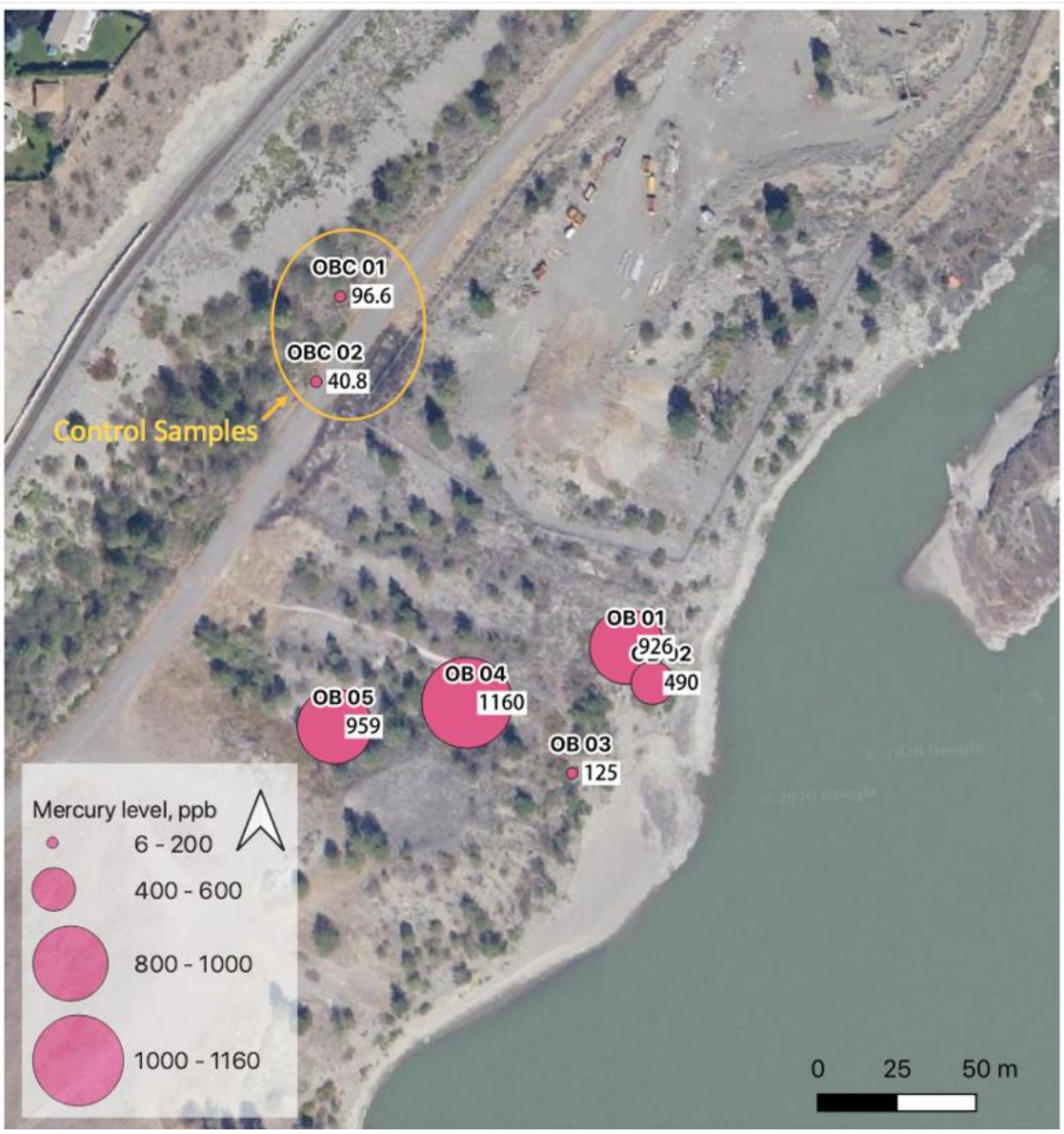

Figure B.1 **Sample locations and tHg values in ng/g, equivalent to ppb, for the Lillooet Hydraulic Mining Company site**

Figure B.2 Sample locations and tHg values in ng/g, equivalent to ppb, for the Fountain Bar Sluice site

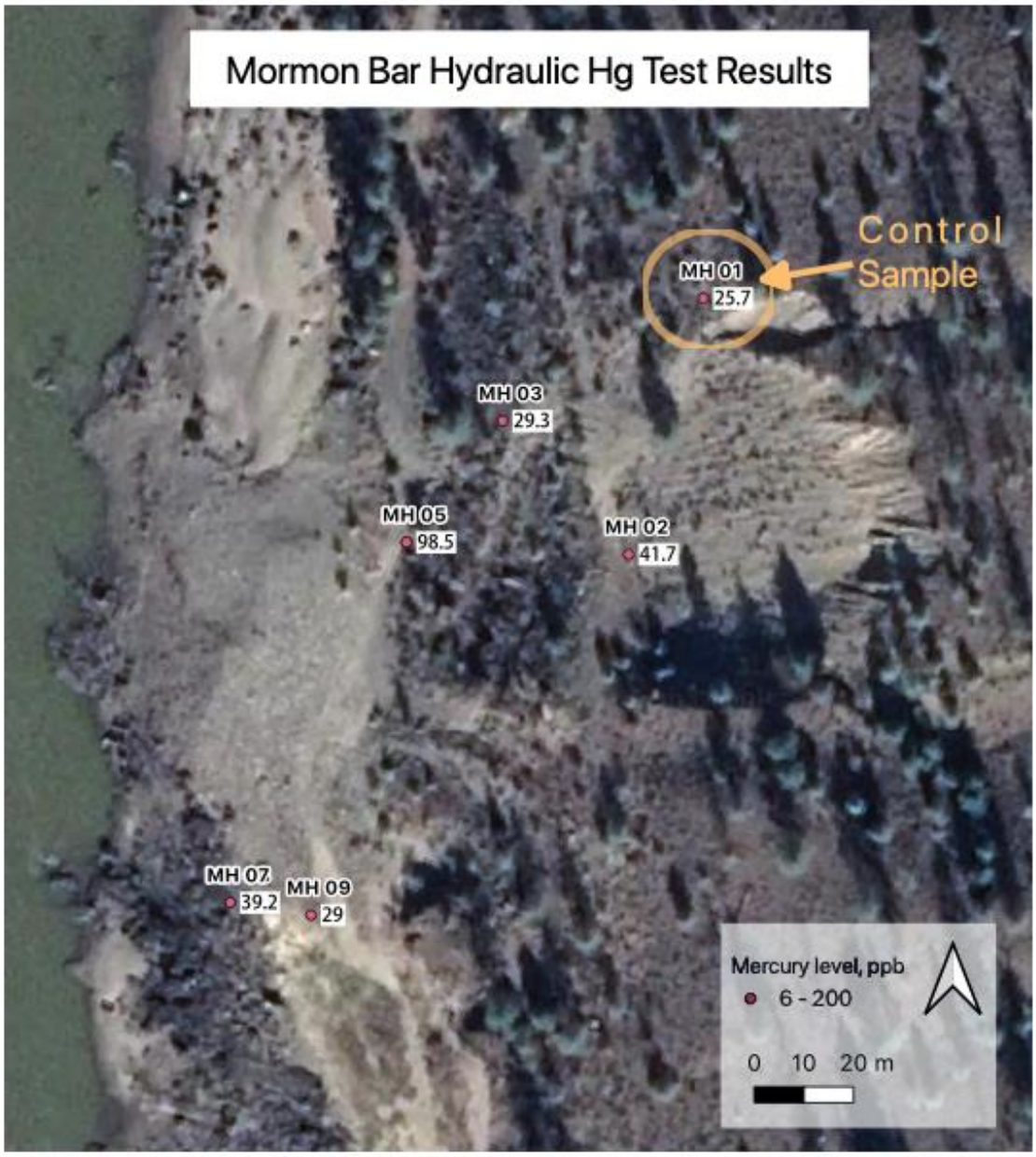

Figure B.3 Sample locations and tHg values in ng/g, equivalent to ppb, for the Mormon Bar Hydraulic Mining Company site