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Elevated soil and blood lead levels with increasing residential proximity to a mine tailings facility in Soweto, South Africa

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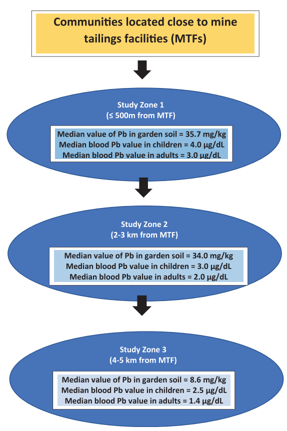
HIGHLIGHTS

- Pb exposure in South African metropolis intersected by gold mining waste facilities
- Decreasing soil Pb and blood Pb levels with increasing distance from mine tailings
- The study was conducted upwind of a mine tailings cluster.
- Implications for elevated community exposure to Pb downwind of gold mine tailings

GRAPHICAL ABSTRACT



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ABSTRACT

Mining has long been associated with the release of a range of toxic metals including lead, elevated levels of which have been found in land surrounding mine dumps as far afield as Spain, India, Macedonia and Nigeria. Mining has been a key pillar of economic development in South Africa for around a century and a half, and has left a legacy of major environmental contamination, with the poorest experiencing the highest burden of exposure. The current study was undertaken to ascertain the concentrations of lead in soil and in the blood of adults and children residing at increasing distances from a cluster of large tailings facilities (MTFs) in greater Johannesburg, South Africa. Through a cross-sectional survey data on household characteristics were collected through a questionnaire survey, and supplemented with samples of soil from household gardens, together with blood samples from child-adult pairs from all households included in the study. Soil lead concentrations decreased significantly (median = 35.7 mg/kg closest to the mine tailings facility (MTF) and 8.6 mg/kg at the furthest point in the study site) with increasing distance from the MTF. Blood lead levels were highest in both adults (median = 3.0 μg/dL) and children (median = 4.0 μg/dL) who lived closest (≤500 m) to the MTF, and lowest (1.4 μg/dL in adults and 2.5 μg/dL in children) in those who lived furthest away (4–5 km). The study findings point to a need for greater emphasis on the precautionary principle in environmental health and for health impact assessments to inform decisions on planning, especially with regard to the location of human settlements relative to major, polluting development initiatives.

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1. Introduction

There is widespread consensus regarding the toxicity of lead, especially to children and the developing fetus (Caito and Aschner, 2017). The detrimental cognitive and intellectual effects associated with prenatal and childhood exposure to lead are well established (Bellinger et al., 2018). More recently, lead exposure during childhood and at the prenatal stage, has also been associated with aggressive and violent behavior later in life (Wright et al., 2008). In adults lead exposure has been associated with elevated burdens of hypertension and cardiac disease (Lanphear et al., 2018; ATSDR, 2007). These and other concerns around lead exposure have led the World Health Organization to list lead among chemicals of global public health concern (WHO, 2015).

Mining has been associated with the release of a range of toxic metals including lead, elevated levels of which have been found in land surrounding mine dumps as far afield as Spain (García-Giménez and Jiménez-Ballesta, 2017), India (Naz et al., 2018), Macedonia (Serafimovski et al., 2018) and Nigeria (Opaluwa et al., 2012). Similarly, epidemiological studies conducted in various parts of the world have shown elevated human lead exposure in those living close to mining waste sites compared with those living further away (Loh et al., 2016; Kim et al., 2012). While childhood blood lead levels have been falling at a global level, there are certain locations, such as mining areas, in which they remain persistently elevated. In the 2011–2015 period, for example, studies showed that children living downwind of a mine had significantly elevated blood lead levels relative to their counterparts living upwind (Dong et al., 2019).

Mining has been a key pillar of economic development in South Africa for around a century and a half. While it has been a boon to certain groups, mining has also left a legacy of major environmental contamination, in both rural and urban areas, especially the poorest. Having commenced in the Johannesburg area in 1886, gold mining in particular has generated considerable amounts of waste material, mainly in the form of large mine tailings facilities (MTFs) containing a range of metals other than gold, including arsenic and lead (Olobatoke and Mathuthu, 2016). The MTFs range in size from a few hundred thousand up to a million cubic metres, and are usually situated near mining sites (Trois et al., 2007), and many are unrehabilitated (Mpanza et al., 2020; Agboola et al., 2020). Material from MTFs may be transported through environmental media, including soil, air, dust and water, across considerable distances, to cause exposure in human settlements (Fuller et al., 2022). Such MTFs dominate parts of the landscape of South African mining towns and cities such as Johannesburg. Poor planning policies and weak environmental controls have led to the development of human settlements close to MTFs, in some instances with negligible or absent buffer zones (Fig. 1) (Rösner et al., 1998). A growing number of studies undertaken in various parts of the country have demonstrated significant levels of contamination of land surrounding MTFs (Fashola et al., 2016; Dudu et al., 2018). However there is a particular dearth of epidemiological information regarding the human health risks associated with residency close to MTFs. This study sought to examine lead concentrations in residential garden soil and in the blood of members of households living at increasing distances from a large cluster of MTFs in Johannesburg.

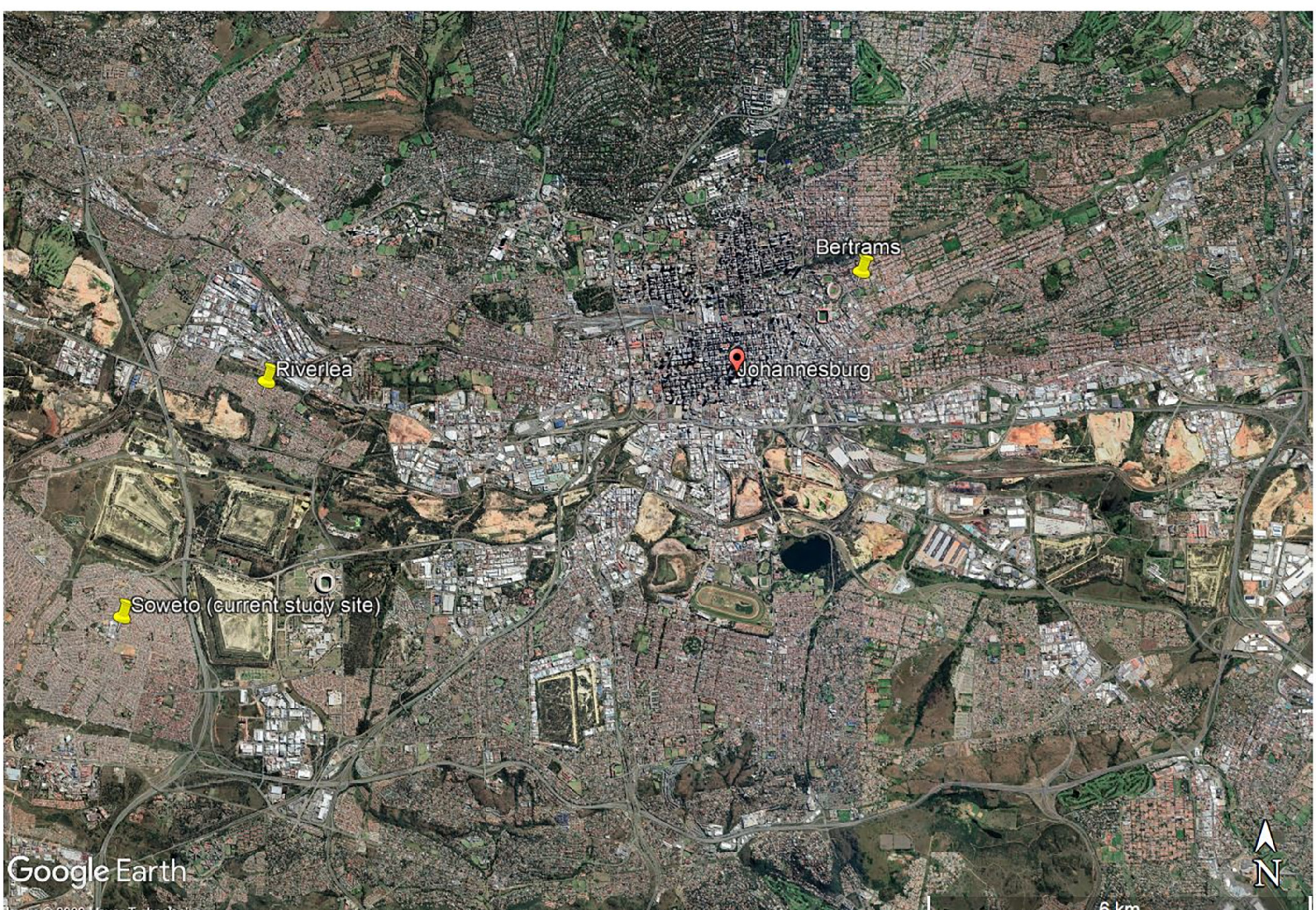

Fig. 1. Interspersion of mine tailing facilities and human settlements in Johannesburg, South Africa.

2. Methodology

2.1. Study area

A cross-sectional survey, stratified by three zones at increasing distance upstream from a cluster of MTFs in Soweto (specifically the suburbs of Diepkloof, Noordgesig, Orlando East, Orlando West and Meadowlands East), South Africa, was conducted. Zone 1 was located within 500 m of the MTF cluster, whiles zones 2 and 3 were 2–3 and 4–5 km away, respectively (Fig. 2).

2.2. Study population

In each zone dwellings were randomly selected for fieldworker visits to ascertain eligibility for inclusion in the study. Households living in the selected dwellings were eligible if they had resided in the area for at least three years, and if they included an adult and a child between the ages of 7 and 14 years who was willing to participate in the study. Households were defined as a group that shares the same meals at night. For those who provided written, informed consent, a pre-structured questionnaire was administered to a household member of at least 18 years of age to obtain information related to socio-economic status and risk factors for elevated lead exposure. Responses were entered onto a digital device loaded with Mobenzi software (http://www.mobenzi.com, Cape Town, South Africa), which allowed for data access and cross-checking in real time.

2.3. Soil sampling

Soil samples were collected from the garden, preferably where vegetables were grown or where children played most of the time, using the methods of the United States Environmental Protection Agency. Using a hand held auger, soil samples were collected into plastic zip lock bags, and transported to a laboratory, where they were dried in an oven at a temperature of 40 °C for a period of 48 h and milled prior to analysis with a hand held x-ray fluorescence analyser in accordance with the manufacturer's guidelines (Grodzins and Grodzins, 2004).

2.4. Blood sample collection

Venous blood (approximately 5 mL) samples were collected from all consenting (and in children also assenting) study participants by registered medical professionals for lead content analysis. Blood samples were collected into sterile test tubes containing ethylenediaminetetraacetic acid (EDTA), and kept under refrigeration prior to being transferred to Lancet Laboratories (https://www.lancet.co.za/) in Johannesburg for lead content analysis. Blood samples were analysed through ICP-MS (Inductively Coupled Plasma - Mass Spectrometry) using an Agilent 7900 ICP-MS instrument (Agilent Technologies, Santa Clara, California, USA). The lowest level of detection is 0.4 μg/dL.

2.5. Data analysis

To provide the required statistical power, and allowing for a 10 % non-response rate, it was ascertained that 180 households (60 in each zone) would be required. From each eligible household, one adult and one child was selected for the study, resulting in a total sample size of 360 participants. Data were entered into Mobenzi (mobile data collection and capturing tool) and exported into STATA statistical package version 14 for analyses. Descriptive statistics such as frequencies, percentages, mean,

Fig. 2. Location of stratified study Zones 1–3.

median, ranges and standard deviations were used to summarize data. The Chi-squared test was applied to determine the relationship between the socio-demographic profile of the study population and different types of zones. A Kruskal-Wallis equality of population rank test was applied to determine whether the mean blood levels among adults and children differed significantly across study zones.

2.6. Ethics

Prior consent to conduct the study had been obtained from the Human Research Ethics Committee of the South African Medical Research Council (Protocol number EC001-2/2015).

3. Results

The socio-demographic profile of the study population is given in Table 1, by study zone and for the total population. As can be seen, the study populations across the three zones were similar with respect to age distribution, sex, income, employment status, household size and type of cooking fuel. Unemployment was rife in the study communities, and the vast majority of households earned meagre incomes (overall the monthly income for 75.9 % of households was less than ZAR 5000/USD 337 [exchange rate on 22/10/2021]). Across study zones the samples differed with regard to home language, housing type (formal versus informal) and the presence of a ceiling.

Table 2 describes the lead concentrations in samples of residential garden soil collected across the three study zones. As can be seen the mean and median soil lead concentrations were highest in Zone 1, which was closest to the MTF cluster, and decreased with increasing distance from the cluster of MTFs. These differences were statistically significant.

In the total sample, adult blood lead levels ranged from 0.5 to 12.2 μg/dL, while in children the range was 0.8 to 16.1 μg/dL (Table 3). Blood lead levels in children (mean = 3.4 μg/dL) were higher than in adults (mean = 2.5 μg/dL); this applied to the total sample ($p = 0.001$), as well as to the sample within each Zone. Blood lead levels were highest in Zone 1, which was closest to the MTF cluster, and lowest in Zone 3 located furthest away. Zone 1 also had the highest proportion of both adults (20.8 %) and children (37.5 %) with blood lead levels ≥5 μg/dL (Table 3). Within households the blood lead level of the adults was predictive of the blood lead levels of children ($p \leq 0.001$).

Adult blood lead levels (P = 0.030), as well as blood lead levels in the total sample (P = 0.002) were significantly associated with soil lead concentrations; however, the relationship between soil and child blood lead levels did not reach statistical significance ($p = 0.250$). Child blood lead levels were however significantly associated with those of adults ($P < 0.001$).

4. Discussion

Lead concentrations in the majority of residential soil samples collected in this study undertaken in Johannesburg, South Africa, were below the reference levels for South Africa (99.4 %) and Canada (97.0 %). Nevertheless, analyses indicate that mean and median lead concentrations in the soil samples increased with increasing proximity to a cluster of MTFs resulting from gold mining in the area. All soil samples with elevated lead concentrations were collected in Zones 1 and 2 (closest to the MTFs), while none of the samples collected in Zone 3 exceeded either the South African or the Canadian guideline levels. Put another way, the soil lead concentrations in Zone 1 (around 500 m from the MTF) as well as Zone 2 (2–3 km from the MTF), were statistically significantly elevated compared with Zone 3, which was 4–5 km away from the MTF. The current study confirms in an African setting the trend of declining soil lead concentrations with increasing distance from mining sites that has been found around the world, including in the USA (Loh et al., 2016; Zota et al., 2011), Australia (Dong et al., 2019) and Brazil (Cunha et al., 2005), in currently operating as well as historical sites. Within South Africa, Maseki et al. (2017) found highly elevated levels of lead in soil in the vicinity of mines associated with the Witwatersrand Basin gold deposits, of which the mine tailings facilities around Soweto are part (Maseki et al., 2017).

The 2017 Lancet Commission on Pollution and Health identified pollution as "the largest environmental cause of disease and premature death in the world today". A recent update indicates inadequate action to prioritise pollution and public health (Fuller et al., 2022). Soil was identified as an important potential pathway of exposure to toxic metals (Landrigan,

Table 1
Socio-demographic profile of the study population.

Characteristics	Zone 1		Zone 2		Zone 3		*P*-value		Total sample (*N* = 398)	
	Adults n = 72 (%)	Children n = 72 (%)	Adults n = 64 (%)	Children n = 64 (%)	Adults n = 63 (%)	Children n = 63 (%)	Adult	Children	Adults N = 199 (%)	Children N = 199 (%)
Average age (years)	41	11	42	11	44	10	0.856	0.851	42	11
Sex										
Female	58 (80.6)	36 (50.0)	57 (89.0)	28 (47.8)	55 (87.3)	34 (54.0)	0.287	0.509	170 (85.4)	98 (49.2)
Male	14 (19.4)	36 (50.0)	6 (9.4)	36 (56.2)	8 (12.7)	29 (46.0)			28 (14.1)	101 (50.8)
Missing	0 (0.0)	0 (0.0)	1 (1.6)	0 (0.0)	0 (0.0)	0 (0.0)			1 (0.5)	0 (0.0)
Home language										
African (isiZulu, isiSotho)	17 (23.6)		58 (90.6)		62 (98.4)		<0.001		137 (68.8)	
Non-African (English/Afrikaans)	53 (73.6)		1 (1.6)		0 (0.0)				54 (27.1)	
Missing	2 (2.8)		5 (7.8)		1 (1.6)				8 (4.0)	
Average monthly household income			Number of households (%)							
No income	2 (2.8)		1 (1.6)		5 (7.9)		0.490		8 (4.0)	
<[a]ZAR 1000	12 (16.7)		10 (15.5)		10 (15.9)				32 (16.1)	
ZAR 1001 – R 5000	38 (52.8)		36 (56.3)		37 (58.7)				111 (55.8)	
>ZAR 5000	18 (25.0)		11 (17.2)		10 (15.9)				39 (19.6)	
Missing	2 (2.8)		6 (9.4)		1 (1.6)				9 (4.5)	
Number of people in household	$\bar{x}$ = 4 $\tilde{x}$ = 3 1–13	$\bar{x}$ = 3 $\tilde{x}$ = 3 1–10	$\bar{x}$ = 3 $\tilde{x}$ = 2 1–8	$\bar{x}$ = 3 $\tilde{x}$ = 3 1–10	$\bar{x}$ = 3 $\tilde{x}$ = 3 1–7	$\bar{x}$ = 3 $\tilde{x}$ = 2 1–7	0.282 0.403	0.342 0.365	$\bar{x}$ = 3 $\tilde{x}$ = 3 1–13	$\bar{x}$ = 3 $\tilde{x}$ = 3 1–10
% respondents currently employed	10 (13.9)	n/a	8 (12.5)	n/a	9 (14.3)	n/a	0.987		27 (13.6)	n/a
% living in formal house	62 (86.1)		42 (65.6)		54 (85.7)		0.007		158 (79.4)	
% dwellings without ceiling	38 (52.7)		54 (84.3)		64 (100)		<0.001		156 (78.4)	
% using electricity for cooking	71 (98.6)		62 (98.9)		63 (100.0)		0.427		196 (98.5)	
% observed to eat soil	15 (20.8)	9 (12.5)	7(10.9)	0 (0.0)	5 (4.8)	1 (1.6)	0.077	0.001	54 (13.6)	
% households with a smoker	29 (40.2)		12 (18.8)		6 (9.5)		0.001		47 (23.6)	

[a] ZAR – South African Rand.

Table 2
Residential garden soil lead concentrations, by zone (mg/kg).

	Zone 1 (≤500 m from MTFs) (n = 71)	Zone 2 (2–3 km from MTFs) (n = 62)	Zone 3 (4–5 km from MTFs) (n = 35)	Total Sample (N = 168)	#p-value
Range	[a]BDL–281.0	BDL–159.8	7.0–12.1	BDL–281.0	<0.001
Mean (SD)	44.6 (44.92)	41.56 (30.5)	9.0 (1.36)	36.0 (37.23)	
Median	35.7	34.0	8.6	27.3	
% ≥SA reference level (230 mg/kg)	1 (1.4 %)	0 (0.0 %)	0 (0.0 %)	1 (0.6 %)	
% ≥Canadian reference level (120 mg/kg)	3 (4.2 %)	2 (3.3 %)	0 (0.0 %)	5 (3.0 %)	
% ≥sample mean (38.9 mg/kg)	46.5 %	44.3 %	0.0 %	35.9 %	

P-value of Kruskal Wallis equality of population rank test.
[a] BDL – below detection limit.

2017). People come into contact with soil on a daily basis, either directly or indirectly, such as through eating fruits and vegetables to which soil particles are attached. Having high rates of ingestion relative to adults, pronounced mouthing behavior and a predilection for the ingestion of non-food items such as soil, children are particularly vulnerable to toxic metal exposure from soil, especially those playing in areas with bare soil (Abrahams, 2002; Bacigalupo and Hale, 2012). There is further impetus for action from the evidence that in certain communities in Johannesburg around one fifth of pregnant women practise geophagia (the intentional ingestion of soil) during pregnancy, implying the potential for foetal exposure to toxic metals such as arsenic (Mathee et al., 2014).

As was the case for soil, blood lead concentrations in this study, in both adults and children, were similarly found to decrease with increasing distance from the MTFs. This trend held true for male as well as female children, and for female, but not male adults (Table 3). Lead concentrations in soil were statistically significantly associated with blood lead concentrations in the total sample ($P = 0.002$), and when broken down by age, also with adult blood lead levels ($P = 0.030$), but not with that of children ($P = 0.250$).

An important consideration in this study is that the sites are located upstream from the predominant wind direction in the area. The relatively low soil lead concentrations observed in the current study should therefore not be regarded as representative of similar locations elsewhere in the county. Instead further research is needed to document metal exposure in residential communities close to, and downstream from, mining sites. A key limitation to this study is that blood lead levels from younger children who habitually practice more hand- and object- to-mouth behavior were not included.

Table 3
Blood lead distribution by zone and sex.

	Zone 1	Zone 2	Zone 3	Total sample	#p-Value (difference across zones)
Adults					
Range	1.0–10.0	1.0–7.0	0.5–12.2	0.5–12.2	0.001
Mean (SD)	3.38 (1.97)	1.90 (1.90)	1.90 (1.81)	2.46 (1.82)	
Median	3.0	2.0	1.4	2.0	
% ≥5 μg/dL	20.83	6.25	7.94	12.06	
Children					
Range	1.0–12.0	1.0–16.1	0.8–7.4	0.8–16.1	0.001
Mean (SD)	4.23 (2.13)	3.06 (2.15)	2.64 (1.21)	3.37 (2.03)	
Median	4.0	3.0	2.5	3.0	
% ≥5 μg/dL	37.50	9.38	4.76	18.09	
Sex: mean (SD)					
Children – male	4.72 (2.11)	3.20 (1.34)	2.90 (1.23)	3.64 (1.81)	0.001
Children – female	3.83 (2.17)	2.93 (2.91)	2.42 (1.18)	3.09 (2.21)	0.003
Adults – male	3.64 (1.82)	2.20 (0.75)	2.33 (1.31)	2.95 (1.63)	0.069
Adults – female	3.31 (2.01)	1.90 (1.11)	1.91 (1.87)	2.37 (1.84)	0.001
All males	4.42 (2.07)	3.02 (1.32)	2.77 (1.25)	2.64 (2.01)	0.001
All females	3.51 (2.08)	2.23 (1.96)	2.09 (1.66)	3.49 (1.79)	0.001

P-value of Kruskal Wallis equality of population rank test.

To our knowledge, there are no mandatory, health-based buffer zones between mining operations and residential areas in place in South Africa to safeguard nearby communities from the highest levels of exposure to toxic substances from historical or ongoing mining operations or MTFs. The implementation of such basic, minimum protections is especially important in the light of lax enforcement of the requirement of rehabilitation within the Mineral and Petroleum Resources Development Act (MPRDA) in South Africa. This concern is heightened in Johannesburg and surrounding areas where there may be as many as 200 MTFs (IHRC, 2016), and where mining land and human settlements are often contiguous. For example, in some parts of the country a "best-case scenario" of 1000 m and a "worst-case scenario" of 500 m is adopted (Bobbins and Trangoš, 2018, p, 70). It is not known whether there was a health basis for the selection of these distances, or whether they were informed by exposure studies taking local conditions into account. The data generated in this study appear to indicate that guidelines such as these may be inadequate to protect communities against excessive exposure to mining-related hazardous substances, and the concomitant health risks. It is also a major concern that in both the Apartheid era (prior to 1994) as well as since, even the "worst-case scenario" exclusion zone has not always been observed in human settlement planning close to MTFs, with communities oftentimes located <100 m from mining land. Such close proximity of residential land to mining operations potentially earmarks the affected communities for chronic exposure to elevated levels of associated toxic substances, as well as the concomitant ill health outcomes. Explicit, mandatory and nationally applicable standards for exclusion zones in South Africa would provide a basic level of community protection, and need to be part of a holistic, health-based strategy to protect communities living in close proximity to MTFs from excessive exposure to mining-related exposures. Further elements of such a strategy might include effective blood lead surveillance and research programmes, especially among children (currently absent, meaning that children with elevated blood lead levels are unlikely to be detected), healthier planning practices, public awareness campaigns, the promotion of exposure reduction measures and practices (including soil reclamation where necessary) and suitable health services.

5. Conclusions

In this study we have shown relatively low levels of lead in soil collected from gardens in neighbourhoods that are upstream of an MTF in Johannesburg, South Africa. Nevertheless, soil lead concentrations decreased significantly with increasing distance from the MTF. Blood lead levels were highest in Zone 1, which was closest to the MTF cluster, and lowest in the Zone 3 located furthest away. Zone 1 also had the highest proportion of both adults (4.9 %) and children (13.9 %) with blood lead levels ≥5 μg/dL (Table 2). Within households the blood lead level of the adults was predictive of the blood lead levels of children ($p \leq 0.001$).

Further investigation is needed to ascertain the risks of exposure to soil lead, as well as other toxic metals, in residential areas located close to MTFs in the current study area, as well as elsewhere in South Africa, especially in downstream communities. Specifically, the authors call for consideration of environment and health-based mandatory standards for exclusion zones between MTFs, active mines and human settlements as part of a broader strategy to protect the public against exposure to mining-related toxic substances.

5.1. Study limitations

The study was taken on the upwind side of the mine tailings facility, and is therefore likely to be an underestimate of the exposure to lead among communities living close to, and on the downwind side of the mine tailings facility. The study did not include the group that is most vulnerable to lead exposure, which is very young children.

CRediT authorship contribution statement

A. Mathee: Methodology, Conceptualization, Funding, Investigation, Data Curation, Formal analysis, Visualization, Writing - Original Draft, Writing - Review & Editing, **T. Haman**: Methodology, Conceptualization, Investigation, Data Curation, Formal analysis, Writing - Editing, **V. Nkosi**: Funding, Supervision, Project administration, Writing - Review & Editing, **N. Naicker**: Supervision, Investigation, Writing - Review, **R. Street**: Writing - Review.

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Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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