Appl. Sci. **2014**, *4*, 240-254; doi:10.3390/app4020240

OPEN ACCESS

applied sciences

ISSN 2076-3417

www.mdpi.com/journal/applsci

Article

Mobilization of Toxic Elements from an Abandoned Manganese Mine in the Arid Metropolitan Las Vegas (NV, USA) Area

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Received: 2 January 2014; in revised form: 21 April 2014 / Accepted: 23 April 2014 / Published: 12 May 2014

Abstract: Active and abandoned mines may present health risks, especially to children, from environmental exposure to airborne chemical elements, such as Pb, As, and Mn. X-ray fluorescence analysis of tailings at the Three Kids Mine show they contain high levels of: Pb (15,300 mg/kg), As (3690 mg/kg), and Mn (153,000 mg/kg). Soil was sampled along eight transects, radiating from the dried tailings ponds. Concentrations of Mn and Pb to the NE are at background concentrations at 4.8 km, and, As and Sr at 3.2 km from the mine. Going SW to the City of Henderson, all elements are at background at 1.6 cm, with the closest houses at 1.8 km. The United States Environmental Protection Agency (USEPA) Regional Screening Levels (RSLs) are exceeded for Pb, As and Mn at 0.8 km on all transects except one. The RSLs are exceeded for Pb, As and Mn on the NE transects at 1.6 km. Future home sites are on a NE transect between 0.4 km and 2.3 km downwind from the tailings ponds, in an area highly impacted by tailings which exceed the USEPA RSLs. This research demonstrates that there has been the farthest transport of tailings offsite by the prevailing winds to the NE; the closest currently-built homes have not received measurable tailings dust because they are upwind; and that precautions must be taken during the proposed remediation of the mine to restrict dust-transport of Pb, As, and Mn to avoid human exposure and ecological damage.

Keywords: abandoned manganese mine; tailings; X-ray fluorescence; lead; arsenic; manganese; strontium; EPA-RSL; transport

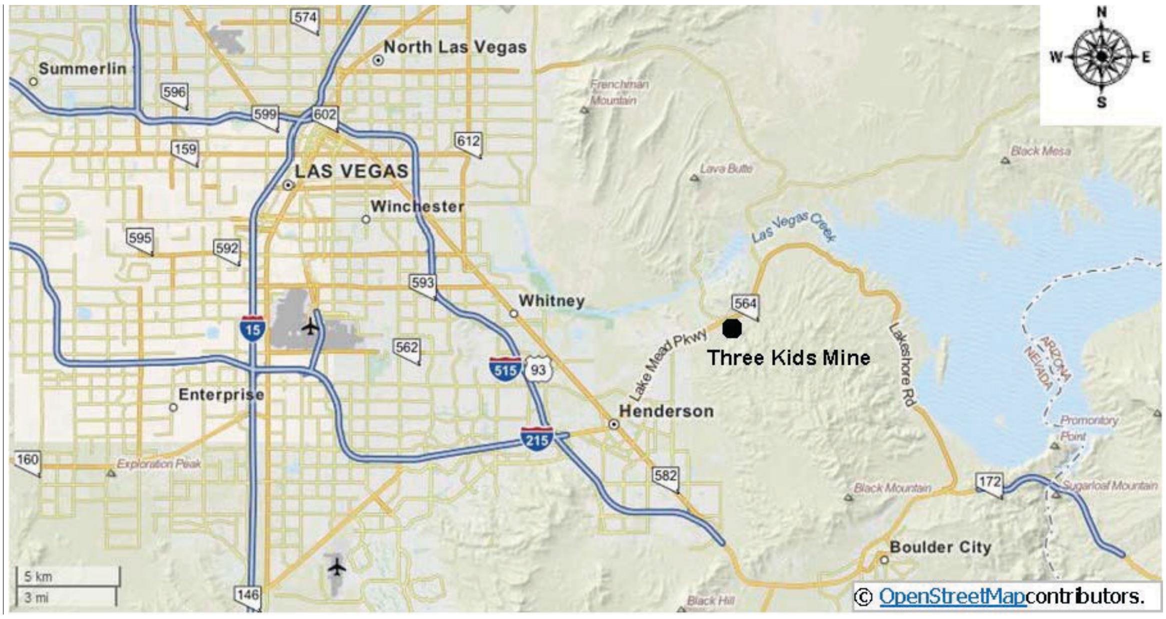
1. Introduction

The tailings ponds at the Three Kids Mine (TKM) cover an area of approximately 0.4 km^2 and their dry surface soil contains, according to the results reported herein, high concentrations of Mn (153,000 mg/kg), Sr (18,700 mg/kg), Pb (15,300 mg/kg), As (3690 mg/kg), Zn (2050 mg/kg), and are enriched in Cu (260 mg/kg). Since this mine is located in an arid climate with frequent high winds, and dust devils, the transport of tailings particulates offsite is highly probable. Four hypotheses were formulated to be tested during the study of this abandoned mine: (1) the most distant transport of particles containing Mn, Sr, Pb, As, Zn, and Cu from the surface of the dried tailings ponds will be found to be in directions predicted from wind rose diagrams from the closest air quality monitoring station; (2) toxic material has been carried offsite; (3) the concentrations of Mn, Pb, and As offsite will exceed the U.S. Environmental Protection Agency's Regional Screening Levels (EPA RSLs); and (4) the sensitivity of the portable X-ray fluorescence spectrometer will be sufficient to follow the concentrations of several toxic elements from the center of the tailings ponds to background levels offsite.

Of the elements found in high concentrations at the TKM, the toxic effects of Pb and As in the environment are well known [1]. A report on the chronic exposure to airborne manganese (Mn) in the vicinity of an active Mn mine in Mexico, suggests that "airborne Mn-environmental exposure is inversely associated with intellectual function in young school-age children" [2]. Another study of children living near active Mn mining operations in the Ukraine concludes that "chronic Mn exposure is a health hazard" [3]. Additionally, a study of mineworkers in South Africa concludes that there were "adverse effects on the central nervous system" from breathing Mn-containing dust [4]. Manganism, or manganese poisoning, results in impaired motor functions, psychiatric disturbances, and symptoms resembling Parkinson's disease [5]. Chronic inhalation of Mn in excess of 5 μg/m^3, may result in manganism [6]. In a report on strontium in soil, the authors conclude that there was a significant increase in the clinical signs of rickets when the concentration of Sr in the soil was greater than 350 mg/kg [7]. The EPA has established RSLs for Mn, Sr, Pb, As, Zn, and Cu [8]. The RSLs "are based on human risk assessment, but do not address ecological risk" [8]. The RSLs are not cleanup levels, but suggest that more information is needed on: "the site, land use, impacted media, and the likely pathway for human exposure" [8].

The TKM is an abandoned manganese mine, which is located in metropolitan Las Vegas, NV, USA (population 2.0 million [9]), on the eastern border of the City of Henderson (population 270,000) [9]. The mine is located about 8 km NE of downtown Henderson, 20 km SE of downtown Las Vegas, and 18 km east of McCarran International Airport, see Figure 1. It was discovered in 1917 and operated intermittently when the need for manganese was stimulated by WWI, WWII, and the cold war [10–14]. When in operation, the TKM was an open-pit mine and processing operation. The mine accounted for a third of the Mn production in the U.S. from 1955 to 1961 [15]. During the years it was active, the TKM contributed significantly to the development of the cities of Henderson and Las Vegas, and the state of Nevada. At the high temperatures reached during the calcination process, Pb and Zn were released to the atmosphere [10]. It is one of thousands of abandoned mines in the state of Nevada [16].

Figure 1. Location of Three Kids Mine in Nevada.

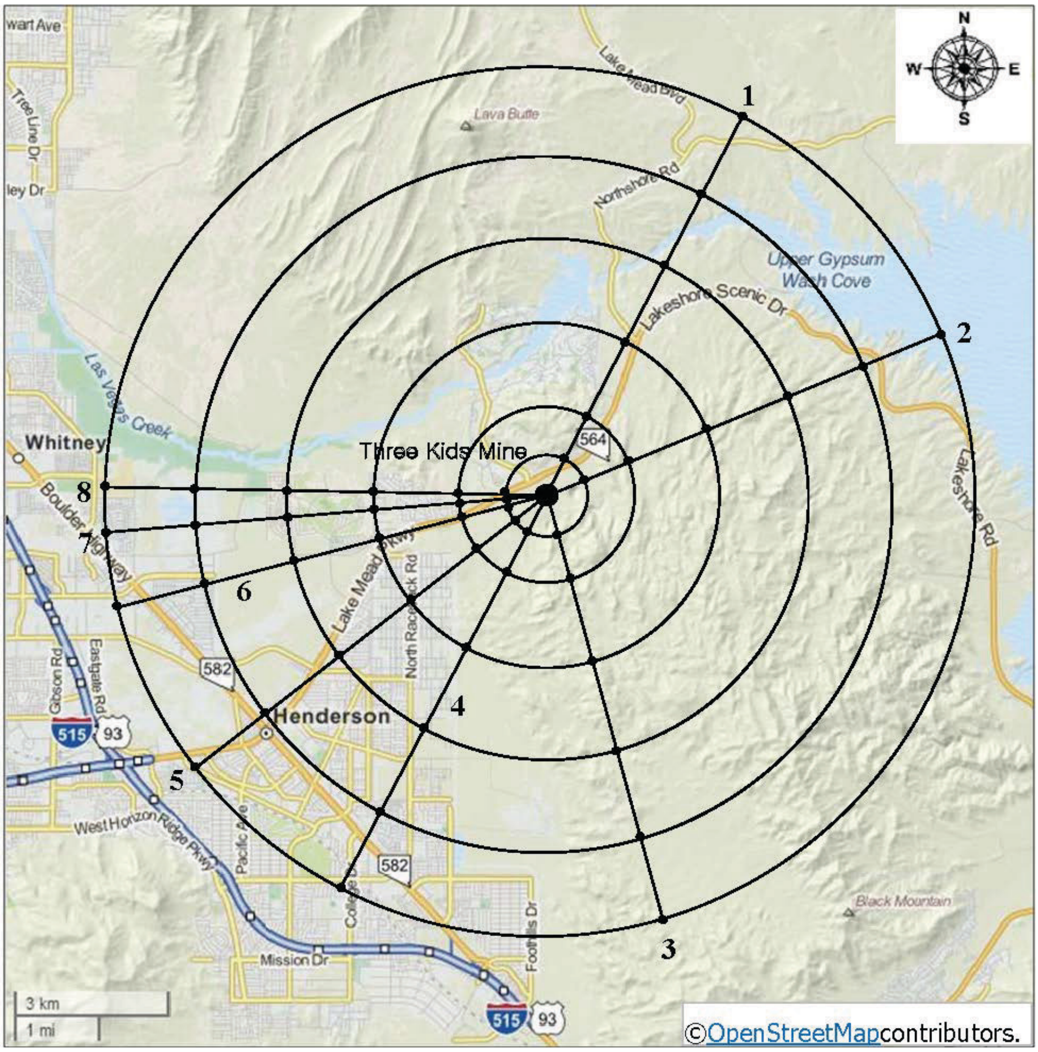


The mine site has: (1) large-unprotected tailings ponds (containing approximately 2 to 3 million cubic meters of material) with high concentrations of lead, arsenic, manganese, strontium, and petroleum hydrocarbons; (2) large quantities of waste rock; (3) four open pits; and (4) the remains of seven circular ore processing thickeners [10,13,14,17]. The TKM has been abandoned for about 50 years in this arid environment, while the growing city of Henderson encroached upon its boundaries. There are occupied houses, in Lake Las Vegas Resort, within 0.8 km to the north of the tailings ponds and newly graded pads are within 0.5 km to the NE. Another subdivision, called Calico Ridge, is 1.6 km to the NW. The mine borders on Lake Mead Parkway, which leads east 1.6 km to the 6053 km^2 Lake Mead National Recreation Area (LMNRA) [18]. Lake Mead is the largest volume water reservoir in the United States and is used for drinking water and irrigation water in Nevada, Arizona, California, and Mexico [19].

The U.S. House of Representatives passed a bill, HR697, called "The Three Kids Mine Remediation and Reclamation Act" in July of 2010, but it died before action by the U.S. Senate [20]. The bill was reintroduced and passed the house in July of 2012, but there has still been no action by the Senate [21]. After the proposed cleanup, land developers plan to build a residential community on 900 acres of the proposed 1262-acre site (total acreage with the proposed addition of some government-owned land) [14,22]. During the remediation, it is planned to move approximately 12 million cubic meters of the tailings material and waste rock, and dump it into the open pits from where the manganese bearing ore was mined [21–23].

Early investigations of the site produced three M.S theses in Chemistry at the University of Nevada, Las Vegas (UNLV) [23–26]. The results of these studies showed that there is wide-spread contamination of manganese, lead, and arsenic on the surface soils due to past mining activities. The present study was undertaken to ascertain how far material, attributed to mining activities, has traveled off-site, if at all, from the tailings ponds.

Figure 2. Sampling Locations on eight transects at 0.8 km, 1.6 km, 3.2 km, 4.8 km, 6.4 km, and 8.0 km around the middle point of the Three Kids Mine tailings ponds. Google Earth.



2. Experimental Section

2.1. Sampling Site Selection

A sampling map was created to investigate the directional transport of tailings from the approximate center of the tailings ponds. Eight transects were chosen based on: (1) wind data from the closest continuous air monitoring site (CAMS 298, 12 km to the SW of the TKM), that is maintained by the Clark County Department of Air Quality and Environmental Management (CCDAQ & EM) [27], and (2) a requirement that the topsoil be undisturbed for the last 50 years, since the mine closed. Wind data was used to construct a wind rose diagram. The wind rose diagram shows that the wind direction at the monitoring site is predominantly from the SW. If this was representative of the wind direction at the TKM, the tailings would be carried primarily toward vacant land and Lake Mead. However, since the mine is flanked by mountains on the east and south, the wind direction at the mine could be unpredictable. It was decided to set transects primarily toward Henderson where the population density is high, others toward Lake Mead, and in any other direction where the land appeared to be untouched by human activity in the last 50 years [24,27–29]. There has been major home construction to the north of the mine and massive work on the Las Vegas Wash to the north. Unfortunately, undistrubed land in those directions could not be found for sampling. The sampling diagram that resulted is shown in Figure 2. Sampling was conducted at 0.8 km, 1.6 km, 3.2 km, 4.8 km, 6.4 km, and 8.0 km along eight transects, which emanate from the middle point of Three Kids Mine tailings ponds at N36°4.993', W114°55.196' (Figure 2). The tailings ponds, whose surfaces are dry, constitute a point source of possible pollution to the surrounding offsite environment.

2.2. Sample Collection

Sampling was conducted during the summers of 2010 and 2011. A total of 124 samples of topsoil (about 3.5 kg) were collected to a depth of 0.5 cm using a square-edged stainless steel shovel and subsequently transferred to new Ziploc® polypropylene bags (Indianapolis, IN, USA). The samples were assigned an I.D. and sealed. Each field sample from the 48 intersections of transects and radii, was a composite of five samples. One sample was taken at the intersection and combined with soil from the four corners of a 3 m square plot, centered about the intersection. The location of each intersection was established with an Etrex global positioning system (Garmin International, Inc., Olathe, KS, USA), along with the temperature and wind direction. If the sample site was disturbed from anthropogenic activities, a nearby site was used if it met the sampling requirements. In addition to the presence of very mature natural shrubs, varnished rocks with only top-side varnish were often present, suggesting that the site had been undisturbed for thousands of years [30,31]. Sometimes the samples were taken under bushes, where there was a sufficient quantity of topsoil.

2.3. Analytical Methods

Soil samples were stored in the plastic collection bags prior to laboratory analysis. They were analyzed at the UNLV Environmental Health Laboratory and Department of Chemistry. The composite sample (five soil samples from each site) was thoroughly mixed, air-dried, sieved (2.29 mm), and placed in polyethylene, open-ended XRF samples cups (Chemplex® Industries, Inc., PalmCity, FL, USA). Three analytical samples were prepared from each composite sample. The sample cups were capped on one end with Diamond® plastic wrap (Reynolds consumer products, Richmond, VA, USA), filled with 16–18 g of soil, and capped on the other end. The chemical composition at each site of triplicate samples was determined with a Niton XLp 703A portable X-ray spectrometer, equipped with a 40 mCi ^{109}Cd radioisotope source and a silicon PIN Peltier-cooled detector (Thermo-Scientific Niton, Tewksbury, MA, USA). This instrument was designed to measure 15 elements. They are, in order of increasing atomic number (with detection limits in mg/kg in parenthesis): Cr (115), Mn (60), Fe (100), Co (50), Ni (75), Cu (50), Zn (30), As (10), Se (7), Rb (5), Sr (10), Zr (5), Mo (5), Hg (15), and Pb (12). The soil samples were measured for 60 s in bulk sample mode. Each triplicate sample was analyzed six times, three runs from the top of the sample cup and three runs from the bottom. Thus, each composite sample concentration value is the average of 18 measurements. The XRF's readout is in ppm (mg/kg) with ± one standard deviation.

2.4. XRF Quality Assurance

EPA Method 6200 "Field portable x-ray fluorescence spectrometry for the determination of elemental concentrations in soil and sediment" was followed for accuracy and precision of the XRF measurements [32]. The method uses 20% as an upper limit for both accuracy and precision. The Standard Reference Materials used were NIST SRM 2709, San Joaquin Soil (low level) and NIST SRM 2711, Montana Soil (high level).

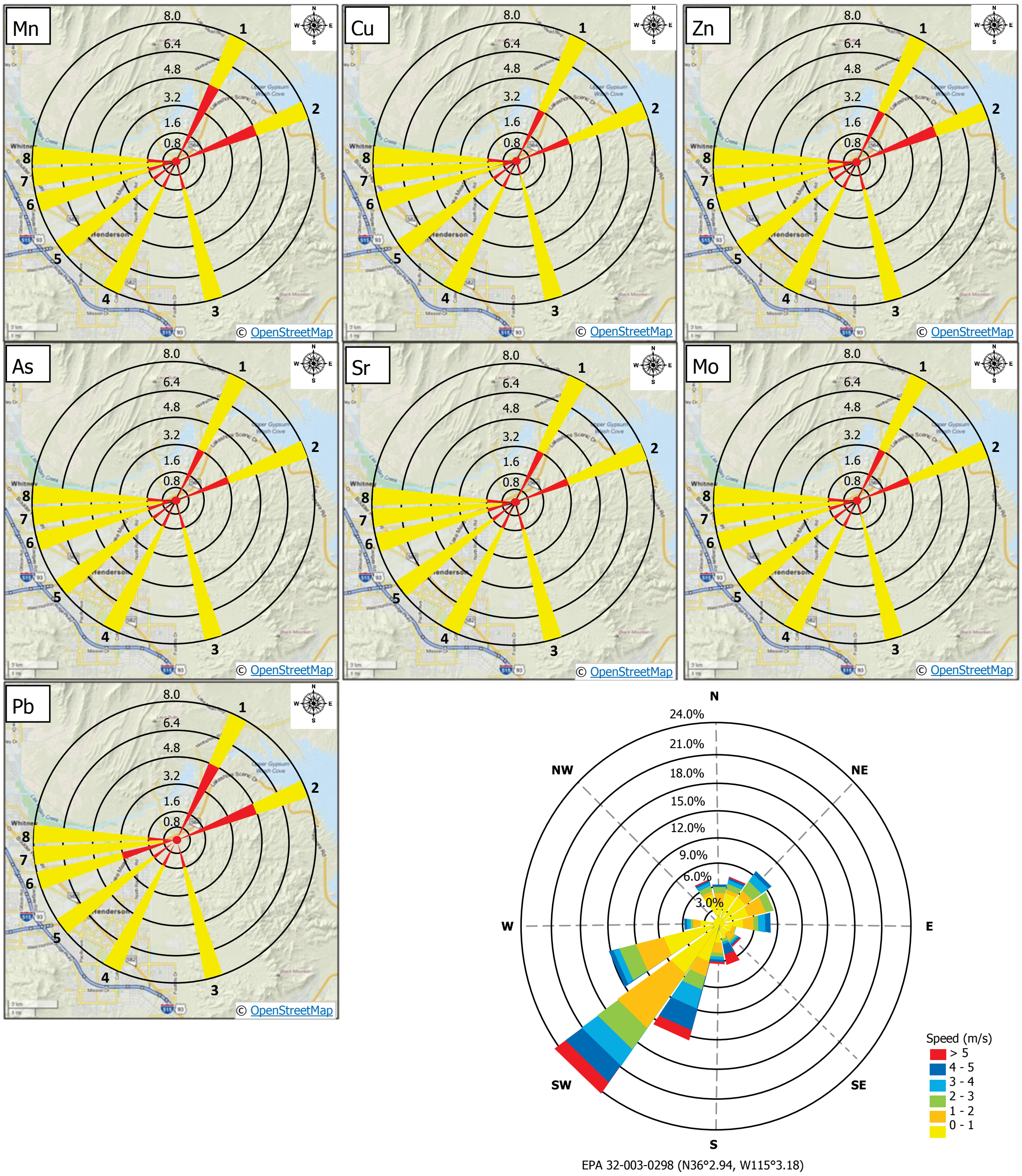
3. Results and Discussion

The results for all of the concentrations of the elements in the composite surface soil samples are found in Appendix Table A1. In this paper, the elements are generally listed in order of increasing atomic number or decreasing concentration. The concentration values for the tailings soil are the average values from 17 samples collected from throughout the tailings ponds. The ponds are on the N.W. edge of the mine site. Not surprisingly, nine of the elements measured have their highest values in the tailings ponds. These concentrations are, in order of decreasing concentration: Mn (153 ± 0.01) × 10^3 mg/kg or 15.3% ± 0.1%; Fe (40.8 ± 0.4) × 10^3 mg/kg or 4.08% ± 0.04%; Sr (18.7 ± 0.1) × 10^3 mg/kg or 1.87% ± 0.01%; Pb (15.3 ± 0.1) × 10^3 mg/kg or 1.53% ± 0.01%; As (3690 ± 80) mg/kg; Zn (2050 ± 50) mg/kg; Cu (260 ± 40) mg/kg; Rb (120 ± 10) mg/kg, and Mo (44 ± 3) mg/kg). The concentration of Zr (190 ± 30) mg/kg is lower than offsite. Five elements (Cr, Co, Ni, Se, and Hg) are below the limit of detection (LOD) of the XRF instrument. In one place, where the tailings had been washed away exposing a shelf, samples were collected to a depth of about 30 cm. Analysis showed that the concentrations of all of the elements in this vertical profile were uniform to 30 cm.

Along the eight transects, going from the Three Kids Mine tailings ponds to 8.0 km, the concentrations of nine elements decrease, or level off, to what appears to be background concentrations. Manganese goes from 153,000 mg/kg to 580 mg/kg; Fe 40,800 mg/kg to 25,000 mg/kg; Cu 260 mg/kg to <50 mg/kg; Zn 2050 mg/kg to 69 mg/kg; As 3690 mg/kg to <10 mg/kg; Rb 120 mg/kg to 79 mg/kg; Sr 1,8700 mg/kg to 730 mg/kg; Mo 44 mg/kg to <5 mg/kg; and Pb 1,5300 mg/kg to 43 mg/kg. On the other hand, Zr appears to be depleted in the tailings relative to background and goes up from 190 mg/kg in the tailings to background levels of about 360 mg/kg. The presence of Sr in the tailings is most likely because it was used in calcination at the mine [24].

Figure 3 contains transport diagrams for each element of interest and shows where the concentrations reach background concentrations (in yellow). The direction and distance of transport of contaminated soil from the mine, for the elements, is along the transect lines or spokes. These diagrams could be called dispersal diagrams, since they show the distances and directions to which particles from the mine have been dispersed. For comparison, the wind rose diagram from the closest air quality monitoring station is in the lower right hand corner. It shows the velocity frequencies and directions from which the winds come from.

Figure 3. Transport diagrams of the chemical elements in the tailings of the Three Kids Mine. The yellow color begins closest to the tailings ponds, where the concentrations first drop to background levels. OpenStreetMap.



Transect 1 goes to the NNE and intersects Lake Las Vegas property after it crosses Lake Mead Parkway, see Figure 3. There are newly graded house pads from about 0.4 km from the tailings ponds to 2.4 km, where the transect exits Lake Las Vegas property and continues to 8 km through desert land in the Lake Mead National Recreation Area (LMNRA). Transect 2 goes to the ENE and is in the LMNRA after it leaves the mine site. Transect 3 goes to the SSE and does not encounter developed land by 8.0 km. This transect crosses low mountains at the edge of the mine site and continues through mountainous terrain. Transect 4 is to the SSW and intersects occupied houses at 4.0 km. Transect 5 extends to the SW, toward downtown Henderson and encounters houses at 2.5 km. Transect 6 goes

WSW toward the city of Henderson and intersects houses in Calico Ridge at 1.8 km. Transect 7 goes W toward the north edge of Henderson and intersects houses at 1.8 km in Calico Ridge. Transect 8 goes west into South Las Vegas, toward the Las Vegas strip and intersects Calico Ridge houses at 2.4 km. The McCarran International Airport is between Transects 7 and 8 about 18 km to the west.

The yellow color on the transport diagrams in Figure 3 is the first site where the sample contained background concentrations of the elements in question. A closer look at the Mn concentration data (Appendix Table A1) in Transects 1 and 2 suggests that the concentrations decrease continuously from the tailings ponds out to 8.0 km. However, if a three-measurement standard deviation (3σ, 99.7%) probability difference is required between the sample measurements, then background concentrations are reached at 4.8 km, meaning that concentrations of Mn fall to background somewhere between 3.2 km and 4.8 km. The background concentrations for Sr and Pb were identified as the point where concentrations drop to average values and required a judgment call by the authors. However, the data for Cu, Zn, As, and Mo show a clear transition from contaminated soil at the tailings ponds to background values as the distance increases. Thus, Cu, As, Sr, and Mo concentrations are at background levels at 3.2 km on Transects 1 and 2. Zinc reaches background at 3.2 km on Transect 1 and 4.8 km on Transect 2. Like Mn, Pb concentrations in soil are at background on these transects at 4.8 km, like. Thus, the transport diagrams in Figure 3 for Mn, Cu, Zn, As, Sr, Mo, and Pb show the same result, maximum transport on Transects 1 and 2 to the NE.

For comparison, the wind rose diagram in the lower right hand corner (drawn from data recorded at the closest air quality monitoring station 12 km to the SW [27]), shows the velocity frequencies and directions from where the winds blow. The wind direction with the longest spoke shows that the highest frequency winds come from the SW and blow to the NE. On either side of this spoke, there are the two next-largest spokes, also showing wind directions from the SSW and WSW. This wind direction is very similar to the dispersal of TKM tailings into the environment to the NE as shown in Figure 3, and supports dispersal of particulates from the tailings ponds to the NE by the winds.

On Transect 3, background concentrations of Mn, Zn, As, Sr, and Pb are reached at 1.6 km and Cu and Mo fall to background at 0.8. There are no houses on this transect. All elements fall to background concentrations by 1.6 km on Transect 4. There are no houses on this transect until 4 km. All elements fall to background by 1.6 km on Transect 5, before the first houses at 2.5 km. However, Mn goes back up slightly above background at 8.0 km. There is no explanation for this. Concentrations of Mn, Zn, As, Sr, and Mo fall to background by 1.6 km on Transect 6. Copper reaches background by 0.8 km and Pb reaches background by 3.2 km. Houses are at 1.8 km. Transport on Transect 7 is the lowest, with Mn, Cu, Zn, As, Sr, and Mo reaching background before 0.8 km, and Pb by 1.6 km. Houses begin at 1.8 km. On Transect 8 all elements reach background by 1.6 km, with houses at 2.5 km. The transport diagrams in Figure 3 are very useful and akin to wind rose diagrams.

Table 1 lists the elemental concentrations in the tailings, the average background concentration, the tailings/background, the crustal abundance concentration [33], EPA's Regional Screening Levels (RSLs) and the ratio of the elemental concentration in the tailings to the RSL. The RSLs are not cleanup levels, but, when exceeded, suggest that more information is needed [8,34]. Only Mn, As, and Pb exceed the RSLs in the tailings, Mn by 85 times, As by 6000 times, and Pb by 38 times. The EPA RSLs are also exceeded for As, Pb, and Mn at 0.8 km on Transects 1, 2, 3, 4, 5, 6, and 8. Only on Transect 7 are the RSLs not exceeded at 0.8 km. At 1.6 km, only Mn, As and Pb exceed the RSL on

Transects 1, 2, and 5. The RSL for arsenic is very low, 0.6 mg/kg, far below the XRF detection limit of 10 ppm. Thus, As could be measurable farther out on the transects with a more sensitive instrument. However, since As seems to follow the other elements, it is likely that background As levels in soils are reached at the same distances that background concentration are reached by all other elements measured. Interestingly, the crustal abundance for As is 10 ppm, and, the background concentrations of all other elements measured in this study are close to the crustal abundances listed in reference [31].

Table 1. Concentrations of the elements in the tailings, "background", tailings/"background", natural abundance [31], U.S. Environmental Protection Agency's (EPA's) RSL (Regional Screening Levels) and the tailings/RSL [2].

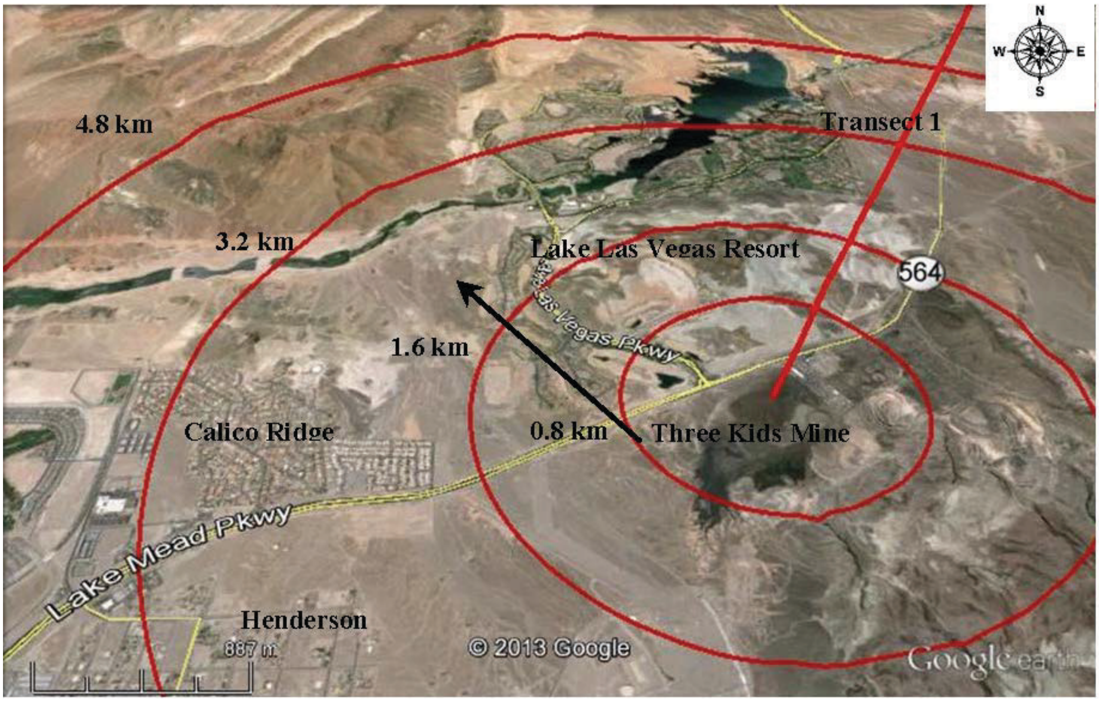
Element	Tailings (mg/kg)	Background (mg/kg)	Tailings/ background *	Natural abundance (mg/kg)	EPA's RSL (mg/kg)	Tailings/ RSL
Mn	1.53×10^5	580	264	440	1.8×10^3	85
Fe	4.08×10^4	2.5×10^4	1.63	$0.5–5 \times 10^4$	5.5×10^4	0.7
Cu	260	<50	13	20	3.1×10^3	0.084
Zn	2050	69	30	64	2.3×10^4	0.089
As	3690	<10	369	10	6.1×10^{-1}	6000
Rb	120	79	1.5	30–250		
Sr	1.87×10^4	730	26	$18–3.5\times 10^3$	4.7×10^4	0.40
Zr	190	360	0.5	35–550		
Mo	44	<5	22	2	3.9×10^2	0.11
Pb	1.53×10^4	43	356	23	4.0×10^2	38

* Natural abundance used if "background" less than LOD.

Figure 4 is a Google® photo of the mine site showing the two major housing projects, Lake Las Vegas and Calico Ridge. The partial sampling radii are shown for 0.8 km, 1.6 km, 3.2 km and 4.8 km. The 1.6 km radius just shy of the eastern edge of Calico Ridge and the 3.2 km radius cross through the NW edge of Calico Ridge. Soil samples are at background levels for all of the chemical elements before reaching Calico Ridge's eastern edge. There are houses in Lake Las Vegas at the 0.8 km, 1.6 km, and 3.2 km radii. Unfortunately, no transects were taken going to the N and NW, because of the extensive anthropogenic activity since 1980: house construction, road building, landscaping and construction of weirs on the Las Vegas Wash. The wind rose diagram in Figure 3 shows that there are low frequency winds from the S, SSE and SE, which have episodes of winds with speeds of >5 m/s. Along with wind devils that occur periodically, one could speculate that there is transport of tailings to the N, NNW and NW to 0.8 km. Also, there is transport of tailings to 0.8 km on all transects, except Transect 7 (which goes west). Transect 1 passes through the light gray new home sites across Lake Mead Parkway. These future home sites are on this NE transect between 0.4 km and 2.3 km downwind from the tailings ponds, in an area highly impacted by tailings which exceed the USEPA RSLs.

In the NE corner of the tailings ponds (Figure 4), there is a short white line near the base of the Transect 1 arrow. This is a bike rental-boat storage business. It is definitely impacted by tailings transport to the NE. At the base of the tailings ponds is a water culvert, where the black arrow crosses Lake Mead Parkway. It is apparent that water runoff from the tailings ponds does not carry tailings downhill to the City of Henderson, but is almost immediately channeled to this culvert which goes under Lake Mead Parkway (the black arrow in Figure 4) onto property belonging to the Lake Las Vegas Resort. It ultimately goes into the Las Vegas Wash. Before Lake Las Vegas was built, the runoff from the tailings ponds flowed freely downhill to the Las Vegas Wash, which in turn discharged into Lake Mead. In addition, in Figure 4, is Lake Las Vegas, a man-made lake. The Las Vegas Wash flows under this lake on its way to Lake Mead. Over the years, large quantities of tailings must have been transported by water to the wash and to Lake Mead.

Figure 4. Photo showing encroachment of housing projects in the vicinity of the TKM. The light colored area to the east and just north of Lake Mead Parkway has new home sites. Google Earth.



4. Conclusions

- The Three Kids Mine tailings may present human health risks from their transport offsite on airborne particles. The XRF was used to successfully follow the concentrations these and other tailings elements to background levels along eight transects leading away from the dried tailings ponds.
- The most distant transport of Mn, Cu, Zn, As, Sr, Mo, and Pb is to the N.E. from the tailings ponds on Transects 1 and 2. A wind rose diagram from the closest air quality monitoring station data, situated to the SW of TKM, shows that the predominant winds are from the SW, suggesting that the predominant dispersal of mine tailings will be to the NE, in agreement with results shown in transport diagrams for the tailings chemical elements. Future home sites are on a NE transect between 0.4 km and 2.3 km downwind from the tailings ponds, in an area highly impacted by tailings which exceed the USEPA RSLs.

- Along all transects, except Transect7, the U.S. EPA Regional Screening Levels for As, Pb, and Mn are exceeded at 0.8 km. The RSLs are also exceeded for As, Pb and Mn on the two NE transects at 1.6 km.
- From visual inspection of the topography, water runoff from the tailings ponds is funneled downhill through a culvert under Lake Mead Parkway, through the Lake Las Vegas Resort, to the Las Vegas Wash. Thus, the results reported in the transport diagrams in Figure 3, are due to the mobilization of particulates from the mine by wind, not water transport.
- This research suggests that, because of the high concentrations of Mn, As, Sr, and Pb in the tailings, they may present a health hazard in relocating the tailings material back to the pits from which it came. Therefore, stringent precautions must be taken, if and when the proposed remediation of the TKM site goes forward, to prevent the tailings from being transported offsite as dust to the natural environment and to the surrounding occupied houses.

Appendix

Table A1. XRF results for Three Kids Mine Soil (1σ; 68% confidence interval).

Distance	Concentration of Manganese (mg/kg)							
	Transect 1	Transect 2	Transect 3	Transect 4	Transect 5	Transect 6	Transect 7	Transect 8
Tailings	153 ± 1 k	153 ± 1 k	153 ± 1 k	153 ± 1 k	153 ± 1 k	153 ± 1 k	153 ± 1 k	153 ± 1 k
0.8 km	126 ± 1 k	116 ± 1 k	13.4 ± 0.2 k	80.9 ± 0.6 k	74.0 ± 0.5 k	14.6 ± 0.2 k	920 ± 80	44.5 ± 0.4 k
1.6 km	32.9 ± 0.3 k	65.4 ± 0.5 k	NA	870 ± 90	420 ± 70	830 ± 90	520 ± 80	680 ± 90
3.2 km	1700 ± 100	1190 ± 90	500 ± 100	660 ± 80	630 ± 90	550 ± 80	430 ± 70	410 ± 80
4.8 km	630 ± 90	710 ± 80	300 ± 100	480 ± 80	980 ± 90	490 ± 80	NA	NA
6.4 km	410 ± 80	510 ± 80	380 ± 90	470 ± 80	900 ± 100	600 ± 100	430 ± 90	390 ± 80
8.0 km	290 ± 90	NA	420 ± 80	NA	1300 ± 100	<60	410 ± 80	360 ± 80
Distance	**Concentration of Iron (mg/kg)**							
	Transect 1	**Transect 2**	**Transect 3**	**Transect 4**	**Transect 5**	**Transect 6**	**Transect 7**	**Transect 8**
Tailings	40.8 ± 0.4 k	40.8k ± 0.4 k	40.8 ± 0.4 k	40.8 ± 0.4 k	40.8 ± 0.4 k	40.8 ± 0.4 k	40.8 ± 0.4 k	40.8 ± 0.4 k
0.8 km	27.1 ± 0.3 k	29.0k ± 0.3 k	19.5 ± 0.2 k	48.3 ± 0.4 k	27.2 ± 0.3 k	20.1 ± 0.2 k	18.9 ± 0.1 k	23.0 ± 0.2 k
1.6 km	18.3 ± 0.2 k	23.2k ± 0.2 k	NA	20.2 ± 0.1 k	16.1 ± 0.1 k	20.3 ± 0.1 k	17.7 ± 0.1 k	22.8 ± 0.2 k
3.2 km	24.5 ± 0.2 k	23.4k ± 0.2 k	20.8 ± 0.1 k	21.6 ± 0.1 k	23.1 ± 0.2 k	17.7 ± 0.1 k	14.5 ± 0.1 k	19.4 ± 0.1 k
4.8 km	24.1 ± 0.2 k	19.0k ± 0.1 k	19.2 ± 0.1 k	18.7 ± 0.1 k	20.9 ± 0.1 k	21.7 ± 0.1 k	NA	NA
6.4 km	20.9 ± 0.1 k	22.6k ± 0.2 k	19.8 ± 0.1 k	21.4 ± 0.1 k	26.3 ± 0.2 k	27.9 ± 0.2 k	24.0 ± 0.2 k	21.4 ± 0.1 k
8.0 km	20.5 ± 0.1 k	NA	23.2 ± 0.2 k	NA	28.2 ± 0.2 k	9680 ± 90	20.2 ± 0.1 k	19.9 ± 0.1 k
Distance	**Concentration of Copper (mg/kg)**							
	Transect 1	**Transect 2**	**Transect 3**	**Transect 4**	**Transect 5**	**Transect 6**	**Transect 7**	**Transect 8**
Tailings	260 ± 40	260 ± 40	260 ± 40	260 ± 40	260 ± 40	260 ± 40	260 ± 40	260 ± 40
0.8 km	220 ± 30	260 ± 50	<50	180 ± 30	120 ± 30	<50	<50	100 ± 30
1.6 km	110 ± 30	110 ± 30	NA	<50	<50	<50	<50	<50
3.2 km	<50	<50	<50	<50	<50	<50	<50	<50
4.8 km	<50	<50	<50	<50	<50	<50	NA	NA
6.4 km	<50	<50	<50	<50	<50	<50	<50	<50
8.0 km	<50	NA	<50	NA	<50	<50	<50	<50

Table A1. *Cont.*

Distance	Concentration of Zinc (mg/kg)							
	Transect 1	**Transect 2**	**Transect 3**	**Transect 4**	**Transect 5**	**Transect 6**	**Transect 7**	**Transect 8**
Tailings	2050 ± 50	2050 ± 50	2050 ± 50	2050 ± 50	2050 ± 50	2050 ± 50	2050 ± 50	2050 ± 50
0.8 km	920 ± 30	2710 ± 40	190 ± 10	860 ± 30	640 ± 30	260 ± 20	76 ± 11	340 ± 20
1.6 km	260 ± 20	480 ± 30	NA	78 ± 11	63 ± 11	78 ± 12	61 ± 11	84 ± 11
3.2 km	87 ± 12	160 ± 10	70 ± 10	78 ± 11	85 ± 12	68 ± 11	60 ± 10	60 ± 10
4.8 km	61 ± 12	60 ± 10	45 ± 10	63 ± 11	82 ± 11	56 ± 11	NA	NA
6.4 km	91 ± 11	81 ± 12	42 ± 11	59 ± 11	81 ± 12	74 ± 12	91 ± 12	58 ± 11
8.0 km	63 ± 11	NA	53 ± 11	NA	86 ± 12	83 ± 11	53 ± 11	44 ± 12
Distance	**Concentration of Arsenic (mg/kg)**							
	Transect 1	**Transect 2**	**Transect 3**	**Transect 4**	**Transect 5**	**Transect 6**	**Transect 7**	**Transect 8**
Tailings	3690 ± 80	3690 ± 80	3690 ± 80	3690 ± 80	3690 ± 80	3690 ± 80	3690 ± 80	3690 ± 80
0.8 km	2890 ± 60	820 ± 40	120 ± 10	2260 ± 50	1030 ± 40	420 ± 30	<10	820 ± 40
1.6 km	800 ± 40	800 ± 40	NA	<10	17 ± 5	<10	<10	<10
3.2 km	<10	<10	<10	<10	<10	<10	<10	<10
4.8 km	<10	<10	<10	<10	<10	<10	NA	NA
6.4 km	<10	<10	<10	<10	<10	<10	<10	<10
8.0 km	<10	NA	<10	NA	<10	<10	<10	<10
Distance	**Concentration of Rubidium (mg/kg)**							
	Transect 1	**Transect 2**	**Transect 3**	**Transect 4**	**Transect 5**	**Transect 6**	**Transect 7**	**Transect 8**
Tailings	120 ± 10	120 ± 10	120 ±10	120 ± 10	120 ± 10	120 ± 10	120 ± 10	120 ± 10
0.8 km	64 ± 7	53 ± 5	83 ± 4	150 ± 10	78 ± 8	45 ± 5	76 ± 3	60 ± 5
1.6 km	57 ± 5	44 ± 7	NA	71 ± 3	69 ± 3	74 ± 3	66 ± 3	79 ± 3
3.2 km	74 ± 3	79 ± 3	93 ± 3	70 ± 3	72 ± 3	62 ± 3	63 ± 3	55 ± 2
4.8 km	64 ± 3	85 ± 3	72 ± 3	76 ± 3	76 ± 3	75 ± 3	NA	NA
6.4 km	72 ± 3	73 ±3	87 ± 3	79 ± 3	74 ± 3	70 ± 3	70 ± 3	72 ± 3
8.0 km	70 ± 3	NA	86 ± 3	NA	63 ± 3	38 ± 2	63 ± 3	68 ± 3
Distance	**Concentration of Strontium (mg/kg)**							
	Transect 1	**Transect 2**	**Transect 3**	**Transect 4**	**Transect 5**	**Transect 6**	**Transect 7**	**Transect 8**
Tailings	18.7 ± 0.1 k	18.7 ± 0.1 k	18.7± 0.1 k	18.7± 0.1 k	18.7 ± 0.1 k	18.7 ± 0.1 k	18.7 ± 0.1 k	18.7 ± 0.1 k
0.8 km	13.63 ± 0.05 k	14.83 ± 0.05 k	3690 ± 20	9320 ± 40	18.54 ± 0.05 k	5180 ± 20	740 ± 10	8520 ± 30
1.6 km	7540 ± 30	14.14 ± 0.04 k	NA	800 ± 10	1890 ± 10	750 ± 10	860 ± 10	620 ± 10
3.2 km	990 ± 10	620 ± 10	710 ± 10	600 ± 10	680 ± 10	860 ± 10	830 ± 10	790 ± 10
4.8 km	990 ± 10	460 ± 10	600 ± 10	580 ± 10	550 ± 10	540 ± 10	NA	NA
6.4 km	660 ± 10	570 ± 10	500 ± 10	590 ± 10	740 ± 10	920 ± 10	870 ± 10	820 ± 10
8.0 km	660 ± 10	NA	440 ± 10	NA	830 ± 10	500 ± 10	660 ± 10	740 ± 10
Distance	**Concentration of Zirconium (mg/kg)**							
	Transect 1	**Transect 2**	**Transect 3**	**Transect 4**	**Transect 5**	**Transect 6**	**Transect 7**	**Transect 8**
Tailings	190 ± 30	190 ± 30	190 ± 30	190 ± 30	190 ± 30	190 ± 30	190 ± 30	190 ± 30
0.8 km	190 ± 20	210 ± 30	380 ± 10	160 ± 20	230 ± 30	220 ± 10	420 ± 10	270 ± 20
1.6 km	230 ± 20	200 ± 30	NA	430 ± 10	360 ± 10	400 ± 10	340 ± 10	560 ± 10
3.2 km	480 ± 10	560 ± 10	460 ± 10	460 ± 10	480 ± 10	340 ± 10	330 ± 10	330 ± 10
4.8 km	500 ± 10	630 ± 10	380 ± 10	390 ± 10	490 ± 10	510 ± 10	NA	NA
6.4 km	430 ± 10	600 ± 10	410 ± 10	400 ± 10	460 ± 10	480 ± 10	390 ± 10	410 ± 10
8.0 km	610 ± 10	NA	410 ± 10	NA	400 ± 10	190 ± 10	410 ± 10	360 ± 10

Table A1. *Cont.*

Distance	Concentration of Molybdenum (mg/kg)							
	Transect 1	Transect 2	Transect 3	Transect 4	Transect 5	Transect 6	Transect 7	Transect 8
Tailings	44 ± 3	44 ± 3	44 ± 3	44 ± 3	44 ± 3	44 ± 3	44 ± 3	44 ± 3
0.8 km	47 ± 3	54 ± 3	<5	29 ± 2	29 ± 3	20 ± 3	<5	23 ± 3
1.6 km	22 ± 2	22 ± 2	NA	<5	<5	<5	<5	<5
3.2 km	<5	<5	<5	<5	<5	<5	<5	<5
4.8 km	<5	<5	<5	<5	<5	<5	NA	NA
6.4 km	<5	<5	<5	<5	<5	<5	<5	<5
8.0 km	<5	NA	<5	NA	<5	<5	<5	<5
Distance	**Concentration of Lead (mg/kg)**							
	Transect 1	**Transect 2**	**Transect 3**	**Transect 4**	**Transect 5**	**Transect 6**	**Transect 7**	**Transect 8**
Tailings	15.3 ± 0.1 k	15.3 ± 0.1 k	15.3 ± 0.1 k	15.3 ± 0.1 k	15.3 ± 0.1 k	15.3 ± 0.1 k	15.3 ± 0.1 k	15.3 ± 0.1 k
0.8 km	12.4 ± 0.1 k	4260 ± 50	1060 ± 20	4820 ± 50	3880 ± 60	830 ± 20	96 ± 7	2530 ± 40
1.6 km	2100 ± 30	4170 ± 50	NA	76 ± 7	30 ± 10	100 ± 10	42 ± 6	72 ± 7
3.2 km	160 ± 10	110 ± 10	44 ± 6	60 ± 10	55 ± 6	32 ± 6	31 ± 5	24 ± 5
4.8 km	55 ± 7	62 ± 6	23 ± 5	39 ± 5	82 ± 7	40 ± 10	NA	NA
6.4 km	49 ± 6	53 ± 6	<12	35 ± 5	60 ± 10	26 ± 6	31 ± 6	22 ± 6
8.0 km	24 ± 6	NA	<12	NA	29 ± 6	<12	<12	21 ± 5

NA = Not Available due to measurements below the limit of detection (LOD) or not collected at the sampling site; 1k = 1000 mg/kg.

Conflicts of Interest

The authors declare no conflict of interest.

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