An investigation of cadmium and lead from a High Arctic waste disposal site, Rsesolute Bay, Nunavut, Canada*

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Abstract Heavy metal contamination in the High Arctic is a growing concern. Cadmium and lead are recognized by the Canadian Government as metals of concern but little research has been done on small point sources such as municipal waste disposal sites. In 2003 a study was conducted near Resolute, Nunavut, Canada (74°43′N, 95°55′W) to determine the extent of cadmium and lead leaching from a local dumpsite which lay adjacent to a large late-lying snowbed. Three transects (reaching ~700 m in length) were established downslope from the waste site and water and soil samples were collected for metal analysis at regular intervals. Information on snowbed retreat, water table position, soil moisture conditions and frost table decline were also obtained. Cadmium levels in water samples exceeded government guidelines and along one transect increased with distance. Little lead in surface waters supports the notion that it does not travel easily in soil solution. Overall, soil cadmium and lead levels were low and did not exceed government guidelines. Some spatial patterns did emerge and can be linked to variations in water flow patterns, nearness to the dumpsite and ground cover conditions.

Keywords Arctic environment; cadmium; contaminants; hydrology; late-lying snowbed; lead

Introduction

Permafrost communities in the High Arctic have been established since the early 1950 s but policies regulating waste disposal sites are still limited (Haertling 1989). They are often placed in areas which are convenient rather than in appropriate areas for waste management. This strategy can have impacts on both ecosystems and local water supplies. Dump sites can be local sources of pollutants since they often house old drums of fuel, paint cans, electrical conduit, tires, etc. Since most communities are coastal, contaminants from these waste disposal sites have the potential to leach into nearby wetlands and the ocean, eventually accumulating in the food web of marine birds and mammals. Since northern people consume this wildlife on a regular basis, these food sources could potentially endanger their health.

Relatively little research has been done to determine health risks involved with northern dumps. In one study Haertling (1989) determined trace metal concentrations (Cd, Pb, Cu, Fe, and Zn) in water and sediment samples at a Central Arctic municipal waste site in Pangnirung, Nunavut. He found that metals were being rapidly removed from the active intertidal zone located directly adjacent to the dump.

The metals of focus in this study are cadmium (Cd) and lead (Pb). The Canadian Northern Contaminants Program regards both Cd and Pb as metals of concern because they

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accumulate in the liver and kidneys of mammals, posing a serious health risk to upper trophic species (Macdonald *et al.* 2000). Atmospheric deposition from these metals has been studied (Macdonald *et al.* 2000) and the Arctic is considered to be an atmospheric sink for global anthropogenic emissions of Cd (3.2–12.0 kt/yr) and Pb (287.5–376.0 kt/yr). However, local point sources such as municipal waste disposal sites have generally been overlooked. Cadmium and lead entering the waste disposal site can be transported as a solute or as a precipitate in suspension. Metals may precipitate and dissociate, depending on soil pH and other conditions. Once the metal is dissolved, it can be transported through soil solution and has the potential to move rapidly if water flow is high. In a recent paper by Lund and Young (2005), the factors governing the potential movement of cadmium and lead were investigated using a tracer-lithium (Li^+) as a proxy. No Li^+ exists in polar soils and its presence, following experimental applications, offers reasonable insight on the possible pathways that metals with a similar ionic charge to Li^+ can take. It was applied to several contrasting arctic environments (e.g. climate, topography, surficial materials and vegetation cover) and its movement was evaluated over the short- and long-term (1 week vs. 1 year). Results indicated that contaminants have the potential to actively move through coarse materials and steep slopes. Contaminant movement is slowed on level ground and by fine-textured soils, in addition to heavily vegetated areas. The snowmelt period with frozen ground and excess water availability was also identified as a critical time for contaminant movement.

The local dumpsite near the Hamlet of Resolute Bay, Cornwallis Island, Nunavut, Canada (74°43′N, 95°55′W) is used here as a case study to explore further the environmental factors and hydrological processes which are enhancing or minimizing contaminant movement (i.e. cadmium and lead) into a nearby wetland site. Insights gained from this study may be useful to other small northern communities considering a monitoring program or full clean-up of their local waste facilities (e.g. Duhaime *et al.* 2005).

Study area

The study took place from July 6–August 12, 2003 near the Hamlet of Resolute Bay, Cornwallis Island (74°43′N, 95°55′W). It is a small community of 200 residents. Travelers and research scientists double that number during the summer. The local vicinity can be described as a polar desert with average summer temperatures of 5°C and winter temperatures reaching less than −35°C (Woo and Steer 1983). Annual precipitation, when corrected for snow gauge under-catch (e.g. Yang *et al.* 1999) is about 200 mm. Eighty per cent of the annual precipitation falls as snow and snowmelt usually begins in late May or June (Woo *et al.* 1983). Rainfall is seldom heavy and the bulk arrives in July and August. The area is underlain by continuous permafrost and the active layer reaches about 1.0 m in gravelly soils and about 0.3–0.4 m in poorly drained soils (Young and Woo 2000).

The municipal waste disposal site selected for this study is an abandoned garbage dump about 10 km to the northwest of Resolute (Figure 1(a)). This waste disposal site is classified as an "embankment type" and is common in the north (Johnson 2001). While in use (1960–1997), solid waste at the dump was disposed of over a west-facing slope (ca. 18°) with much of the waste accumulating just below the ridge and in the slope concavity. Combustibles were burned in the open, either in barrels before disposal or at the dumpsite itself (Underwood McLellan and Associates Limited 1980). Since 1997, only sewage generated by the airport and the surrounding area (e.g. hotel, scientific research centre) is disposed of here, as opposed to the entire hamlet of Resolute Bay. The sewage is dumped daily into a series of sewage lagoons, which ultimately run downslope into the waste disposal site below.

This particular dump was selected due to its multiple sources of moisture and therefore increased opportunity for metal transport. A late-lying snowbed occurs in the break-of-slope, both blanketing the garbage and providing a steady supply of moisture long after the seasonal

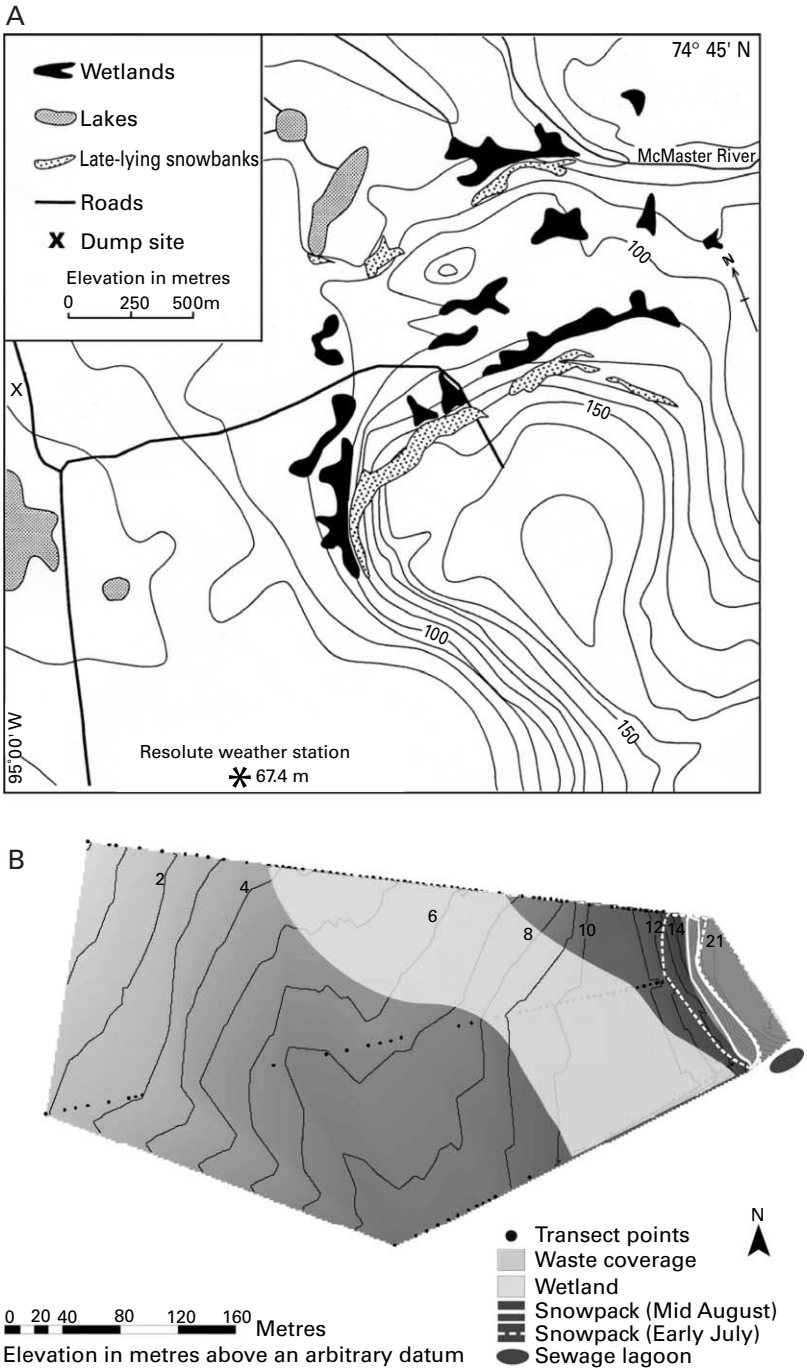

Figure 1 Location of the study site (a) and a more detailed diagram of the dump site (b), showing also the retreat of the snowbed and the wetland zone location

snowpack has disappeared (see Figures 1(b) and 2). These snowbeds are a common feature in this Arctic landscape (Young and Lewkowicz 1988). The sewage lagoons also provide additional moisture and the high nutrient loading has created a relatively lush and extensive wetland below the dump site with many moss and grass species. Much of this area has

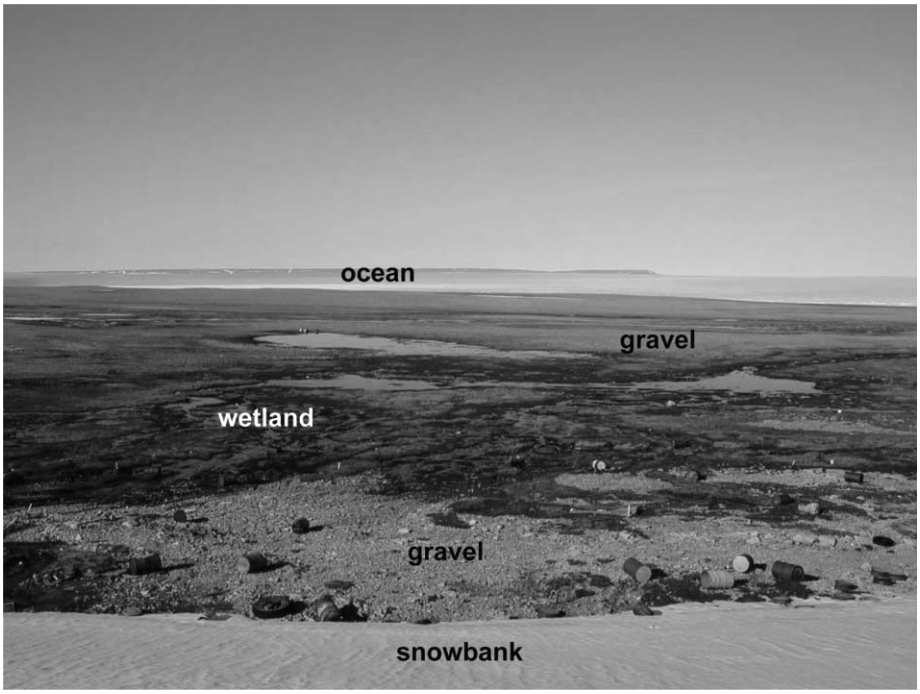

Figure 2 Photograph (looking southwest) taken July 6, 2003 of the dumpsite, snowbed and the terrain downslope of the dump site

standing water or saturated soils and it provides a favoured habitat for both local and migratory birds.

The area in which the waste disposal site is located is generally classified as alluvium, with rocky, patterned and stony ground, and with fine materials located in polygon centres (30–40%) (Cruickshank 1971). Geologically, this area is underlain by carbonates (limestone and dolomite) which have created an alkaline environment. The soils are poorly developed due to high carbonate content and cryoturbation (Edlund 1991).

Methodology

Field

Three transects (see Figure 1) were established in an area of approximately 0.3 km^2. Transects start about 5 m downslope from the edge of the waste disposal site and continue out through the wetland toward the coast. Sample points were established every 5 m along each transect and cross through hydrologically diverse ground (gravels, dry fine-textured soils and wetland). Rocky areas were generally not sampled due to the lack of fine material which is needed to extract for metal concentrations. The entire study site was surveyed on July 29, 2003 using an Ashtech Z-Xtreme GPS system ($\pm$ 30 mm).

Fieldwork began after the seasonal snowpack was depleted (ca. early July). Snowbank retreat was monitored daily at 17 points along the snowbed edge. Weekly frost table measurements allowed the available storage capacity of the ground along transects to be determined (Woo and Xia 1995). Ground type (e.g. moss, diatom, gravel), water depth (mm) and/or moisture status (saturated to dry) was recorded at each sample point. In order to determine the extent of contamination; both with depth and over the area and to identify levels exceeding CCME (Canadian Council of Ministers of the Environment) (1991) guidelines, soil samples were collected once at each transect point. Soil grab samples were

collected between July 18–21, 2003 at the surface (0–100 mm) and at depth (100–250 mm). Near surface soil samples were also obtained with a trowel for soil moisture determination. If surface water was present, a water sample was taken with a sterile syringe and deposited in a clean sample container. Water samples were filtered using Whatman 42 filter paper. Water pH strongly influences the transport mechanisms of Cd and Pb; in particular, pH strongly affects the solubility and therefore mobility of metals (Alloway 1990). Water pH was measured *in situ* with a SPER Water Quality meter 850081 ± 0.01 and calibrated prior to use.

Ten control samples were taken (July 31, 2003) from the area surrounding the dump site in order to determine background levels of Cd and Pb. This can be considered to include naturally occurring metals, in addition to atmospheric deposits. At each control point, three grab surface and subsurface soil samples were taken and treated as described above. Control points in the immediate vicinity with similar topography, soil materials and moisture status comparable to the dump site were difficult to find. In total, 7 gravel sites were sampled, 1 moss site and 2 diatom areas. Water blanks (reverse-osmosis water) served as control for water samples.

All soils for chemical analysis were air-dried, sieved at 2 mm in a fume hood to prevent cross-contamination and then homogenized. About 25 g of each sample, enough for analysis and replication, was shipped south to the laboratory.

Laboratory analysis

The sieved homogenized soil samples underwent extraction procedures that removed Cd and Pb from soil particles by bringing the cations into solution. Three grams of soil was measured and combined with 30 mL of 0.05 M EDTA (disodium ethylenediamine tetracetate $NaB_2C_{10}H_{14}N_2O_82H_2O$) solution (pH 7.0) into a sterile 50 mL falcon tube (Soon and Abboud 1993). The samples were shaken for 1 h at a speed of 120 cycles per min and then filtered into another acid washed scintillation vial. The solution was then analyzed for both Cd and Pb using atomic absorption spectroscopy (Varian AAS Spectra-10). Water samples were analyzed for Cd and Pb using AAS. Detection levels for AAS is 0.0001 mg/L for water and 0.01 mg/kg (ppm) for soils. Presently, Inductive Coupled Plasma-Atomic Emission Spectrometry (ICP-AES) is used to measure small concentrations of cadmium 0.0001 mg/kg, but we did not have access to this instrument. Confidence intervals (±) are reported at the 95% significance level, along with mean values.

The gravimetric approach was utilized to determine soil moisture. Soil samples were weighed and then dried at 105°C for 24 h. Gravimetric values were converted into volumetric soil moisture (θ) using bulk density (ρ_b) values determined by Woo and Marsh (1990) for similar terrain. Particle size analysis (after Sheldrick and Wang 1993) was carried out because soil particle size can affect metal sorption: fine particles (<0.002 mm) can be negatively charged (Essington 2004). Organic content of soil samples was determined through loss on ignition.

Results and discussion

Summer conditions

The study period took place from July 6 to August 12, 2003, following snowmelt for the area. The average temperature during the study period was 3.9°C, which was slightly higher than the 30 year normal of 2.1°C. Higher temperatures occurred at the beginning of the study period for about 11 d, approximately 8°C higher than the 30 year mean. From July 17 to August 12 temperatures cooled remaining below the 30 year mean.

Maximum snowfall recorded at Resolute weather station at the end of May was 150 mm. Woo *et al*. (1983) indicates that this value is usually in error and can be higher in the

surrounding basins. Weather station records indicated that melt began June 4 and was completed by June 30, with rapid melt occurring between June 11 and June 21. The late-lying snowbank at the dump site retreated over 11.5 m by August 9. At the time of soil and water sampling (July 18), the snowbank had already retreated 7.7 m. The total precipitation received during the study period was 71 mm, while the total 30 year normal precipitation is 31 mm for the same period. No rainfall occurred throughout the warm period (July 6–17) but during the few days of soil sampling about 13 mm of rain fell.

Cadmium and lead distribution at the Resolute dump site

Cadmium and lead in water

Sources of cadmium are batteries, plastics, sewage, PVC products and atmospheric deposition. Water samples contained very low concentrations of cadmium ranging from 0.01 to 0.025 mg/L, but were still over the CCME criteria for water (0.001 mg/L), suggesting that remediation may be required (see Figure 3). A trend is apparent in Transect 1, showing an increase in Cd with distance away from the dump site. This can be linked to the topography of the site which slopes in the direction of Transect 1 (see Figure 1(b)). The steeper ground here (Figure 4) enhances the movement of metals via surface flow. Field observations also indicate that a well-defined stream cuts through the wetland area flowing southeast to northwest, possibly capturing and diverting water from the other transects towards Transect 1. The elevated concentrations of Cd over distance support the theory that Cd is one of the most mobile heavy metals in soils (Ingwersen *et al.* 1999). No trend in relation to distance was evident for Transects 2 and 3, though a two-tailed Student t test assuming unequal variance ($\alpha = 0.05$) did indicate significant differences in concentrations along each transect.

There was virtually no detectable lead found in the water samples. The CCME assessment concentration for Pb is 0.01 mg/L, which is detectable using AAS although detection at low concentrations has limited accuracy (Thomas 2003). This finding indicates that it is unlikely for Pb to be readily transported in soil solution.

Cadmium and lead in soil

Most cadmium concentrations ranged from 0 to 0.4 mg/kg at the soil surface, and 0 to 0.25 mg/kg at the 100–250 mm depth with the exception of transect points 2–1 (5 m) and 2–2 (10 m). Here concentrations were 1.0 and 1.7 mg/kg at the surface and 0.5 and 2.7 mg/kg at depth respectively (Figure 5). These elevated values are located directly adjacent to the waste disposal site and occur in the middle of the dump site, an area of gravelly material and high meltwater inputs which would foster Cd movement (see Figure 1). It is also likely that it is a "hot spot" for Cd sources (e.g. batteries). The mean Cd background level for the area ($n = 10$) is 0.02 ± 0.02 mg/kg, which suggests that the dump is in fact a minor source of Cd, though according to CCME guidelines (1 mg/kg), there is no soil contamination risk at this time.

For Transect 1, a two-tailed Student t test (assume unequal variance) indicated that higher mean concentrations occurred at the surface (0.06 ± 0.01 mg/kg) than at depth (0.03 ± 0.01 mg/kg), $\alpha = 0.05$, degrees of freedom (df) = 101. This differed for Transect 2, where no significant differences were noted: mean surface = 0.20 ± 0.07 mg/kg and mean depth = 0.15 ± 0.05 mg/kg, $\alpha = 0.05$, $df = 73$. This can be attributed to the few elevated values occurring at the surface and with depth. For Transect 3, there was a significant difference. Mean concentrations at the surface were 0.04 ± 0.12 mg/kg and at depth they were only 0.01 ± 0.01 mg/L, $\alpha = 0.05$, $df = 45$.

Some spatial differences do occur. Concentrations in surface soils differed between Transect 1 and 2 (TR1 mean = 0.06 ± 0.01 mg/kg, TR2 mean = 0.20 ± 0.09 mg/kg, $\alpha = 0.05$, $df = 43$) but not with Transect 3. There was also a slight significant difference

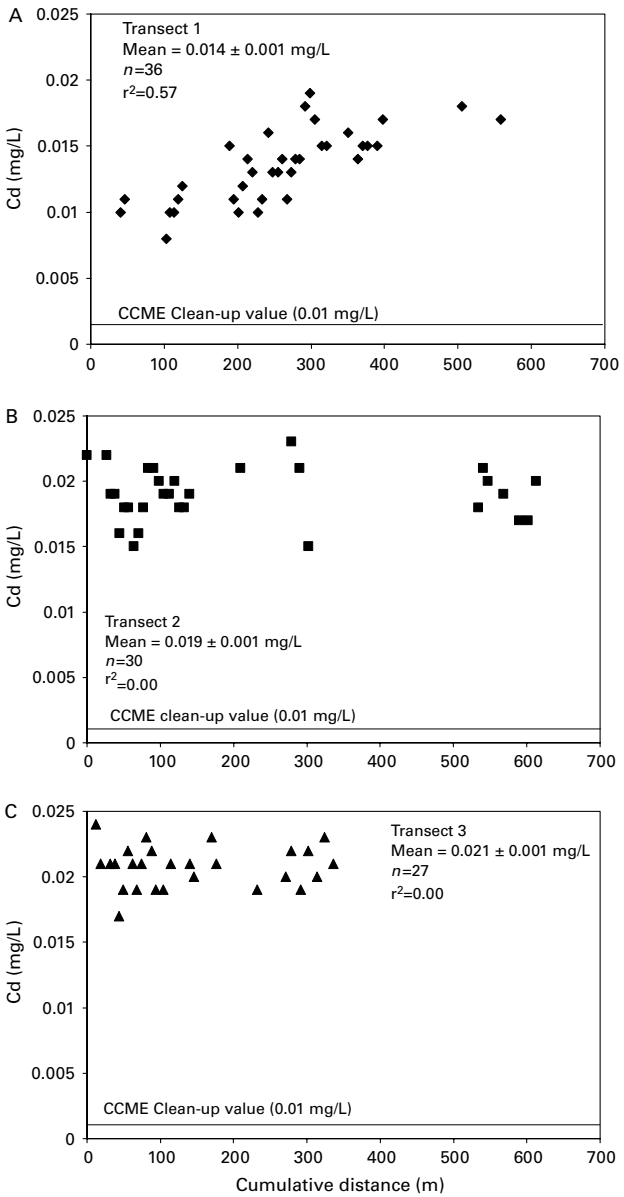

Figure 3 Concentration of cadmium in water samples obtained along transects leading from the late-lying snowbed and main dump location

between cadmium levels in surface soils between Transects 2 and 3 (TR2 mean = 0.20 ± 0.08 mg/kg, TR3 mean = 0.09 ± 0.03 mg/kg, $\alpha = 0.05$, $df = 53$).

In terms of subsurface conditions, there is no significant difference between Transects 1 and 2. Differences in Cd concentrations at the subsurface exist for Transects 1 and 3 (TR1 mean = 0.03 ± 0.01 mg/kg, TR3 mean = 0.01 ± 0.00 mg/kg, $\alpha = 0.05$, $df = 87$) and between Transects 2 and 3 (TR2 mean = 0.15 ± 0.02 mg/kg, TR3 mean = 0.01 ± 0.01 mg/kg, $\alpha = 0.05$, $df = 40$).

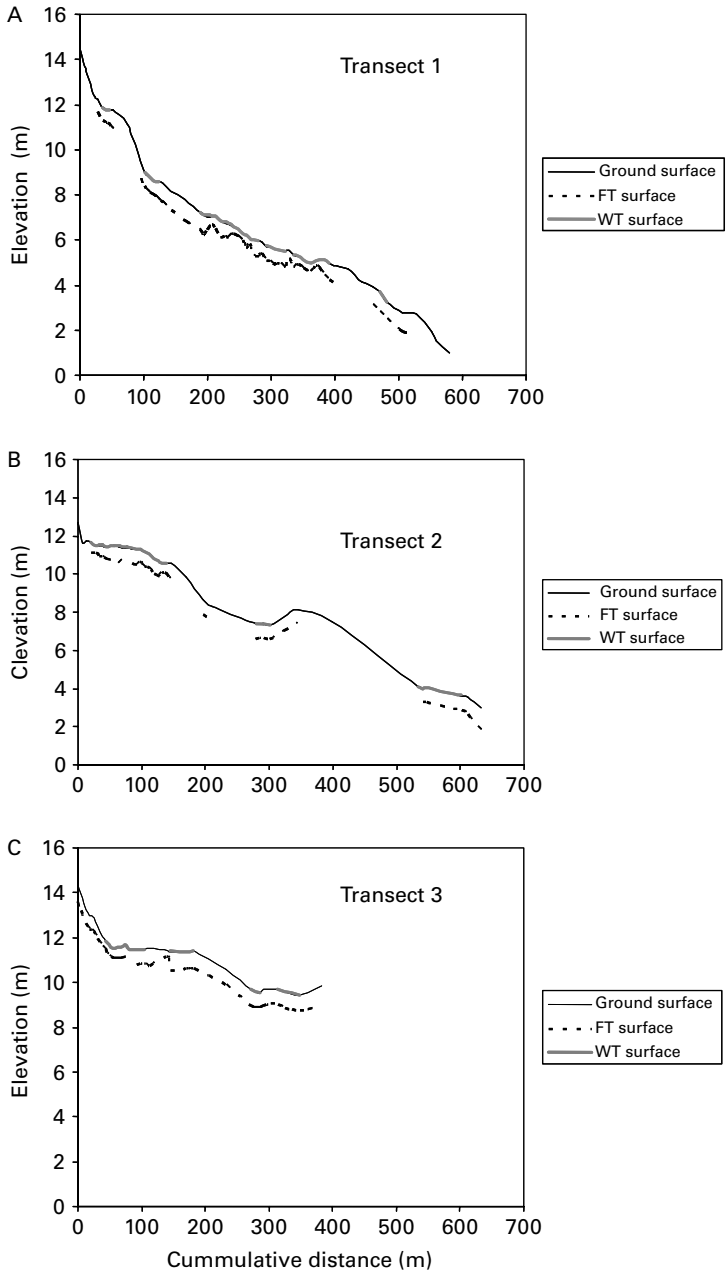

Figure 4 Transects are plotted in relation to surface elevation change with distance. Elevations are in meters above an arbitrary datum. Frost and water tables are also plotted

Higher surface concentrations suggest that snowmelt water is moving metals over frozen ground during the spring snowmelt season and saturated conditions are being sustained by meltwater from the late-lying snowbed and sewage lagoon spillage. To determine if cadmium had an affinity to ground type, the ground types and concentrations along transects were pooled (diatom, moss, grass, gravel, standing water). No significant differences in concentrations were determined for the surface and subsurface samples for these different terrain types in terms of cadmium (Table 1).

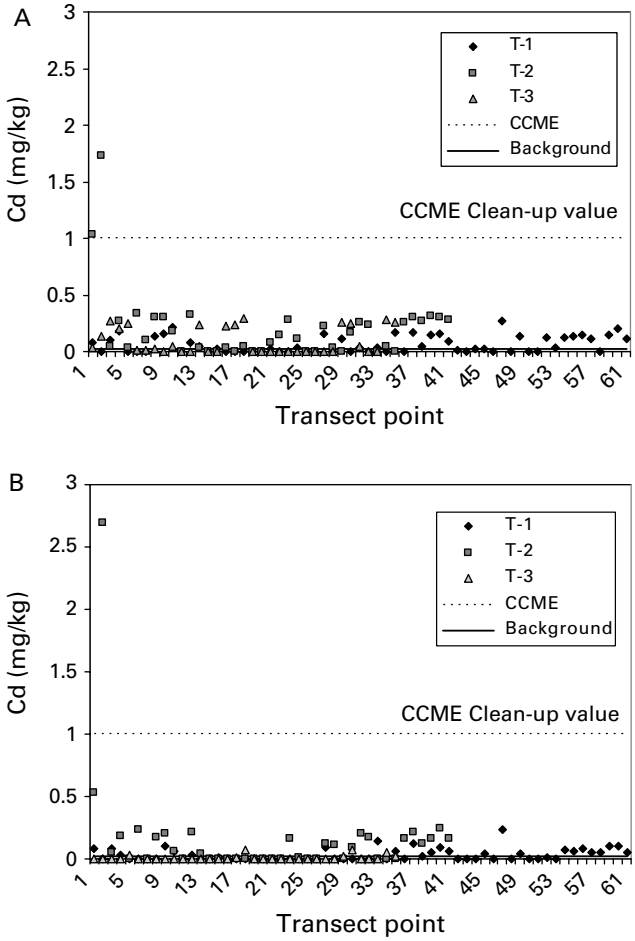

Figure 5 Concentration of cadmium in soil samples: (a) surface soils (0–100 mm) and (b) subsurface soil samples (100–250 mm). CCME clean-up value is 1.0 mg/kg and the background level is 0.02 mg/kg

Lead concentrations were significantly higher than that of cadmium by a magnitude of approximately 50 (Figure 6). Despite elevated levels, lead concentrations do not exceed CCME guidelines for remediation (50 mg/kg) except at two points along Transect 2 (2–1 and 2–2) where high cadmium values also occurred. Aside from the elevated values at 2–1 and 2–2, lead concentrations range from 0 to 20 mg/kg at the surface and 0 to 12 mg/kg with depth (100–250 mm). The average background concentration of lead (4.59 ± 0.58 mg/kg) is more variable than cadmium. The dump is a source of lead that exceeds natural and anthropogenic background concentrations found in the surrounding areas, but like cadmium, the waste disposal site does not require soil remediation.

There are no significant differences in the lead concentrations both with near surface samples (0–100 mm) and below the ground (100–250 mm). In terms of variations between surface and subsurface samples, only those values for Transect 3 were significantly different. Here mean surface concentrations of Pb were 4.98 ± 0.42 mg/kg while those in the subsurface were slightly lower: 4.07 ± 0.32 mg/kg ($\alpha = 0.05$, $df = 64$). Madhaven *et al.* (1989) indicate that lead tends to accumulate on the soil surface. In thin Arctic soils, organics are concentrated at the surface (Lund and Young 2005).

Table 1 Mean cadmium and lead soil concentrations according to ground type found along transects. Confidence level (±) at 95% probability is indicated. Values at Transect 2-1 and 2-2 were excluded from this analysis. Organic content (%) is based on samples obtained from representative terrain plots prior to a LiBr experiment

	Diatom	Grass	Gravel	Moss	Standing water
Mean Cd (mg/kg) (0–100 mm)	0.01 ± 0.01	0.08 ± 0.02	0.11 ± 0.03	0.07 ± 0.03	0.09 ± 0.06
Mean Cd (mg/kg) (100–250 mm)	0.00 ± 0.00	0.05 ± 0.04	0.05 ± 0.02	0.01 ± 0.01	0.05 ± 0.04
Mean Pb (mg/kg) (0–100 mm)	3.00 ± 0.86	7.10 ± 2.04	4.71 ± 0.52	5.52 ± 1.43	5.25 ± 1.32
Mean Pb (mg/kg) (100–250 mm)	2.76 ± 0.86	5.64 ± 1.38	4.52 ± 0.49	4.24 ± 0.54	4.19 ± 0.67
Sample size (–)	9	15	54	32	15
Organic content (%)	–	4.0	0.6	37.8	–
Sample size (*n*)	–	3	3	3	–

There were significant differences noted in terms of a ground type's ability to bind with Pb (see Table 1). All surface types (0–100 mm) had significantly different values than gravel surfaces. Elevated values for grass and moss relate to their high organic matter which Pb has an affinity to. There were no significant differences for Pb concentration with depth for the various ground types, except for moss, which had a mean surface concentration of 5.52 ± 1.43 mg/kg and only 4.24 ± 0.54 mg/kg below. At this site, the dominance of organic matter in saturated wetland areas has a negative feedback effect on metal sorption. Metals are attracted to organic particles but, since these areas are also saturated, metals have the potential for increased mobility due to increased flow. While surface flow was noted in the field, its measurement was hampered by shallow water depths which prevented reliable flow estimates. The gravel and diatom ground types experience less Pb due to the lack of exchange sites present. These ground types, however, could pose a hazard to waste disposal if their drainage pathways lead to ecologically sensitive locations.

Compared to the Sylvia Grinnell Dump in Iqaluit, lead concentrations are low in Resolute. Lead concentrations at Sylvia Grinnell were found to vary from 8.0 to 1185 mg/kg (Peramaki and Decker 2000), clearly exceeding CCME limits. The population of Iqaluit is around 4000 and is rapidly expanding, making waste disposal in this area a growing problem. Resolute is a smaller community, generates less waste and consequently has lower Pb concentrations. However, Pb is still being issued from the waste disposal site and care should be taken to ensure that environmental regulations are being met.

Other environmental factors

No significant relationship between cadmium and lead was found for soil moisture. There was also no significant relationship between cadmium and lead concentration and pH. The pH in this study ranged from 7.1–10.1 with an average of 8.2 ± 0.1 ($n = 80$). It is well known that pH affects the solubility, sorption, and mobility of heavy metals (Essington 2004). At pH 8.0, lead sorption is through ion exchange and surface precipitation due to hydrolysis (Papelis and Um 2001). Low pH environments make cationic metals more mobile since they have to compete for exchange sites with HP^+ ions (Altin *et al.* 1999). Therefore, the alkaline pH of this waste disposal site enhances Cd and Pb sorption, ultimately immobilizing these contaminants. Pangnirtung (66°09′N, 65°43′W) is a more acidic environment with a pH ranging from 5.6–7.8 (Haertling 1989). Here, it is likely that metal mobilization would be more widespread, posing a greater contamination risk.

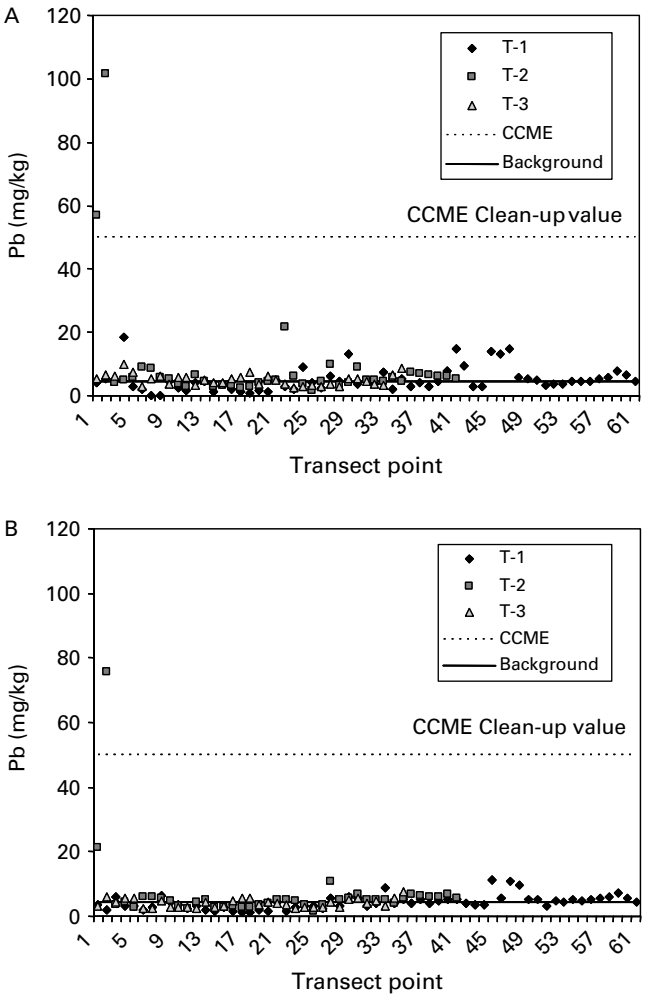

Figure 6 Concentration of lead in soil samples: (a) surface soils (0–100 mm) and (b) subsurface soil samples (100–250 mm). CCME clean-up value is 50 mg/kg and the background level is 4.6 mg/kg

Conclusions

Cadmium was found in all water samples: while concentrations are low, they were still above the threshold set out by the CCME guidelines. Spatial differences in concentrations also occurred. These results confirm the mobility of this metal in solution and indicate that different mechanisms are at play in the dumpsite. First, Cd concentrations were higher at Transect 3 than the other two transects. This area was in direct receipt of sewage lagoon waters along with meltwaters from the snowbank which were moving through contaminated ground. The increase in concentration along Transect 1, with distance from the snowbank, indicates the importance of topography (Lund and Young 2005) in facilitating contaminant movement. Steeper ground in this area enhanced meltwater runoff, allowing Cd to be transported a greater distance.

Soil material affects cadmium and lead mobility in a variety of ways. First, soils with little organic matter do not have as many exchange sites present on soil particles allowing for metal sorption. This was evident as the gravel ground type experiences less Pb sorption than soils with higher organic content. Similarly, there is a negative feedback effect regarding the relationship between soil organic matter and moisture. In High Arctic environments, soil

organic matter is usually present in abundance where soil is very moist or saturated. The high organic content will promote metal sorption, but the high moisture content, if it gives rise to surface flow, may transport metals.

There was no marked relationship between soil moisture and metal concentration found in this study. It is likely that soil moisture has less of an effect on Pb than Cd, due to lead's ability to strongly sorb to soil particles. In addition, no Pb was found dissolved in water samples, confirming lead's strong affinity to soil.

Large spikes in both Cd and Pb in Transect 2 indicates that more effort should go in to examining "hot spots" within these types of dump sites (i.e. sampling a shorter distance from old drums, etc.) and identifying the potential for movement away from these sites to nearby sensitive ecological sites.

Overall, there is little contamination risk from cadmium and lead at the waste disposal site. The great majority of all soils sampled were well below remediation levels set out by CCME. The site's alkaline soils and low organics are also effective in making metals relatively insoluble. While our data suggest minimal risk at this time, accelerated development in the north (e.g. mining development), together with the threat of climate change (ACIA 2005), signals that regular monitoring of these small waste sites is still warranted, so as to identify possible elevated concentrations and to track movement into ecologically sensitive areas.

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