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Geospatial approach to investigate spatial clustering and hotspots of blood lead levels in children within Kabwe, Zambia

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ABSTRACT

Background: Communities around Kabwe, Zambia are exposed to lead due to deposits from an old lead (Pb) and zinc (Zn) mining site. Children are particularly more vulnerable than adults, presenting with greatest risk of health complications. They have increased oral uptake due to their hand to mouth activities. Spatial analysis of childhood lead exposure is useful in identifying specific areas with highest risk of pollution. The objective of the current study was to use a geospatial approach to investigate spatial clustering and hotspots of blood lead levels in children within Kabwe.

Methods: We analysed existing data on blood lead levels (BLL) for 362 children below the age of 15 from Kabwe town. We used spatial autocorrelation methods involving the global Moran's I and local Getis-Ord Gi*statistic in ArcMap 10.5.1, to test for spatial dependency among the blood lead levels in children using the household geolocations.

Results: BLL in children from Kabwe are spatially autocorrelated with a Moran's Index of 0.62 ($p < 0.001$). We found distinct hotspots (mean 51.9 μg/dL) in communities close to the old lead and zinc-mining site, lying on its western side. Whereas coldspots (mean 7 μg/dL) where observed in areas distant to the mine and traced on the eastern side. This pattern suggests a possible association between observed BLL and distance from the abandoned lead and zinc mine, and prevailing winds.

Conclusion: Using geocoded data for households, we found clustering of childhood blood lead and identified distinct hotspot areas with high lead levels for Kabwe town. The geospatial approach used is especially valuable in resource-constrained settings like Zambia, where the precise identification of high risk locations allows for the initiation of targeted remedial and treatment programs.

1. Introduction

Lead (Pb) is a toxic metal and a global health hazard. Over 815 million children worldwide are reported to have dangerously high concentrations of Pb in their bloodstream Burki (2020), (Zhang et al., 2008). Low-income countries of sub-Saharan Africa face the greatest impacts of childhood lead poisoning (Landrigan et al., 2018). Children are more vulnerable to Pb related negative health outcomes, compared to adults, as their still developing central nervous system is more susceptible to Pb exposure, mainly during the primary developmental

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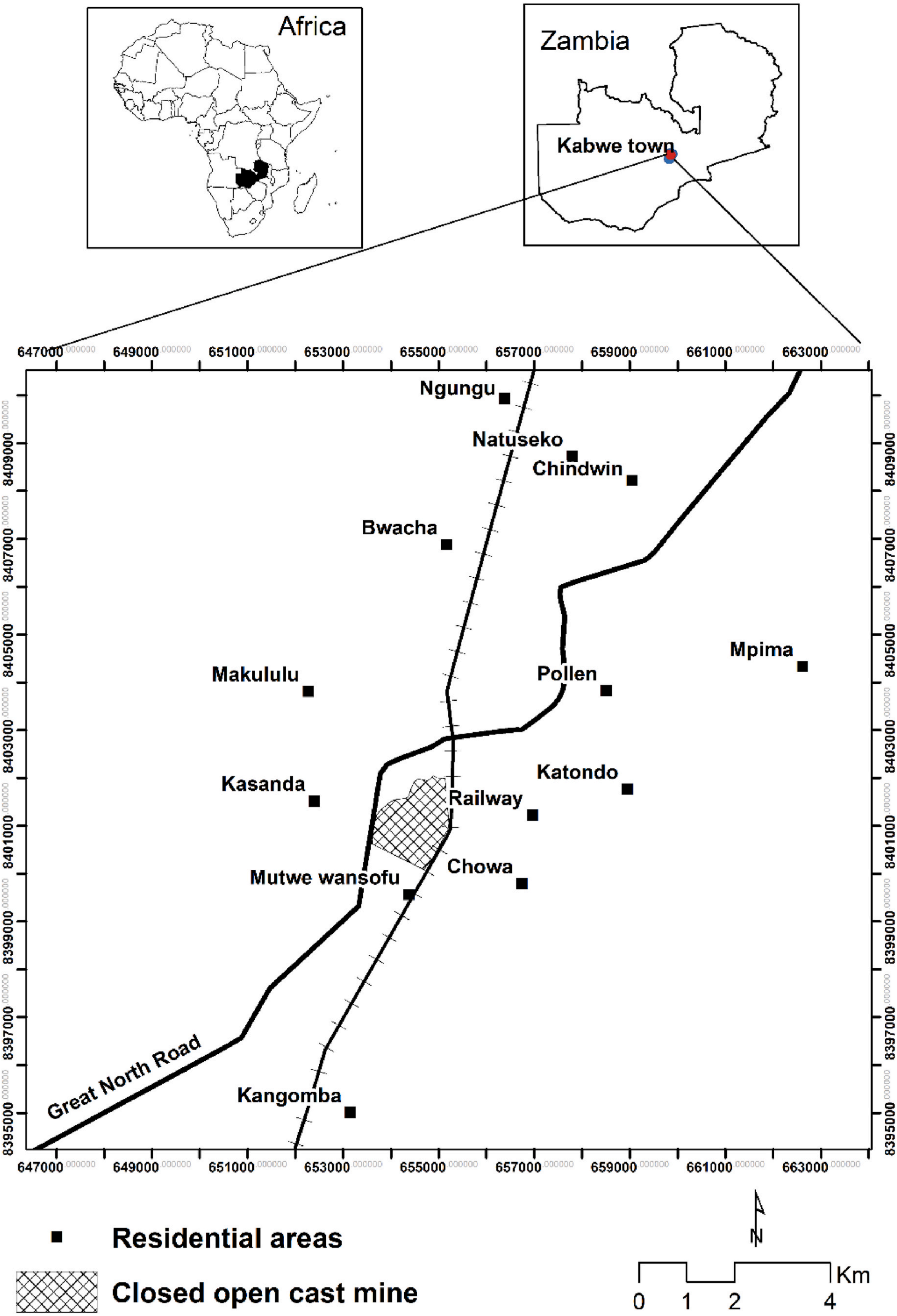

Fig. 1. Study area.

stages (Rooney et al., 2018; Scheuplein et al., 2002). Pb exposure, even at low levels, has been associated with deficits in cognitive functioning and intelligence quotient (IQ) in children (Liu et al., 2011; Lanphear et al., 2005). No level of Pb exposure appears to be safe (Bellinger et al., 1991). High Pb levels of exposure exceeding 80 μg/dL can lead to anaemia, seizures, coma, encephalopathy, and death (World Health Organization, 2010; Wang et al., 2009).

While the physiological mechanisms for Pb dose–response may be similar for all children (Mielke et al., 2019), there are varied exposure pathways. In most settings, blood lead levels (BLL) are related to Pb soil contamination (Matte et al., 1991) and social economic factors (Mielke et al., 2019). The impact of socio-economic and environmental covariates on the Pb exposure in children has been well documented (Stark et al., 1982; Mielke et al., 2019).

Globally childhood Pb poisoning remains a major environmental health concern in cities and communities with Pb-contaminated soils (Ikem et al., 2008; Lo et al., 2012). Contaminated soil, especially if the soil is dry and dusty, can be ingested and absorbed. Children are particularly vulnerable to Pb intoxication due to their hand-to-mouth activities, as such they are more likely to ingest more Pb from contaminated soils. Also, vulnerability is increased due to their much higher gastrointestinal absorption relatively to adults (World Health Organization, 2010; Plumlee et al., 2013).

Kabwe town, located in the Central Province of Zambia had a long history of lead (Pb), zinc (Zn) and cadmium (Cd) mining dating back to the 1900's. The operations came to a stop in 1994, leaving behind ineliminable impact of pollution on the environment (Nakayama et al., 2011). The open cast mining and the resulting big tailing hill still contain a lot of Pb. Neither the tailing hill nor the open pit side were ever properly rehabilitated. Most roads in Kabwe are unpaved; the backyards of the housing areas are dry and dusty. During the 9 months period of dry season, Pb is easily transported towards the windward lying areas and communities.

Previous Pb pollution remediation initiatives in Kabwe have not been sustainable. For example, from 2003 to 2011, the World Bank funded the Copperbelt Environment Project (CEP). The project aimed at cleaning up affected communities, and the treatment of children with high blood Pb levels. Environmental remedial activities included removal of top soil and planting of grass in the affected communities. These activities halted once the project ended in 2011 due to lack of resources and local capacity (Bank, 2011). Currently there is an ongoing project, "the Zambia Mining and Environmental Remediation and Improvement Project (ZMERIP)" aimed at environmental remediation and treatment of 10, 000 children with high BLL. The project has an environmental remediation component with activities including; removal of top soil and planting of grass in affected communities.

Ettler et al. (2020) analysed soil samples from Kabwe townships and main roads and reported that soil Pb levels were above recommended levels for residential areas. They also observed that the geometric mean for soil Pb in townships closer to the mining sites were higher than far off areas. Highly polluted townships were those immediately adjacent to the former Kabwe mining complex and homes downwind from the smelter and the tailings (Bose-O'Reilly, Yabe et al., 2018a,b).

Former reports and scientific publications showed high BLL for people living in Kabwe, due to their continued exposure to Pb. In most compounds, BLL in children is reported to be above 65 μg/dL (Yabe et al., 2015, 2020). The Pb contaminated dust that emanates from the mine dump is the main source of this observed pollution, affecting mostly children (Bose-O'reilly et al., 2018a).

1.1. *Spatial patterns of Pb exposure in Kabwe*

Analysis of the Pb spatial distribution is particularly important in the identification of areas with high risk of exposure (Akkus and Ozdenerol, 2014; Miranda et al., 2002). In resource-limited settings such as Zambia, use of Geographic Information System (GIS) tools to identify affected populations is essential in ensuring that remediation and treatment programmes target communities at greatest risk. The integration of GIS to understand Pb exposure patterns and coverage of interventions also strengthens the implementation of control programmes. Spatial analytical methods such as cluster and hot spot analysis are ideal in this regard (Zhang et al., 2008; Akkus and Ozdenerol, 2014). Moreover, hotspot analysis can help understand disparities in exposure and health outcomes at a lower administrative level. This precision is valuable as it enables quantification of inequalities and identification of successes and failures of programmes and policies at the local level (Osgood-Zimmerman et al., 2018).

Previous studies observed that BLL in Kabwe varied depending on the townships, and relative distance from the mine site (Yabe et al., 2020, Bose-O'reilly et al., 2018b). Children in residential areas (Kasanda, Makululu, Chowa) closer to the mine site have higher average BLL while those from further located areas (Hamududu) have lower BLL (Yabe et al., 2020). Another study observed this trend, in domestic dogs, where the blood Pb concentrations were higher in dogs from communities that were located near the mine than the far-flung residential areas (Toyomaki et al., 2020).

Despite the indication of regional variation in the distribution of BLL in Kabwe, until now no study has investigated the household spatial distribution of BLL to identify hotspot and coldspot areas. Hotspot areas can be clustered (spatial clusters) or exist individually (spatial outliers). Spatial clusters in this context are areas (households) with high BLL values surrounded by observations with also high values. Whereas spatial outliers are households with high BLL surrounded by samples with normal or low values (Zhang and Lin, 2006). The aim of this study therefore was to investigate clustering of BLL and identify hotspot areas using GIS techniques.

2. Methodology

2.1. *Study population*

We re-analysed BLL data that was collected in 2017 by the University of Zambia with collaborators from Hokkaido University under the Kabwe Mine Pollution Amelioration Initiative (KAMPAI) Project. Forty (40) Standard Enumeration Areas (SEA) falling within the catchment area of health facilities were randomly selected, from which 25 households in each were randomly selected and geo-coordinates recorded. Blood was collected from the father, mother and two children. Data was collected on 1000 households with a total of 1190 household members, of which 291 were younger children (three months to three years old), 271 older children (four to nine years old), 412 mothers, and 216 fathers. A detailed description on how the data was collected has been provided by Yabe et al. (2020).

We analysed data for 362 children below the age of 15, each sampled from a single household from the 40 SEAs. Using location parameters (geo-coordinates), we analysed data from these households. We selected the youngest child from each household that was enlisted in the study by Yabe et al. (2020). We focused our analysis on children as they are reported to be the most vulnerable to impacts of lead poisoning (Bose-O'reilly et al., 2018b). Moreover, this is the age range reported to have highest BLL. Fig. 1, shows the residential areas that were included in current study.

2.2. *Laboratory methods*

Pb analysis in whole blood samples was done on-site immediately after blood sample collection using a point-of-care blood Pb testing analyser, LeadCare© II (Magellan Diagnostics, USA). The LeadCare II Analyser used had limits of quantification of 3.3–65 μg/dL, as such, precise levels out of this range could not be determined. BLLs below instrument detection limit were therefore treated as 1.65 μg/dL, the mean of 0 and 3.3. For samples above 65 μg/dL, a 3 times dilution was done using 0.1% HCl. Detailed laboratory procedures are described elsewhere (Yabe et al., 2020).

2.3. Statistical methods

We used spatial autocorrelation methods involving the global Moran's I and local Getis-Ord Gi*statistic to assess the spatial patterns in the children's BLL. These methods are briefly discussed below.

2.3.1. Test for spatial dependency

The global Moran's I was implemented in ArcMap 10.5.1 (Release, 2012) to test for a general spatial dependency among the BLL in children in Kabwe, i.e. to examine whether high or low levels of BLL show spatial clusters or whether they are scattered in a random pattern.

The global Moran's I is given by the formula:

$$I = \frac{n}{S_o} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} r_i r_j}{\sum_{i=1}^{n} r_i^2} \tag{1}$$

where r_i is the deviation of the child's BLL value at area i from its mean $(x_i - \mu)$, $w_{i,j}$ is the spatial weight between area ,i and j, n are the numbers of observations and S_o is the sum of all the spatial weights:

$$S_o = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} \tag{2}$$

2.3.2. Hotspot analysis

To identify the spatial location (coordinates) of cluster of high and of low BLL levels (hotspots and coldspots), we used the local Getis-Ord Gi*statistic (Getis and Ord, 2010). We examined the BLL observation with respect to neighbouring BLL observations. An observation with a high value or low value does not necessarily imply a hotspot or a coldspot, respectively, unless it is surrounded by observations with high values (hotspot) or low values (coldspot). Thus, a large positive Gi*statistic is obtained when the local sum of an observation and its neighbours is larger than the expected local sum indicating clustering of high values, while a small value of the Gi*statistic indicates clustering of low BLL values. In addition, we evaluated whether the Gi*statistic significantly differs from 0, i.e., whether a cluster has a significantly elevated or significantly low BLL level, leading to the definition of hotspot and coldspot, respectively. The Gi*statistic is given as:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \mu \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j} \right)^2 \right]}{n-1}}} \tag{3}$$

where x_j is the BLL value for the child in area j, $w_{i,j}$ is the spatial weight between area i and j, n is the number of observations, mu is the mean BLL level and S is the standard deviation of x, i.e.:

$$\mu = \frac{\sum_{j=1}^{n} x_j}{n} \tag{4}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (u)^2} \tag{5}$$

All spatial analyses were performed using ArcMap 10.5.1. All test decisions were based on a significance level of 0.05.

2.4. Ethical clearance

The University of Zambia Research Ethics Committee (UNZAREC; REF. No. 012-04-16) approved the study. The Ministry of Health through the Zambia National Health Research Ethics Board and the Kabwe District Medical Office granted further approvals (Yabe et al., 2020). In accordance to ethical guidelines and data protection, until the point of data integration and analysis the location coordinates were stored separately from attribute data, all attribute data were de-identified.

Table 1
Blood lead level (BLL) distribution by age.

	All	0–3 years	4–9 years	10–15 years
	n = 362	n = 173	n = 170	n = 19
Mean (μg/dL)	30.1	31.9	28.7	26.9
SD	25.8	28.2	23.4	23.3
Median (μg/dL)	23.8	24.6	21.9	29.7
Minimum (μg/dL)	3.3	3.3	3.3	3.3
Maximum (μg/dL)	162.3	162.3	94.8	67.2

Table 2
Blood lead level (BLL) distribution in cold and hot spots.

	Mean (μg/dL)	Median (μg/dL)	SD	Min (μg/dL)	Max (μg/dL)
Coldspot 90%	15.2	10.9	14.9	3	94.8
Coldspot 95%	15.7	10.7	11.9	3	41.2
Coldspot 99%	7	5.5	6.4	3	38.7
Hot spot 99%	51.9	49.8	20.9	12	162.3

Table 3
Blood lead level (BLL) distribution by residential areas.

Clinic	Mean (μg/dL)	Median μg/dL)	SD	Maximum (μg/dL)	Minimum (μg/dL)
Bwacha	11.1	6.7	16.8	94.8	3
Chowa	24.6	24	10	48.3	7.4
Hamududu	4.5	3	3.2	18.4	3
Kangomba	10.6	10.1	8.8	37.2	3
Kasanda	60.2	56.9	21.8	162.3	30.4
Katondo	11.6	6.7	12.2	38.7	3
Mahatma Ghandi	5.9	5	2.2	9	3.9
Makululu	43.7	40.2	21.1	118.5	9.1
Mpima prison	7.3	6.7	4.7	23.3	3
Natuseko	11.5	10.4	7.1	30.7	3.9
Ngungu	6	4.7	3.9	14.2	3
Pollen	5.3	4.7	1.7	8.3	3.9
Railway	16.4	15.4	7.2	26.2	8.8
Total	29.9	22.3	26	162.3	3

3. Results

3.1. Blood lead level distribution

Table 1 shows age categories and the distribution of BLL in these age groups. The largest age group (47.7%) was 0–3 years while the smallest (5%) was the 10–15 years group. The global mean BLL was 30.1 μg/dL and the median 23.8 μg/dL, which is comparable to the values reported for the young child by Yabe et al. (2020). The distribution of individual blood Pb ranged from a minimum of 3.3 μg/dL to maximum of 162 μg/dL. Age groups 0–3 and 10–15 years had the highest mean (31.9 μg/dL), and median (29.7 μg/dL) respectively. As shown in Table 2, the mean blood Pb in coldspots was 7 μg/dL at 99% confidence level while the hotspots had a mean of 51.9 μg/dL at a similar confidence level. Table 3 shows the distribution of blood Pb in the communities contained in our analysis. Kasanda had the highest mean (60.2 μg/dL) while the lowest mean was observed in Hamududu (4.5 μg/dL).

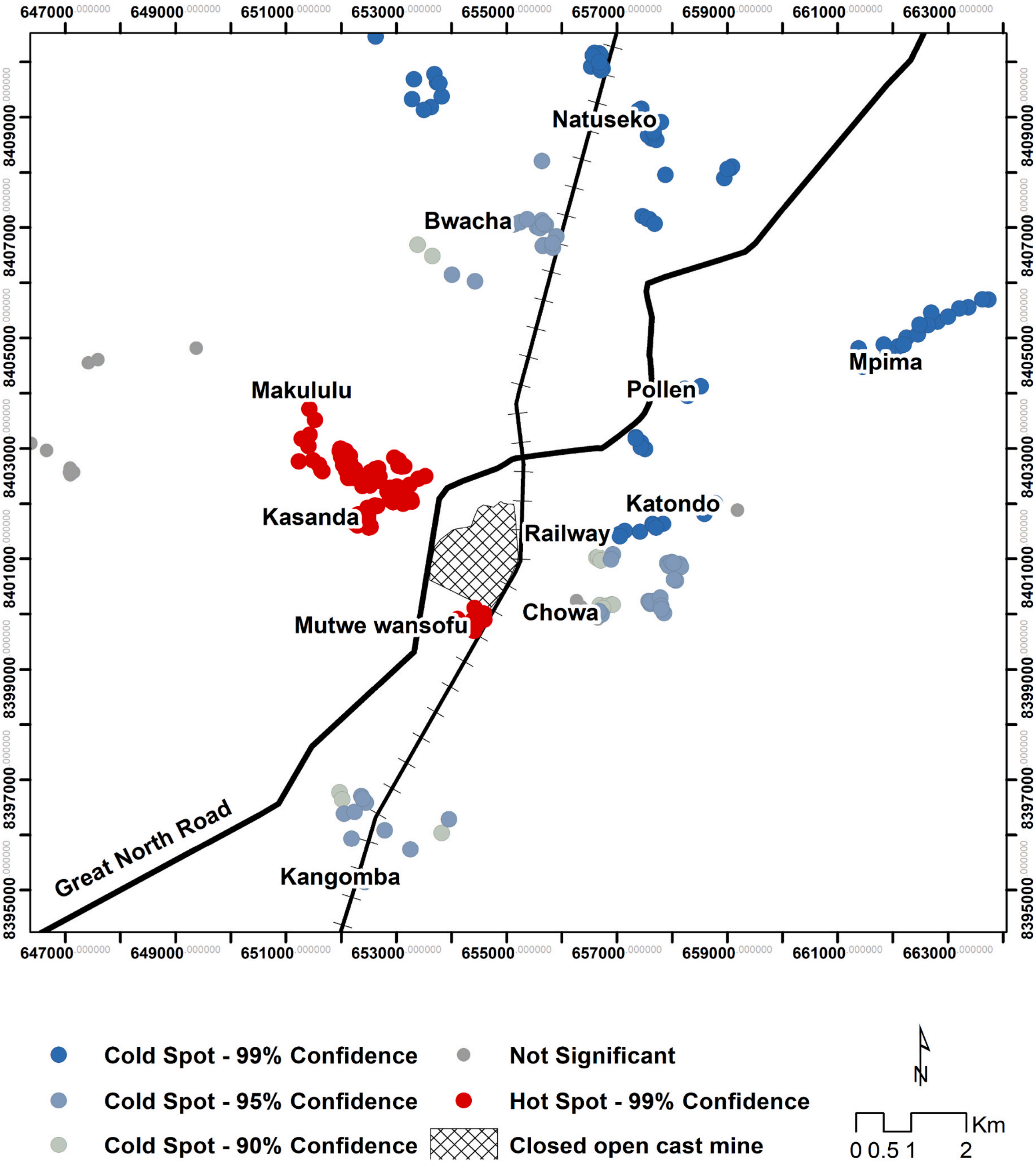

Fig. 2. Spatial distribution of blood lead levels among the children in Kabwe, Zambia.

3.2. *Spatial autocorrelation analysis of blood lead levels*

We observe a positive Global Moran's I (Index) of 0.63 (Z-score 26.1, p-value $<$ 0001) indicating significant spatial clustering of children's BLL levels in Kabwe. In Fig. 2: the red dots indicate areas with high Pb concentration surrounded by other samples with a high concentration (hotspots). Whereas the blue dots indicate areas with low Pb concentration surrounded by other low Pb levels (cold spots).

We see a clear spatial pattern in the distribution of BLL. Hot spot residential areas are seen on the western side of the Pb open cast mine. These areas include Kasanda, which was a mine residential area for the lowest skilled mine workers, and Makululu an informal settlement adjacent to Kasanda. On the south side close to the mine site, Mutwe Wansofu is another hot spot area. On the other hand, the northern side is mainly characterised by cold spots. We see Natuseko on the north, Mpima (northeast) and Katondo (east) all being cold spots.

4. Discussion

Using secondary data of households with geo-coordinates, we analysed the spatial autocorrelation and identified spatial clusters of blood lead level (BLL) from children in Kabwe. This is particularly useful, as a basis for setting up targeted health and environmental interventions in affected areas (Oyana and Margai, 2010; Requia et al., 2017). The study results confirm that distance and wind direction are major factors associated with the observed hotspots. Prevailing wind direction in Kabwe is predominantly east to west. Hotspot areas lie on the western side, and in close proximity to the mine. These areas include Kasanda and Mutwe Wansomfu. Conversely, we found distinct cold spots areas further away from the mine site (Mpima, Natuseko, Kangombe) and generally more on the eastern side.

Wind direction and distance are particularly important because much of the Pb pollution in Kabwe is due to the open pit mine and the tailing hills. Wind blows loose soil particles from the open pit area and the remaining tailing hills. The soil lead levels in these communities on the windward side are high (Bose-O'reilly et al., 2018b; Ettler et al., 2020). These areas generally lack greenness and remain dusty for most of the months. Children are exposed to Pb as they play within these communities and areas close to the mining site.

Social economic differentials are other important factors in relation to the Pb exposure. Historically, Kasanda, Chowa and Luangwa townships belonged to the mine during the operational years. On the western side, Kasanda was for the less skilled workers while Makululu is an informal settlement that sprung up from immigrants, mostly less skilled who were searching for jobs in the mines. These low-income neighborhoods are the least developed, characterised by unpaved roads, and houses made of mad bricks. The Pb exposure is high in these communities. On the other hand, Chowa and Luangwa residential areas are on the eastern side of the old mine and characterised by cold spots. These residential areas were for the skilled workers, expatriates, and rank higher in terms of the social economic class. A high proportion of children from the low-income communities are malnourished and parents are unable to meet the hospital bills. As such, the Pb pollution poses a greater burden on the poorer communities.

The age 0–3 years had the highest average, and maximum BLL. This could be attributed to the increased hand to mouth activity in this age group. Kabwe Soil Pb levels are high and negatively correlated with distance from the mine site. There is still a relative high risk of daily ingestion by young children across age group, as they play around the mine (Nakayama et al., 2011; Smolders et al., 2019).

5. Conclusion

The geospatial approach used in the present study has provided insight in spatial patterns of blood lead levels in the children of Kabwe. The study has established clustering effect of BLL and identified hotspot areas. Clearly, the BLL are dependent on distance and windward direction from the old mine site. Remedial and treatment interventions should consider this, and prioritize these affected communities. The relationship of the observed soil Pb levels and distributions of BLL is yet to be established. Further research is needed to develop a model using lead soil data to predict dangerous childhood Pb exposure. Soil Pb levels are relatively easy and cheap to collect. With a similar spatial analysis on soil Pb levels, hotspot areas could be detected, and the progress of interventions could be very well followed and documented. Spatial modelling would be ideal to establish for Kabwe the still unknown attributable fraction of each exposure pathway (inhalation, ingestion) and each source of exposure (soil, air, water, food).

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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References

Akkus, C., Ozdenerol, E., 2014. Exploring childhood lead exposure through GIS: a review of the recent literature. Int. J. Environ. Res. Publ. Health 11, 6314–6334.

Bank, W., 2011. Implementation Completion and Results Report (IDA-37410 IDA-3741A IDA-H0260).

Bellinger, D., Sloman, J., Leviton, A., Rabinowitz, M., Needleman, H.L., Waternaux, C., 1991. Low-level lead exposure and children's cognitive function in the preschool years. Pediatrics 87, 219–227.

Bose-O'reilly, S., Yabe, J., Makumba, J., Schutzmeier, P., Ericson, B., Caravanos, J., 2018a. Lead intoxicated children in Kabwe, Zambia. Environ. Res. 165, 420–424.

Bose-O'reilly, S., Yabe, J., Makumba, J., Schutzmeier, P., Ericson, B., Caravanos, J., 2018b. Lead intoxicated children in Kabwe, Zambia. Environ. Res. 165, 420–424.

Burki, T., 2020. Report says 815 million children have high blood lead levels. Lancet 396, 370.

Ettler, V., Štěpánek, D., Mihaljevič, M., Drahota, P., Jedlicka, R., Kříbek, B., Vaněk, A., Penížek, V., Sracek, O., Nyambe, I., 2020. Slag dusts from Kabwe (Zambia): contaminant mineralogy and oral bioaccessibility. Chemosphere 127642.

Getis, A., Ord, J.K., 2010. The analysis of spatial association by use of distance statistics. In: Perspectives on Spatial Data Analysis. Springer.

Ikem, A., Campbell, M., Nyirakabibi, I., Garth, J.J.E.M., Assessment, 2008. Baseline Concentrations of Trace Elements in Residential Soils from Southeastern Missouri, vol. 140, pp. 69–81.

Landrigan, P.J., Fuller, R., Acosta, N.J.R., Adeyi, O., Arnold, R., Basu, N.N., Balde, A.B., Bertollini, R., Bose-O'reilly, S., Boufford, J.I., Breysse, P.N., Chiles, T., Mahidol, C., Coll-Seck, A.M., Cropper, M.L., Fobil, J., Fuster, V., Greenstone, M., Haines, A., Hanrahan, D., Hunter, D., Khare, M., Krupnick, A., Lanphear, B., Lohani, B., Martin, K., Mathiasen, K.V., Mcteer, M.A., Murray, C.J.L., Ndahimananjara, J.D., Perera, F., Potocnik, J., Preker, A.S., Ramesh, J., Rockstrom, J., Salinas, C., Samson, L.D., Sandilya, K., Sly, P.D., Smith, K.R., Steiner, A., Stewart, R.B., Suk, W. A., Van Schayck, O.C.P., Yadama, G.N., Yumkella, K., Zhong, M., 2018. The Lancet Commission on pollution and health. Lancet 391, 462–512.

Lanphear, B.P., Hornung, R., Khoury, J., Yolton, K., Baghurst, P., Bellinger, D.C., Canfield, R.L., Dietrich, K.N., Bornschein, R., Greene, T., 2005. Low-level environmental lead exposure and children's intellectual function: an international pooled analysis. Environ. Health Perspect. 113, 894–899.

Liu, J., Mccauley, L., Compher, C., Yan, C., Shen, X., Needleman, H., Pinto-Martin, J.A.J. E.H., 2011. Regular Breakfast and Blood Lead Levels Among Preschool Children, vol. 10, p. 28.

Lo, Y.-C., Dooyema, C.A., Neri, A., Durant, J., Jefferies, T., Medina-Marino, A., De Ravello, L., Thoroughman, D., Davis, L., Dankoli, R.S., 2012. Childhood lead poisoning associated with gold ore processing: a village-level investigation—Zamfara State, Nigeria, October–November 2010. Environ. Health Perspect. 120, 1450–1455.

Matte, T.D., Figueroa, J.P., Ostrowski, S., Burr, G., jackson-Hunt, L., Baker, E.L., 1991. Relationship between soil lead levels and blood lead levels among children living near a lead smelter in Jamaica. Chem. Speciat. Bioavailab. 3, 173–177.

Mielke, H.W., Gonzales, C.R., Powell, E.T., Laidlaw, M.A., Berry, K.J., Mielke, P.W., Egendorf, S.P., 2019. The concurrent decline of soil lead and children's blood lead in New Orleans. Proc. Natl. Acad. Sci. Unit. States Am. 116, 22058–22064.

Miranda, M.L., Dolinoy, D.C., Overstreet, M.A., 2002. Mapping for prevention: GIS models for directing childhood lead poisoning prevention programs. Environ. Health Perspect. 110, 947–953.

Nakayama, S.M., Ikenaka, Y., Hamada, K., Muzandu, K., Choongo, K., Teraoka, H., Mizuno, N., Ishizuka, M., 2011. Metal and metalloid contamination in roadside soil and wild rats around a Pb–Zn mine in Kabwe, Zambia. Environ. Pollut. 159, 175–181.

Osgood-Zimmerman, A., Millear, A.I., Stubbs, R.W., Shields, C., Pickering, B.V., Earl, L., Graetz, N., Kinyoki, D.K., Ray, S.E., Bhatt, S., 2018. Mapping child growth failure in Africa between 2000 and 2015. Nature 555, 41–47.

Oyana, T.J., Margai, F.M., 2010. Spatial patterns and health disparities in pediatric lead exposure in Chicago: Characteristics and profiles of high-risk neighborhoods. Prof. Geogr. 62, 46–65.

Plumlee, G.S., Durant, J.T., Morman, S.A., Neri, A., Wolf, R.E., Dooyema, C.A., Hageman, P.L., Lowers, H.A., Fernette, G.L., Meeker, G.P., 2013. Linking geological and health sciences to assess childhood lead poisoning from artisanal gold mining in Nigeria. Environ. Health Perspect. 121, 744–750.

Release, E.A., 2012. 10.1. Environmental Systems Research Institute, Redlands, CA.

Requia, W.J., Dalumpines, R., Adams, M.D., Arain, A., Ferguson, M., Koutrakis, P., 2017. Modeling spatial patterns of link-based PM2.5 emissions and subsequent human exposure in a large canadian metropolitan area. Atmos. Environ. 158, 172–180.

Rooney, J.P., Woods, N.F., Martin, M.D., Woods, J.S., 2018. Genetic polymorphisms of GRIN2A and GRIN2B modify the neurobehavioral effects of low-level lead exposure in children. Environ. Res. 165, 1–10.

Scheuplein, R., Charnley, G., Dourson, M., 2002. Differential sensitivity of children and adults to chemical toxicity: I. Biological basis. Regul. Toxicol. Pharmacol. 35, 429–447.

Smolders, E., Roels, L., Kuhangana, T.C., Coorevits, K., Vassilieva, E., Nemery, B., Lubaba Nkulu, C.L.B., 2019. Unprecedentedly high dust ingestion estimates for the general population in a mining district of DR Congo. Environ. Sci. Technol. 53, 7851–7858.

Stark, A.D., Quah, R.F., Meigs, J.W., Delouise, E.R., 1982. The relationship of environmental lead to blood-lead levels in children. Environ. Res. 27, 372–383.

Toyomaki, H., Yabe, J., Nakayama, S.M., Yohannes, Y.B., Muzandu, K., Liazambi, A., Ikenaka, Y., Kuritani, T., Nakagawa, M., Ishizuka, M., 2020. Factors associated with lead (Pb) exposure on dogs around a Pb mining area, Kabwe, Zambia. Chemosphere 125884.

Wang, Q., Zhao, H., Chen, J., Gu, K., Zhang, Y., Zhu, Y., Zhou, Y., Ye, L., 2009. Adverse health effects of lead exposure on children and exploration to internal lead indicator. Sci. Total Environ. 407, 5986–5992.

World Health Organization, 2010. Childhood Lead Poisoning.

Yabe, J., Nakayama, S.M., Ikenaka, Y., yohannes, Y.B., Bortey-Sam, N., Oroszlany, B., Muzandu, K., Choongo, K., Kabalo, A.N., Ntapisha, J., Mweene, A., Umemura, T., Ishizuka, M., 2015. Lead poisoning in children from townships in the vicinity of a lead-zinc mine in Kabwe, Zambia. Chemosphere 119, 941–947.

Yabe, J., Nakayama, S.M., Nakata, H., Toyomaki, H., Yohannes, Y.B., Muzandu, K., Kataba, A., Zyambo, G., Hiwatari, M., Narita, D., 2020. Current trends of blood lead levels, distribution patterns and exposure variations among household members in Kabwe, Zambia. Chemosphere 243, 125412.

Zhang, C., Luo, L., Xu, W., Ledwith, V., 2008. Use of local Moran's I and GIS to identify pollution hotspots of Pb in urban soils of Galway, Ireland. Sci. Total Environ. 398, 212–221.

Zhang, T., Lin, G., 2006. A supplemental indicator of high-value or low-value spatial clustering. Geogr. Anal. 38, 209–225.