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Spatial distribution of Pb in urban soil from Port Pirie, South Australia

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HIGHLIGHTS

- A GIS was used to determine the spatial relationship between soil Pb sources and associated health effects.
- Geostatistical interpolation was demonstrated to be efficient for use in environmental health risk assessment.
- Probability kriging was a useful tool to quantify the exceedance of a threshold of bioaccessible Pb above background values.

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ABSTRACT

Exposure to Lead (Pb) from soil and dust in urban areas continues to threaten human health especially that of children, who are more likely to ingest a higher Pb fraction from contaminated soil. Geostatistical approaches were evaluated for the prediction of soil Pb concentrations. Ordinary kriging (OK) and co-kriging (CoK) were used to predict spatial distributions of both soil Pb concentrations and bioaccessibility. The relative accuracies of the developed predictive models were assessed using of coefficients of determination (R^2) and the root mean square error (RMSE) based on the cross validation method. The accuracy of the final model was evaluated via comparison between predicted and traditional soil measurements. While OK models ($n = 73$) were unreliable for predicting a Pb concentration surface, correlation between Pb and Zn was a useful mechanism for obtaining better predictions of soil Pb using CoK. The CoK model of log transformed Pb with Zn resulted in the best fitted model ($R^2 = 0.63$). The percentage relative improvement (RI) for this model was 39% which suggested relatively reliable prediction accuracy. A probability kriging (PK) surface was used to describe the probability of bioaccessibility exceeding a threshold of 17% as an indicator for potential human risk. The areas with highest probability of exceeding the threshold were in agreement with previous risk area divisions related to blood Pb (BPb) levels for children under 5 years of age. The results of this research confirmed that geostatistical methods had the ability to rapidly estimate soil Pb distributions for environmental health risk assessment.

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1. Introduction

Lead (Pb) is a toxic heavy metal and common environmental contaminant which can pose significant threats to public health at high concentration levels (Kachenko and Singh, 2006; WHO, 2010). Elevated Pb concentrations in dust and soil may contribute to elevated blood Pb (BPb) levels, especially in children due to their frequent hand-to-mouth and pica behaviour (Choi et al., 2005). The negative health effects associated with Pb include inhibited brain development and haematological effects, such as anaemia (Bray et al., 2009), due to accumulation of Pb in the kidney, liver, teeth and bones (WHO, 2010).

Since it commenced operation in 1889, the Port Pirie smelter has consistently been cited as a source of soil Pb contamination in this area. Dust particles emitted from the smelter have been deposited throughout the community and thus affect the health of the local population. As the BPb are considered to be an accurate bioindicator of environmental Pb exposure, the study area has been classified to three levels of risk area: high, medium and low according to the mean BPb of children <5 years of age (Maynard et al., 2005). The high risk area included two suburbs: Solomontown and Port Pirie West with differing BPb. Medium risk area included Risdon Park and the northern part of Port Pirie South. Low risk areas included Risdon Park South and Port Pirie South (Fig. 1).

Traditional risk assessment has normally focused solely on the total metal concentration as an indicator of risk. However, currently bioaccessibility of Pb contaminated soils is one of the most significant new concepts for determining the potential risk to human health (Markus and McBratney, 2001). The bioaccessible fraction is defined as the fraction of metal intake that crosses from the digestive tract to the bloodstream (EPA, 2002, 2008) and can be expressed as the ratio of an absorbed to an administered dose.

To improve the understanding of this environment issue, geostatistical analysis has been developed to estimate either the value of a soil attribute at locations between samples, or the probability that the contaminant concentration will exceed a given threshold at a particular location (Luevano et al., 2011; Shi et al., 2007). Common geostatistical methods such as kriging provide an alternative to extensive field sampling and laboratory analysis via cost-effective predictive approaches to create spatial distributions of heavy metal concentration delineating areas of high pollution probability (Hooker and Nathanail, 2006; Cattle et al., 2002; McGrath et al., 2004). Geostatistical approaches can also describe the spatial distributions of contaminant concentrations enabling the identification of pollution sources (Luevano et al., 2011; Liu et al., 2006; Wu et al., 2009). Informed environmental risk assessment requires the determination of not only total metal concentration, but also either the bioavailable fraction (Dao et al., 2013) or blood Pb levels (BPb) (Abel et al., 2012; Mielke et al., 2007).

Heavy metal bioaccessibility in soils is primarily evaluated using leaching or extraction techniques. An *in vitro* physiologically based extraction test (PBET) has been extensively recommended and used (Ruby et al., 1996) to determine bioaccessible (extractable or mobile) fractions of metals in soils (Dao et al., 2013). This test determines the extractability of Pb from soil, and specifically the Pb fraction <250 μm. This fraction is the most important in determining exposure to children because it is readily adhered to hands and easily inhaled or ingested (Morman et al., 2009; Mackay et al., 2013). In addition to improve the delineation of risk areas in previous studies, the aim of this research was to quantify the concentration and distribution of total and bioaccessible soil Pb in urban areas around the Port Pirie smelter which could then be used for environmental protection.

2. Study area

The town of Port Pirie is located on the eastern shore of the Spencer Gulf, 230 kms north of Adelaide, in South Australia. The small provincial city (population 14,000) covers an area of 18 km^2. Port Pirie is low-lying land, which exists in a region with a warm semi-arid climate, fairly dry, dusty and mostly sparsely vegetated (Kutlaca, 1998). The principal wind direction extends from NNW-SSE but varies with the season, emanating from the NW in the winter and from the SE in the summer (Kutlaca, 1998; Simon et al., 2013). The average annual precipitation is around 345 mm yr^{-1} and the mean evaporation/precipitation ratio is approaching 6.5/1 (Kutlaca, 1998). Port Pirie has been affected by Pb smelting emission for more than 120 years. The Nyrstar lead and zinc smelter located at the northern end of the town, is one of the largest smelters in the world, producing approximately five percent of the global Pb production (Kutlaca, 1998). The highest Pb concentration in the surface soil was detected within 2 km of the smelter (Kutlaca, 1998), with average Pb soil concentrations varying from <50 ppm to >5000 ppm (Tiller, 1976), including Port Pirie West and Solomontown which exhibited the highest soil and dust lead concentrations and represented high health risk areas (Kutlaca, 1998). The study area included both urban and rural zones which were exposed to both historical and current Pb emissions from smelting and refining. Smelter emissions have resulted in considerable contamination of the surrounding soil, where the smelter is considered to be the major source of elevated BPb in children (Kutlaca, 1998; Taylor, 2012).

3. Methods and materials

3.1. Soil sampling

Sampling sites were initially selected using aerial orthophotographs (10 cm resolution, MGA 54 projection) of Port Pirie provided by Aerometrex Pty Ltd taken on 25 February 2011 (http://aerometrex.com.au). Soil samples were collected at the