Sä DENA HES MINE SITE: TEASING-APART MINING-RELATED VERSUS NATURALLY ELEVATED METALS CONCENTRATIONS IN ENIVORNMENTAL MEDIA – IMPLICATIONS FOR RISK MANAGEMENT

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ABSTRACT

The Sä Dena Hes Mine is a former lead-zinc mine near Watson Lake, Yukon Territory operated for only 16 months in the early 1990s. After operations ceased, the property was acquired by the Sä Dena Hes Operating Company, of which Teck Resources Limited was the operating partner. Between 2013 and 2015, site characterization and ecological and human health risk assessments were undertaken to support permanent closure of the site. During the course of sampling, highly elevated concentrations of cadmium, lead and zinc were observed in inorganic soil and even more so in organic soils (2 – 4x higher than inorganic) downgradient of waste rock areas, especially in the '1380 Gully'. This gully is downgradient of the 1380 adit, directly adjacent to the main mineralized zone. Similarly, lead and zinc were highly elevated in willow and alder twigs (10 – 60 ppm dw vs <1 in reference), ground invertebrates (50 – 125 ppm vs < 2 in reference) and small mammals (10 – 45 ppm vs <1 in reference) in this area, posing elevated ecological risks. Human health risks were also identified in this area from elevated metal concentrations in soils (direct contact) and plants/small animals (consumption). Initially it was assumed that undisturbed areas adjacent to metals-contaminated areas were contaminated via aeolian and/or aquatic pathways from mine sources. Subsequent step out sampling revealed that this trend was also observed in well forested, undisturbed areas beyond the gully. Geochemical investigations confirmed that concentrations and ratios of Pb:Zn in inorganic soils of these areas were characteristic of mineralized zones. Enriched concentrations and different Pb:Zn ratios of organic soils by cationic metals (Cd, Cu, Pb, Zn) was the result of uptake by plants and adsorption into A horizon soils that likely occurred over centuries. These lines of evidence concluded that while mining-related activity may have been a minor contributor, it was not primarily responsible for elevated metal concentrations in the 1380 Gully area. This has significant implications for risk managers when directing remedial efforts and communicating residual risks to regulators, First Nations and other stakeholders.

INTRODUCTION AND BACKGROUND

Azimuth Consulting Group Partnership (Azimuth) was commissioned by Teck Resources Limited (Teck) to conduct Human Health (HHRA) and terrestrial and aquatic Ecological Risk Assessments (ERAs) for the Sä Dena Hes Mine near Watson Lake, Yukon Territory (YT). This zinc-lead mine was operated by Curragh Resources Inc. for only 16 months (August 1991 – December 1992) and then was put into care and maintenance. Teck purchased the property in April 1994, as part of a joint venture, but since 2000 it has been in temporary closure. The HHRA and ERA documents were intended to support Teck's Detailed Decommissioning and Reclamation Plan (DDRP) guiding permanent mine closure and meeting requirements under the Site's Water Licence and Quartz Mining Licence.

ERA is an iterative and on-going process that evaluates the likelihood and magnitude of adverse effects to ecological resources (e.g., plants, invertebrates, birds, mammals) as a result of exposure to multiple, usually chemical, stressors. ERA was used here to support Teck's decision-making during remediation of terrestrial portions of the mine site, guiding and resulting in some revisions to the DDRP. Implementation of the DDRP involved the sealing of adits, grading steep slopes, draining, covering and revegetating the large (29 ha) Tailings Management Facility (TMF), demolition and removal of all site buildings, risk managing hydrocarbon contaminated areas, removing contaminated soils from discrete areas and in some cases, depositing contaminated soils in mine shafts. As well, Azimuth undertook an aquatic ERA, to examine potential health risks to humans that may use the site in the future. The mine site was within the traditional territory of the Liard First Nation and Ross River First Nation and is used for hunting and gathering.

Figure 1. Map showing location of Sä Dena Hes Mine, near Watson Lake, Yukon Territory

Situated in a wildland setting, the Sä Dena Hes Mine (419 ha surface lease) is located within the Boreal Cordillera Ecozone and the Liard Basin Ecoregion. Native vegetation consists predominantly of coniferous forest dominated by white spruce and subalpine fir with occasional lodge pole pine. Balsam poplar, willow and trembling aspen are common near water courses. The Site straddles a drainage divide between the False Canyon Creek and Tom Creek catchments, both of which ultimately drain into the Liard River. The headwaters of False Canyon Creek begin via a spring on the property at "Camp Creek"; which is fishless until about 10 km downstream where it joins False Canyon Creek to flow towards the Liard River.

GOALS AND OBJECTIVES

The main goal of the ERA was to support the DDRP and 'reclaim the land' with a long-term objective of ensuring that ecological resources and humans are protected from exposure to residual metal contamination. To achieve this, features such as soil covers have been applied over disturbed areas of the Site to achieve both "reclamation" and/or "remediation" goals. Reclamation aims to restore the land to a "natural" (pre-mine) state by providing a growth medium for vegetation, while the remediation goal is to provide a growth medium for vegetation to eliminate or reduce exposure of receptors to underlying contaminants over the long term. The remediation cap thickness was designed to be sufficient enough to cut the exposure pathways driving potential risks, creating a permanent physical barrier between plants, animals, and the underlying contaminated media and preventing contaminants from migrating upward through the cap. Different cap thicknesses were allocated to different parts of the mine site depending upon elevation, vegetation type and expected use by different receptors.

There were, however, several challenges that faced the team which made achieving the reclamation / remediation goals difficult. Several areas around the Mine Site including the 1380 Gully area are quite remote and steep, which made recovery of waste rock areas difficult or impossible due to stability hazards. As well, the mine had not operated for many years so there was natural recovery in some areas and Teck never operated the mine, so there was a lack of some background information. We found that metals concentrations in some native areas adjacent to mining-disturbed areas were highly elevated, and in some cases, higher than on mining-disturbed lands. Thus, the question of 'where to draw the line' when undertaking remedial works was uncertain. ERA results showed that there were some undisturbed areas, such as downgradient of some waste rock piles, where predicted risks to some birds and mammals were high or "unacceptable", even if all disturbed lands upgradient of the wildlands were remediated. One of the largest and most problematic areas is known as the 1380 Gully, which is adjacent to the 1380 Adit, west of the Main Zone and Jewelbox pits (see Figures 2 and 3).

This paper addresses how this uncertainty was investigated in order to achieve consensus on remediation between Teck, the various regulatory agencies and First Nations. Ultimately, this investigation influenced the extent of remediation required by Teck to address ecological risks and human health risks in some areas. Continued risk management involving communication with respect to long-term utilization of site resources was required for other parts of the site to address human health risks.

OVERVIEW OF THE MINE SITE AREAS OF ENVIRONMENTAL CONCERN (AECs)

Areas of Environmental Concern (AEC) were identified and delineated based primarily on soil metals concentrations gathered by Golder Associates as part of their Environmental Site Assessment (ESA). Nine AECs were identified, the most important of which were the principal ore extraction areas Jewelbox (AEC 1) and Main Zone (AEC 9) areas (including the 1380 adit and 1380 Gully [AEC 9.4]), Burnick Zone (AEC 2, exploratory, but never mined), Mill Site and ore processing area (AEC 3) and the Tailings Management Facility (AEC 8) (Figure 2).

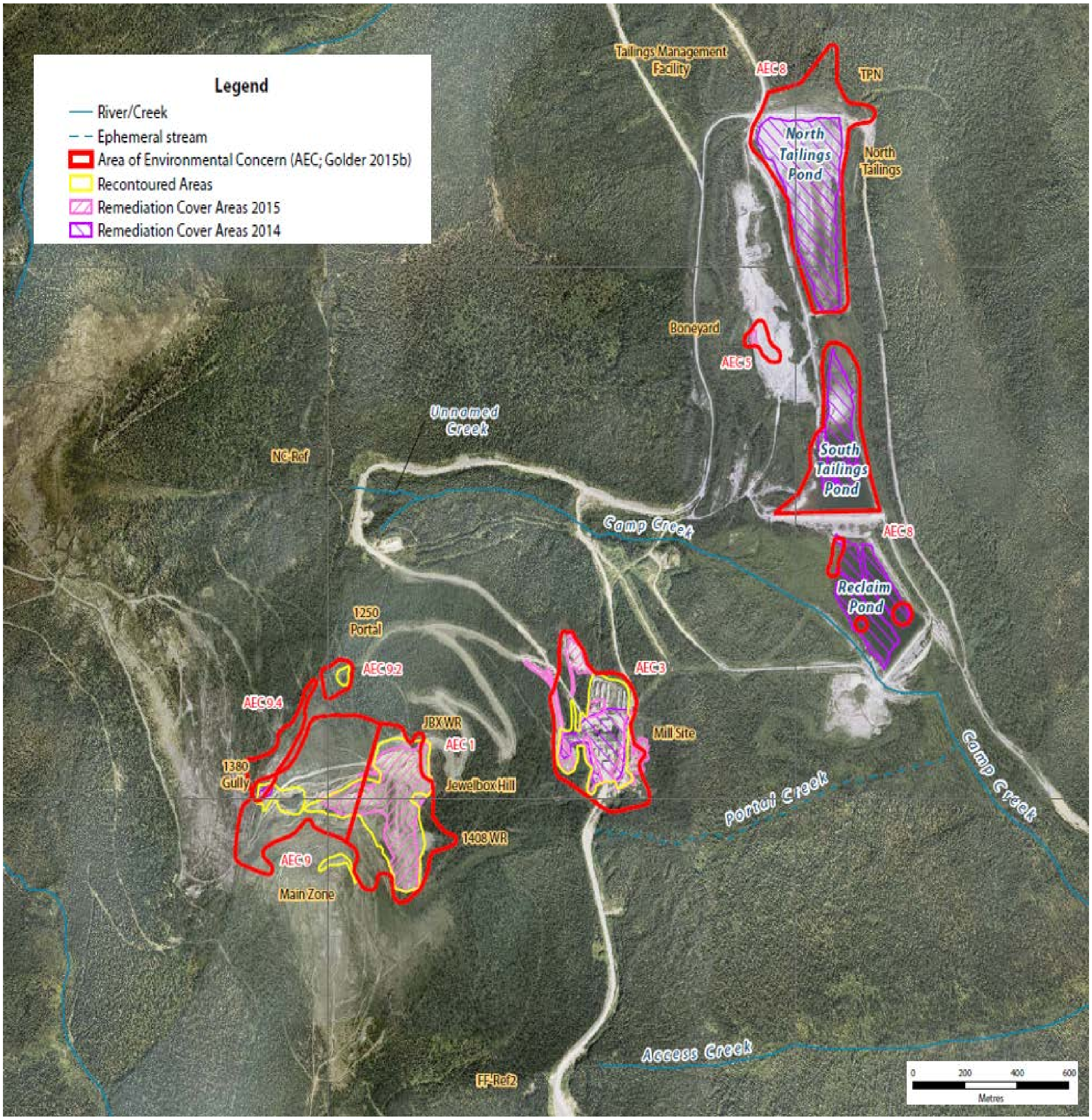


Figure 2. Location of main AECs at Sa Dena Hes; 1380 Gully is AEC 9.4

The contaminants of potential concern (COPCs) identified for the terrestrial ERA for each of these areas are as follows:

Area (AEC)	Contaminants of Potential Concern*
Jewelbox Hill (AEC 1)	Arsenic, cadmium, copper, lead, molybdenum, nickel, selenium, zinc
Burnick Zone (AEC 2)	Arsenic, cadmium, lead, nickel, selenium, zinc
Mill Site (AEC 3)	Arsenic, lead, molybdenum, nickel, selenium, zinc
Boneyard (AEC 5)	Arsenic, copper, molybdenum, nickel, selenium, vanadium
Tailings and Reclaim Ponds (AEC8) (after capping)	Lead, selenium, zinc
Main Zone (AEC 9) including 1380 Gully, Waste Rock areas	Antimony, arsenic, cadmium, lead, molybdenum, selenium, silver, vanadium, zinc

*Hydrocarbon COPCs identified in some AECs were risk managed by applying 0.6m soil covers.

AECs 1 and 9 (AEC 1/9) were assessed as a single area in the ERA, due to the overlapping nature of contamination. Using soil data representative of site conditions, the final list of COPCs carried into the ERA was antimony, arsenic, cadmium, copper, lead, molybdenum, selenium, silver, vanadium, and zinc.

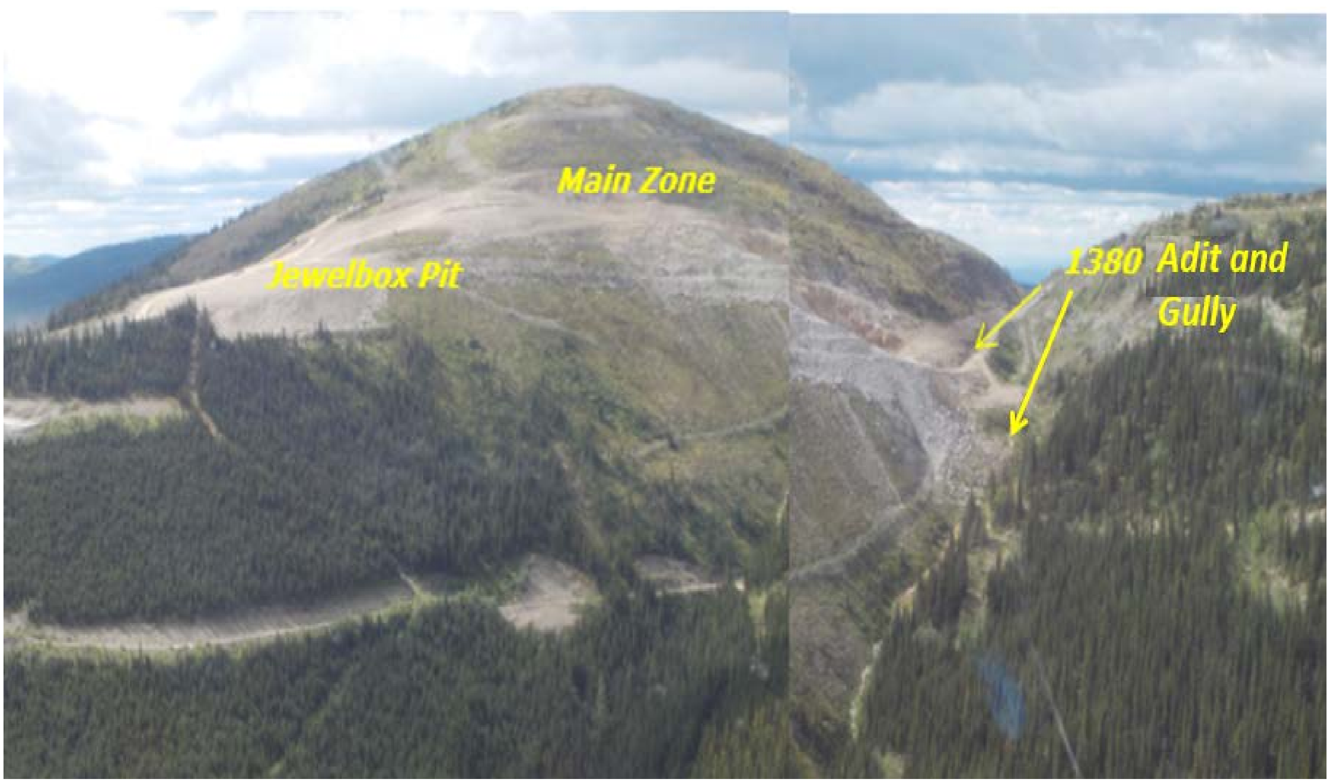


Figure 3. Looking south towards the 1380 Adit and Gully, flanked by the Main Zone pit to the east and Mt. Hundere to the west.

METHODS

Over the course of 2012 – 2015 a large amount of metals data was collected from within and outside of each of the main AECs, as well as two off-site reference areas within the same geologic area and elevation as the Site. COPC concentrations were contrasted within and between AECs as well as against reference area conditions. The terrestrial environmental media sampled included the following:

Soils – In disturbed areas of the AECs, surface soils (top few cm) were collected for analysis of metals and in some cases, hydrocarbons. In forested or vegetated areas where there was an organic soil cover at least 2-3 cm thick, discrete samples were collected from A-horizon and underlying B-horizon mineral layers, to define metal concentrations between the two layers to more accurately represent what terrestrial organisms are primarily exposed to in their diet.

Vegetation – Willow (*Salix* sp.) and alder (*Alnus* sp.) were the most common and abundant vegetation species consumed by mammals. These species were present at nearly all locations and were expected to be most abundant during post-closure conditions. During most of the year, resident moose and snowshoe hare consume the shoots and twigs of willow and alder respectively. Twigs were analysed for metals to determine exposure via the principal dietary items of these species. Metal concentrations in fecal pellets from moose and hare from overwintering habitats were also analysed and correlated with soil and vegetation metals to determine exposure.

Soil invertebrates – Pitfall traps were set within or immediately adjacent to each AEC to collect ground invertebrates, mostly beetles, spiders, ants, thrips and earwigs for analysis of total metals.

Flying invertebrates – Malaise traps were set at each location and collected a wide variety of flying insects (black flies, mosquitos, true flies, chironomids, wasps, moths) for analysis of total metals as means of estimating exposure to birds.

Small mammals – Two small mammal species were targeted for capture – the carnivorous dusky shrew (*Sorex monticolus*) and the omnivorous northern red-backed vole (*Myodes rutilus*). Snap-traps and pitfall traps were set within each AEC and whole animals were analysed for total metals to measure dietary exposure to higher organisms (carnivorous birds, raptors, lynx, marten, wolverine).

RESULTS AND DISCUSSION

Risks to ecological receptors were evaluated following Yukon Contaminated Sites Regulation (CSR) protocols as well as guidance developed by Environment Canada (EC 2012) and BC Science Advisory Board (SAB 2008). While risks to some receptors (e.g., plants) were evaluated by direct field evaluations, others (higher trophic mammals, birds) were evaluated indirectly using a food chain model to integrate metals chemistry from all environmental media (soil, water, vegetation, invertebrates, small mammals) with information on habitat quality and feeding preferences to predict exposure and potential effects from foraging on the Site. Terrestrial and flying invertebrate communities may be exposed to contaminants in soil or water and were evaluated by assessing the ecological function (biomass) of the invertebrate community as food for wildlife. Seventeen bird and 16 mammal species, including both common and rare or endangered ("listed") species, were evaluated in the ERA. The selection process targeted species with different foraging niches and included plant-eaters such as dark-eyed junco and hoary marmot, insect-eaters such as barn swallow, Wilson's warbler and common shrew, meat-eaters such as American kestrel and American marten, and mixed-diet animals such as gray jay and deer mouse. These receptor groups were evaluated by assessing the viability of common species and the survival, reproduction, and growth of listed species.

Despite the broad perspective of the terrestrial ERA, this paper focuses on a very narrow aspect of our findings that arose during the course of our investigations, as we were challenged with risk-management and communication decisions. As noted above, this ERA was an iterative process, with further data being collected over time from discrete areas to further delineate potential contamination sources, verify findings from previous years, fill data gaps and reduce uncertainty. One of the aspects revealed during the course of our studies was the discovery that metal concentrations in all environmental media within certain discrete areas were quite elevated. Much more so than expected, given that these areas were physically unaltered, with undisturbed vegetation and a mature, intact soil cover. Some of these areas were well-forested, in areas downgradient of waste rock piles near the Main Zone and Jewelbox pits and adjacent to the 1380 Gully. Further delineation in 2014 also revealed highly elevated metals in organic soils perpendicular to the axis of the 1380 Gully and downgradient into undisturbed forest. Our initial interpretation of elevated metals concentrations based on limited investigations in 2013 was that off-site migration of metals was due to aeolian transport (e.g., blasting, dust) or carried down and away from the gully via rainfall and snowmelt, causing elevated metals in soils in adjacent forest.

The 1380 Gully is a deeply incised channel squeezed between the mineralized zone and Mt. Hundere to the west (Figure 3). The gully forms an erodible channel that accumulates snow in winter and rapidly transports water during snowmelt and rainfall events. Water discharged from the 1380 Adit (~1 L/s) also reports to the gully, but goes underground well above the gully, presumably joining groundwater. While the underground deposit was never mined via the 1380 Adit, exploratory work resulted in the accumulation of highly metal contaminated soils and waste rock that was perched on, or cast down into the gully, resulting in soil metals contamination within the thalweg, extending at least several hundred meters downgradient. But also, as noted above, exceedances of CSR soil standards extended well into undisturbed soils with higher concentrations in organic soil (2 – 4x) than the underlying inorganic, mineral soil layer.

Figure 4 below illustrates the distribution of soil metals concentrations within and surrounding the main ore bodies, Jewelbox Hill and Main Zone pits, including the 1380 Gully (AEC 9.4). While Figure 4 illustrates exceedence of all COPCs, the magnitude of exceedences was driven primarily by lead and/or zinc. Soil data were gathered over a three-year period from the ESA investigation (e.g., test pit, x-ray fluorescence [XRF]) and ecological and human health sampling of organic and inorganic soil horizons. Symbols that were orange or red exceeded CSR standards for soil metals concentrations by <10x or >10x respectively. It can clearly be seen that the vast majority of disturbed area within the Main Zone and Jewelbox pit areas had metal concentrations >10x CSR standards, and these areas were well delineated with soil samples below standards in surrounding areas. Similarly, elevated metal concentrations in soil extended into the 1380 Gully, downgradient and well away from the pits. However, there were many locations on either side of the gully well into undisturbed, forested areas where metal concentrations in organic soils, as well as underlying mineral soil, exceeded guidelines.

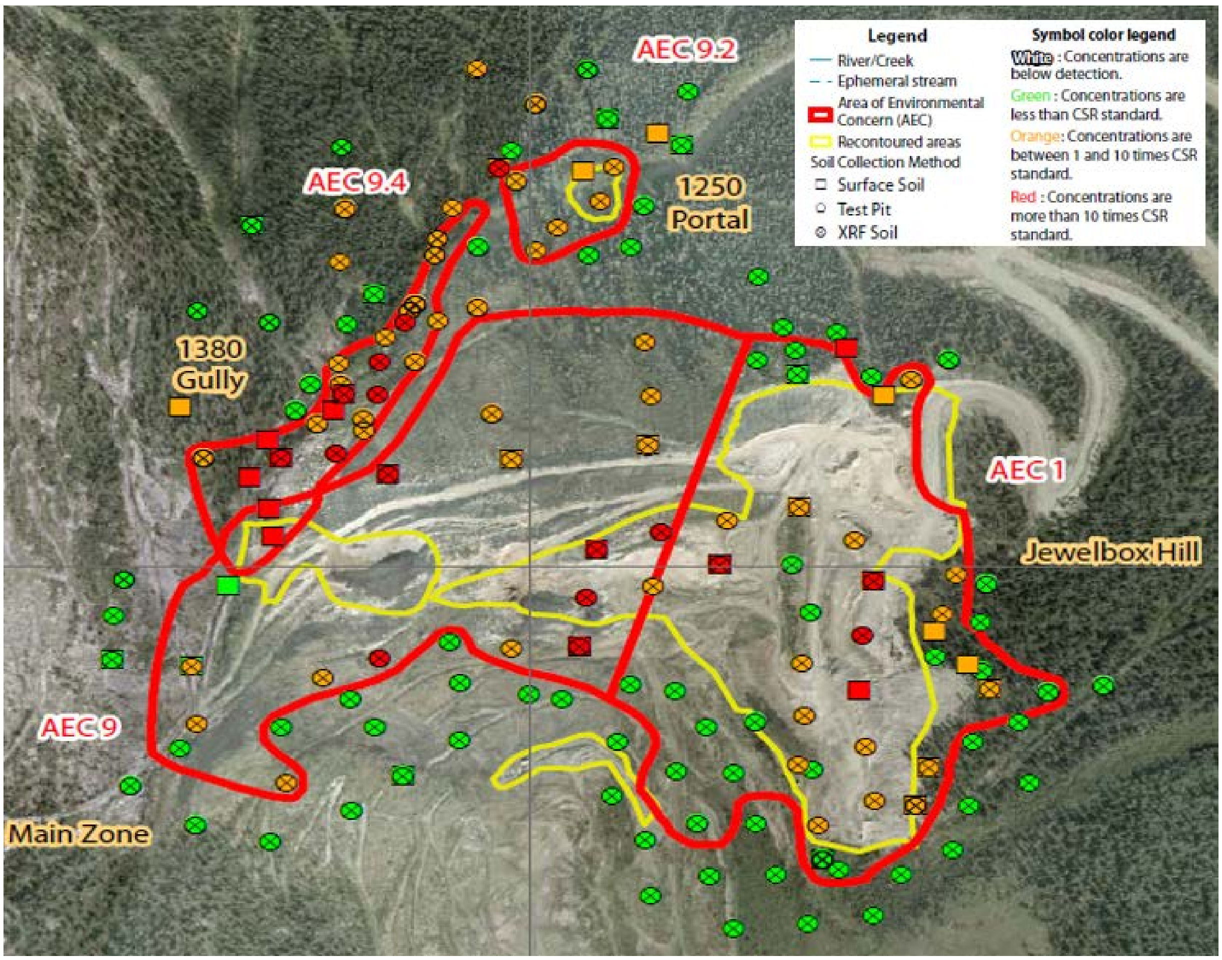


Figure 4. Results of soil metal exceedences of CSR standards (2012 – 2014) at the Jewelbox / Main Zone pits at Sa Dena Hes Mine in near-surface organic or inorganic soils.

Undisturbed habitat downgradient from the 1380 Adit and the 'toes', or bottom one-third portions of the largest waste rock piles on the Site were sampled in 2014 to determine if there was offsite movement or contamination into soils and the terrestrial food web, presumably from the metal-rich waste rock material perched above. The toes of the waste rock piles are located on very steep slopes and remain in-place. This material consists principally of very large boulders with a very sharp transition between the boulder substrate and organic soils and subalpine forest of spruce and pine, with a margin of willow.

The steep, upper part of the gully downgradient from the 1380 settling pond historically received contaminated soils from the developing adit that were washed into the gully. The pattern of soil metals within the gully suggests that this area was contaminated by mining. However, soils sampled outside of the trough of the gully were also elevated above soil standards. Thus, there was some uncertainty whether some of the area was naturally elevated in metal concentrations, perhaps because of its proximity to the ore body, and/or whether water or dust from the gully or waste rock benches had transported metals more broadly in the gully.

To resolve this, additional soil sampling was carried out in 2014 in areas east and west of the gully, as well as downgradient into undisturbed forest, targeting organic and underlying mineral soil horizons. Figure 5 depicts the combined soil lead data set from 2012 – 2014 from the Site AECs using a variety of sampling methods (e.g., XRF, test pits, surface soils) relative to CSR standards. 1380 Gully soils (AEC 9.4) were quite elevated relative to reference area soils (far right) and higher overall than Mine Site AECs such as the Mill (AEC 3) and Tailings Facility (AEC 8). Surface soil (organic layer) lead concentrations (triangles) were higher than underlying mineral soil lead concentrations in a number of locations. The patterns in soil concentrations of the divalent metals arsenic, cadmium and zinc were very similar to the pattern in Figure 5 for lead (Azimuth 2015). Initially, prior to step-out sampling, this pattern suggested that mine related sources may be responsible for the elevated concentrations in the organic soil horizon.

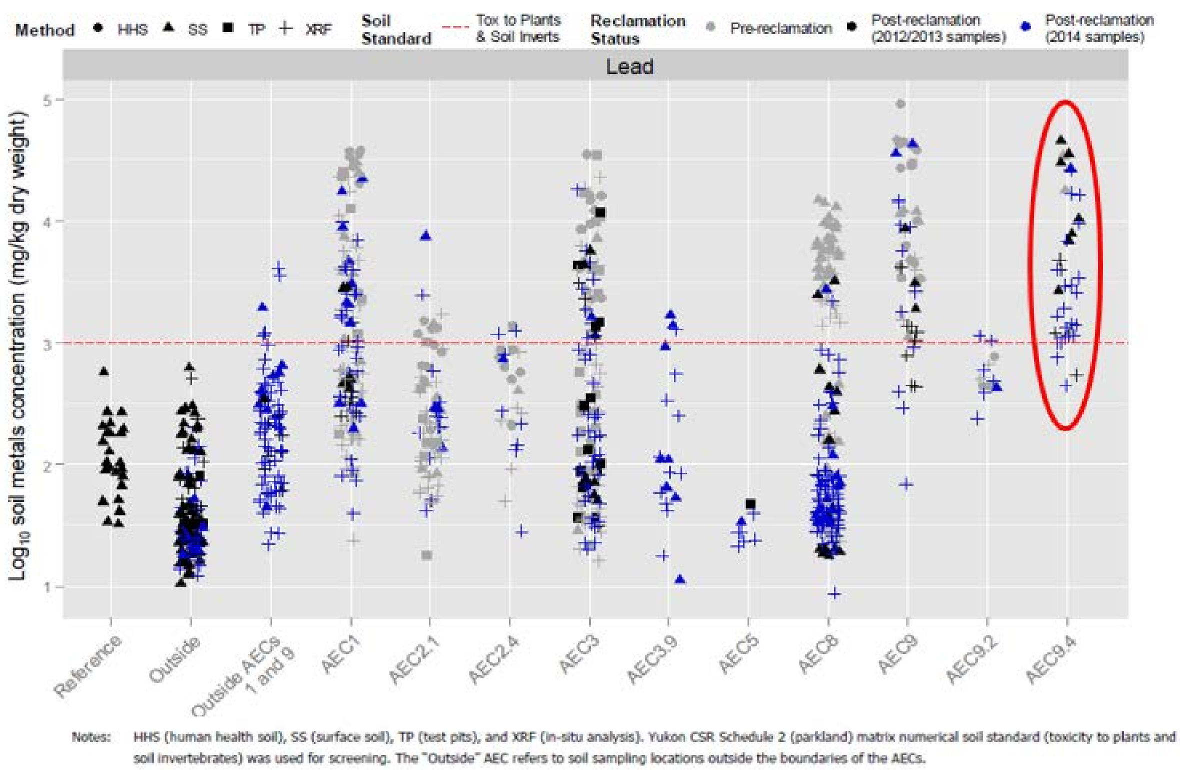


Figure 5. Soil lead (ppm, $\log_{10}$) concentrations from Mine Site AEC relative to the CSR soil standard (red line). The red oval captures the range of 1380 Gully concentrations.

Vegetation was sampled in 2012 (limited), 2013 and 2014. As described above, vegetation sampling focused on twigs of willow and alder, preferred overwintering browse for moose and snowshoe hare, respectively. Sampling of twigs and not leaves would minimize the possible influence of 'dusting' of leaves by wind-borne metals from exposed areas. The highest lead concentration (60 ppm ww) of willow was observed up-gradient out of the gully in 2012 (green symbol), but very near to it (Figure 6). Further sampling in 2013 and 2014 (red and blue respectively) revealed that lead (and other metals including zinc) in willow from the 1380 Gully were highly elevated relative to willow from reference areas in particular, but also from willow growing in or adjacent to the Tailings Facility. Such high concentrations would suggest that herbivorous animals foraging in the 1380 Gully would be exposed to high cadmium, arsenic, lead and zinc concentrations. In fact, metals analysis of moose and snowshoe hare feces confirmed that animals foraging along the 1380 Gully (117 ppm dw) and adjacent to the Tailings Facility (34 ppm dw) were much more exposed than from reference areas, which had feces lead concentrations of 2.4 ppm. Lead in feces from all other areas was < 2x higher than reference area concentrations. Thus moose (and hare) are more exposed to lead when foraging in the 1380 Gully area in particular, either from direct ingestion of plants, incidental soil ingestion, or both.

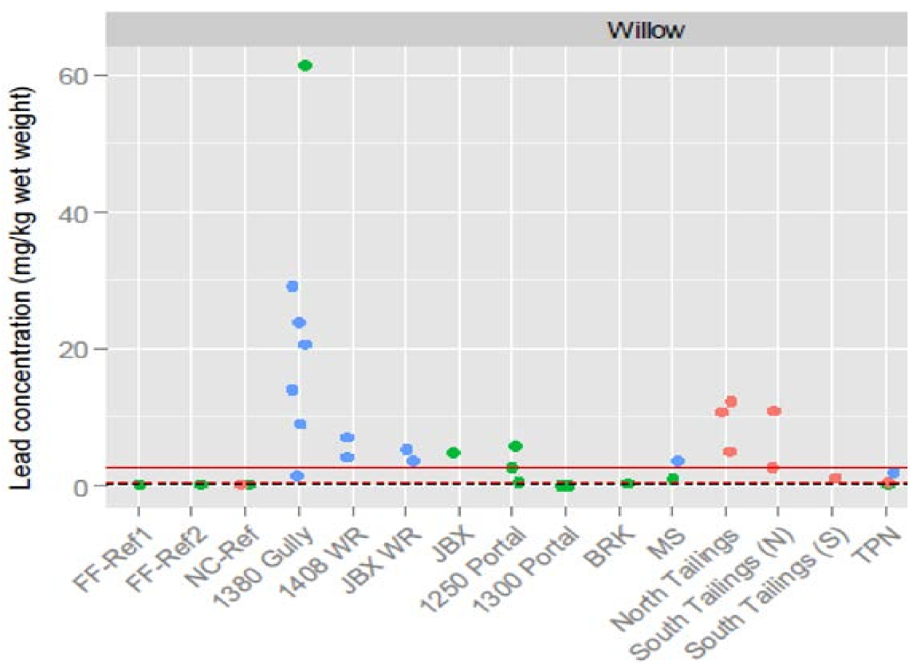


Figure 6. Total lead concentration (ppm ww) in willow twigs (2012 – 2014) from Sä Dena Hes Mine Site AECs (see Figure 2).

Similarly, concentrations of some metals were highly elevated in ground invertebrates in forested areas adjacent to mineralized / disturbed areas (i.e., 1380 Gully and downgradient of a Jewelbox waste rock pile [1408]). Although, ground invertebrates collected from forest areas adjacent to the Mill Site and all areas adjacent to the Tailings Facility had similar metals concentrations as reference areas, invertebrates collected from 1380 Gully were highly elevated in arsenic, aluminum, zinc and lead (Figure 7). Lead concentrations were measured between 50 ppm ww and 115 ppm ww in the Gully downgradient from the 1380 Adit and nearly 150 ppm from the 1408 waste rock area. These data suggest that invertebrates have integrated metals into their tissue via dietary ingestion of soil and/or prey that are apparently more bioavailable in the Gully and 1408 waste rock area than other areas. Given the consistent pattern of elevated metals in soils, vegetation and invertebrates from these areas, and that no 'dusting' of soils was evident on the invertebrates or their habitat, this may be a natural phenomenon that is characteristic of this area. It is also noteworthy that despite elevated metals in invertebrates from both the Jewelbox/Main Zone and 1380 Gully areas there was no apparent difference in abundance, biomass and species richness between these and reference areas (biomass was in fact higher in the 1380 Gully).

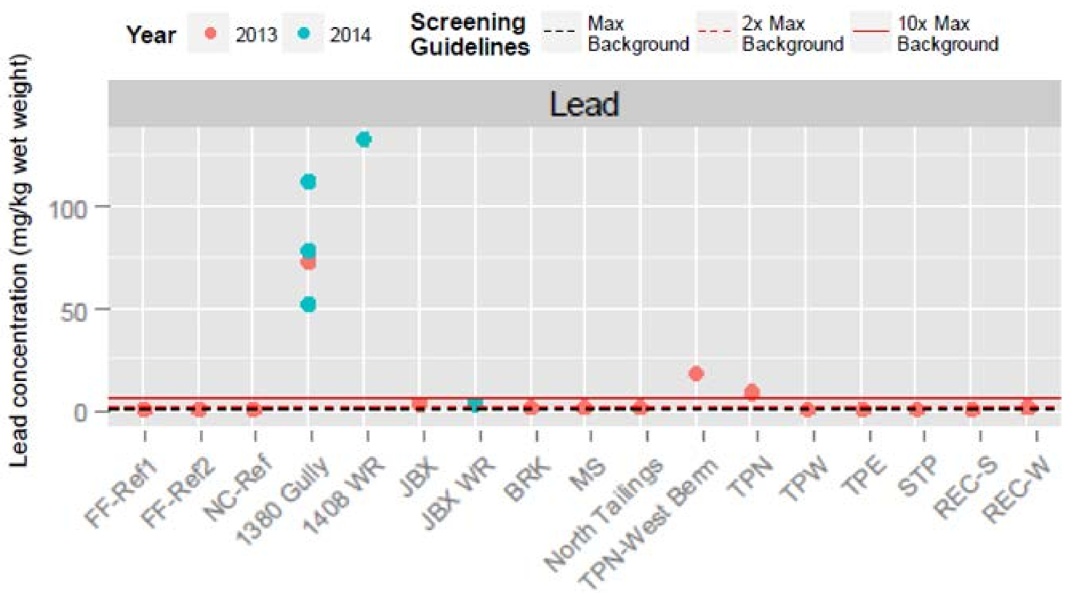
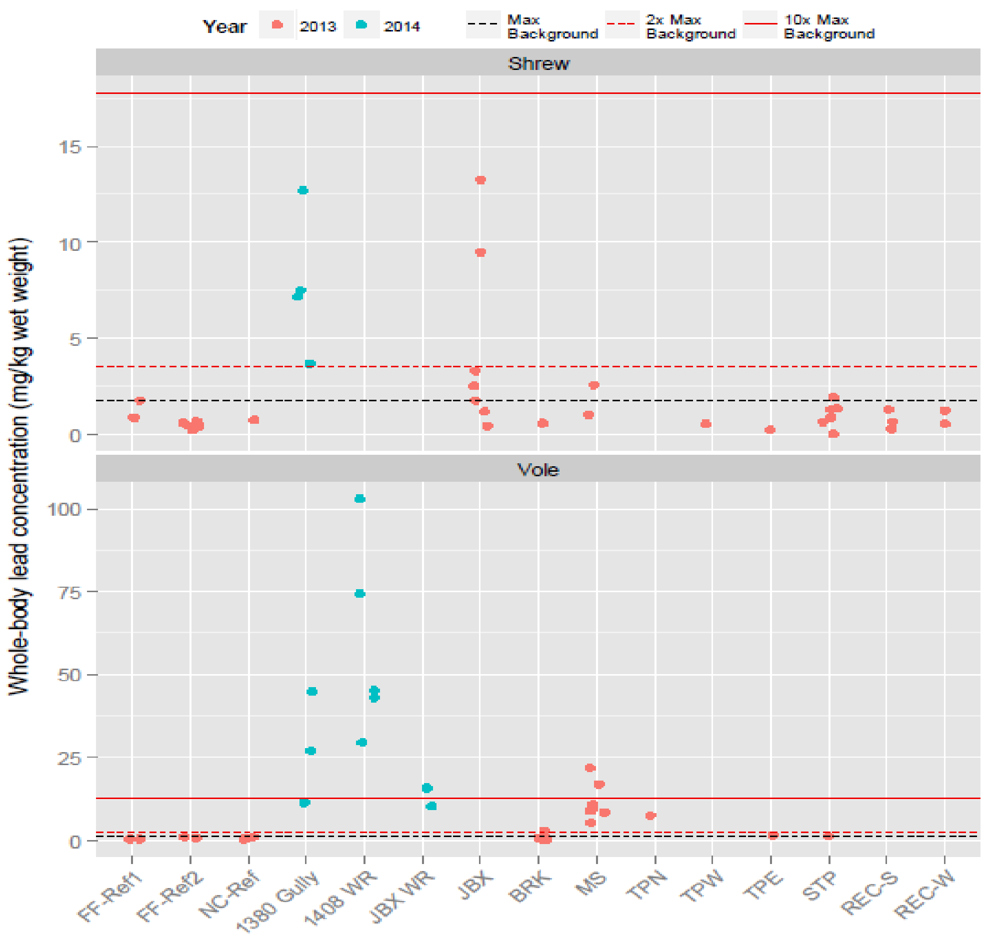


Figure 7. Lead (ppm ww) in ground invertebrates from Mine Site AECs (see Figure 2). The solid red line represents 10x above background (reference) concentrations.

Small mammals (carnivorous shrew and omnivorous vole) were captured from most AECs and analysed on a whole body basis for metals concentrations. Metals concentrations in nearly all small mammals were less than 2x greater than reference animals, with the exception of arsenic in voles, but particularly for lead in both species. Individuals of both species from 1380 Gully and 1408 Waste Rock area had lead concentrations that exceeded reference area concentrations by at least 10x (Figure 8). Lead in shrew was 3 – 13 ppm ww from the 1380 Gully and 12 – 25 ppm downgradient from a Jewelbox waste rock pile. Lead in voles was up to 45 ppm (1380 Gully), 110 ppm (1408 waste rock), and 13 ppm (Jewelbox waste rock). The only other area with lead exceedences of reference concentrations was the Mill Site with 5 – 23 ppm in vole and 2 – 4 ppm in shrew. We were surprised that omnivorous voles had consistently higher metal concentrations than the carnivorous vole, suggesting that vegetation may have contained more available metals than did animal tissues. The high concentrations of arsenic, cadmium, lead and zinc in willow and alder twigs and in organic soils suggests that metals are being absorbed from the inorganic soils, sequestered in vegetation and concentrated in the organic soils.

Leaves and woody elements of plants can play a key role in extracting metals from contaminated soil, as part of the importation process of essential mineral elements during leaf transpiration. Many studies have examined how plants are potentially adversely affected however, by heavy metals, especially cadmium and lead. For example, cadmium interferes with the uptake, transport and use of different macro- and micronutrients, especially iron and zinc, with considerable inter-species differences in uptake, tolerance and effect to different plants (Vollenwider et al. 2006, Zhivotovsky et al. 2011 and others). Woody plant species that produce high biomass, especially willow species (*Salix* sp.) have been proposed for use in phytoremediation technology and several authors have investigated the accumulation of heavy metals cadmium and zinc, by several willow species. For example, Santos-Utmazian and Wenze (2007) found that willow were very effective at taking up metals and that they tolerated large metal concentrations in soils.

Zhivotovsky et al. (2011) investigated growth and lead uptake by seven willow varieties in pot and field experiments to assess the suitability of willows for phytoremediation of lead contaminated sites. Willow took up and translocated lead grown in contaminated soil, showing tolerance to very high soil lead concentrations, in excess of 20,000 mg/kg, similar to concentrations found at Sä Dena Hes.



5. **Figure 8.** Lead concentration (ppm ww) in shrew and vole from Sä Dena Hes AECs (see Figure 2).

6.
In summary, there is evidence of enrichment of metals within the trough of the 1380 Gully but also in organic soils well away from the 1380 Adit, in forested areas where translocation by water or dust deposition is unlikely. This pattern was also observed at several stations at least 300 m down the gully (although to a lesser degree), away from the trough and above the elevation that water might have carried metal contaminated soils into the adjacent forest. Lead and zinc concentrations of organic soils were 2 – 4 times higher than the mineral layer underneath. A similar pattern of metals concentrations was observed at the toe of the 1408 and Jewelbox Waste Rock areas, where organic soils are enriched in cadmium, lead and zinc, relative to inorganic soils.

7. Taken together, the pattern of elevated metal concentrations in organic soils, willow and alder twigs, ground invertebrates and omnivorous small mammals of the 1380 Gully and surrounding forest indicates that this phenomenon is wide-spread and well established. These data, combined with habitat quality measurements in our food chain modeling indicated that even following remediation of the pits and majority of waste rock areas, there would still be elevated residual ecological risks to two common wildlife (e.g., Arctic ground squirrel and common nighthawk) and six listed bird species (e.g., yellow-bellied flycatcher, American kestrel, and white-throated sparrow), with moderate uncertainty, even if contamination was limited to the 1380 Gully and areas downgradient of the waste rock piles. From a human health perspective, elevated risks were identified in the 1380 Gully for two types of exposure: (1) direct contact with contaminated soil, and (2) consumption of plants and small animals.

8. There was however, uncertainty as to whether contamination of the Gully and areas downgradient of waste rock piles was due to dispersal of metals from disturbed areas, or was a natural phenomenon. Despite the apparent natural enrichment of the organic layer, we could not rule out off-site migration of metals. To help resolve this, Golder Associates (2015) undertook a geochemical investigation of the historic soil data from exploration records (Kidlark 1980) and geological reports (Anvil 1993). With the use of geostatistics, they derived Pb:Zn:Ag ratios that are indicative of mineralized ore versus otherwise disturbed (e.g., waste rock, pits) but highly mineralized areas, to identify soil metals concentrations considered 'anomalous' (i.e., outside of the Main Zone/Jewelbox showing). In particular, a fault extending along the southeast spur of Mt. Hundere coincides with the location of the 1380 Gully (Anvil 1993). Soils 'heavily enriched' in Pb, Zn and Ag, similar to ore body concentrations, are naturally occurring and outside the area directly impacted by mining. Golder concluded that while contributions from exposed mine wastes cannot be completely ruled out, it is a minor component of soil chemistry relative to natural sources. If the 1380 Gully was formed as a result of a fault, exposing mineralized rock, this would lead to similar geochemical features and ore-grade Pb and Zn concentrations in mineral soils. Water in contact with exposed mineralization can leach metals and metal salts in this acid neutral drainage, causing organic matter and clay particles to adsorb and precipitate metals. However, given that the adit and waste rock area are also perched above the Gully, some contribution may have arisen here, but from a mass balance perspective, contribution from this area was deemed to be a small part of the load.

9. Golder (2015) concurred that enrichment of metals in organic soil was the result of a natural, long-term process. High (up to 40%) carbon content of the organic soils increases the potential for metal immobilization because of the ability of humic substances to adsorb and accumulate cationic metals Cu, Pb, Zn (Schnitzer and Hanson 1970, Gamble and Schnitzer 1973) over a long period of time. A single, point-source area was not responsible for observed metal concentrations in the 1380 Gully and surrounding soils, but was due to a combination of factors: exposure of primary mineralization, secondary precipitation of metals, leaching from waste rock areas, adsorption/accumulation by plantsand precipitation by detritus. This was corroborated by observations from the literature and the pattern of Pb:Zn concentrations in willow twigs, organic soil, ground invertebrates and herbivorous mammals observed in this area.

10. **Risk Management Implications**

This study uniquely combined ecological and geochemical information in a "weight of evidence" approach to demonstrate/delineate between mining-related and natural metals contamination across a wide variety of environmental media in an area that was initially assumed to have been contaminated by historic mining activities. Based on these findings, although contamination of the 1380 Gully area was high enough to pose risks to human health and ecological receptors, it was not considered to be mine-related, which was an important finding influencing mine closure decision-making. Food chain modeling indicated that following remediation of pits and waste rock areas, residual risks to some ecological receptors remained. In addition, from a human health perspective, elevated risks were also identified in the 1380 Gully. However, the risk management option here is to restrict access/consumption of berries in these areas, which has implications for local First Nations resource users who may be not wish to be restricted.

Nevertheless, territorial regulatory authorities and Elders from the Liard and Ross River First Nations' Elders and their advisors were engaged throughout the ERA process to discuss post-closure risks and seek their input on future land use at the mine site. This was critical to closure plan success. Appropriate risk communication with respect to identifying the contribution of mining-related contamination versus natural mineralization was also key to discussions with regulators and First Nations.

In summary, based on our evaluation of all information generated from the ecological and human health risk assessments, geochemical evaluation and remedial options analysis, combined with agreement from regulators and First Nations, Teck proceeded with remediating mine-disturbed areas upgradient of the 1380 Gully. However, no direct physical remediation of the gully was required or undertaken. Risk management, such as restricting access to certain areas or limiting harvesting of some berries or traditional plants in or near the 1380 Gully is required to address human health risks. On the ecological side, this area is included in long-term monitoring plan for the Site to ensure that concentrations are stable or improving and Teck will communicate this information to local First Nations on an on-going basis.

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