Implementing Spatial Mapping and Sequential Gaussian Simulation for Probabilistic Risk Modeling of Heavy Metals Contamination in Urban Soils

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Background and objectives

This study aims to assess heavy metal contamination in urban soils (n=2957) of Seoul city, South Korea, focusing on the risks to vulnerable populations. A advanced statistical methods, including the ordinary kriging and Sequential Gaussian Simulation were used for a detailed analysis of contamination levels and spatial patterns. Additionally, the spatial data were overlain with demographic data to assess exposure risks, particularly among the elderly and infants, within the framework of the USEPA's health risk assessment guidelines. We would identify high-risk areas as the initial step to inform strategies for public health and environmental protection.

Procedure of the study

Interpolate heavy metals concentration → Examine distribution of vulnerable population → Calculate dermal absorption hazard index → Combine with population distribution → Compare with human health risk assessment

Study area

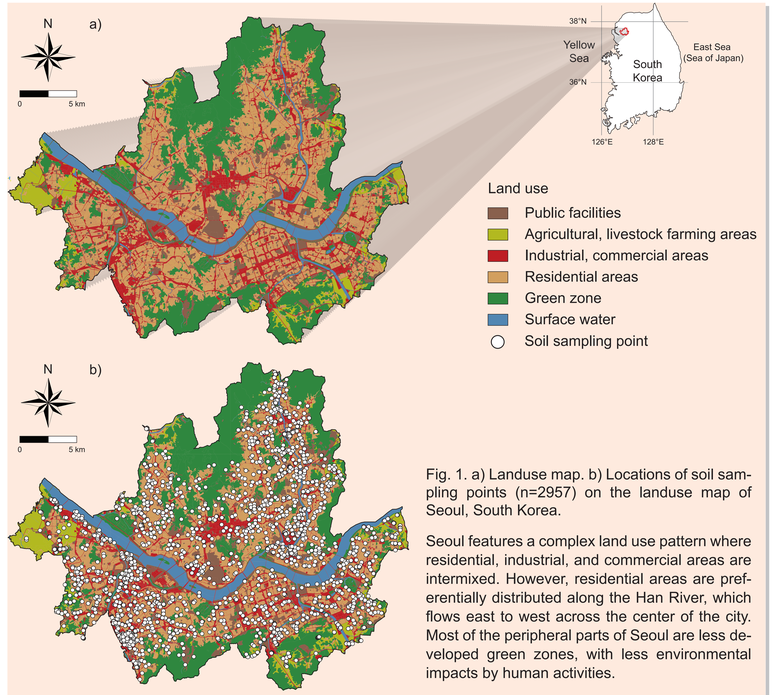
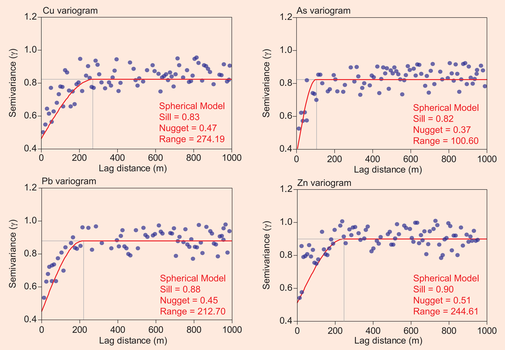


Fig. 1. a) Landuse map. b) Locations of soil sampling points (n=2957) on the landuse map of Seoul, South Korea.

Seoul features a complex land use pattern where residential, industrial, and commercial areas are intermixed. However, residential areas are preferentially distributed along the Han River, which flows east to west across the center of the city. Most of the peripheral parts of Seoul are less developed green zones, with less environmental impacts by human activities.

Geostatistical analysis: Variogram



Variogram: *spatial correlation of data points by measuring the variance of their differences*
Nugget: *small-scale variability not captured by the sampling*
Sill: *measure of the total variance*
Range: *spatial extent over which data points are considered correlated, influencing the weight assigned to each point during interpolation*

Fig. 2. Semi-variogram of 4 heavy metals(Zn, Cu, As, Pb) in soil. All four metals follow a spherical model. The distance at which the variogram reaches the sill value is longest for Cu (274 m) and shortest for As(100 m). This indicates that arsenic exhibits the lowest spatial correlation throughout the study area, possibly owing to its spatial distribution control mostly by non-point, pervasive source (i.e. largely geogenic).

Ordinary kriging and Sequential Gaussian Simulation (SGS)

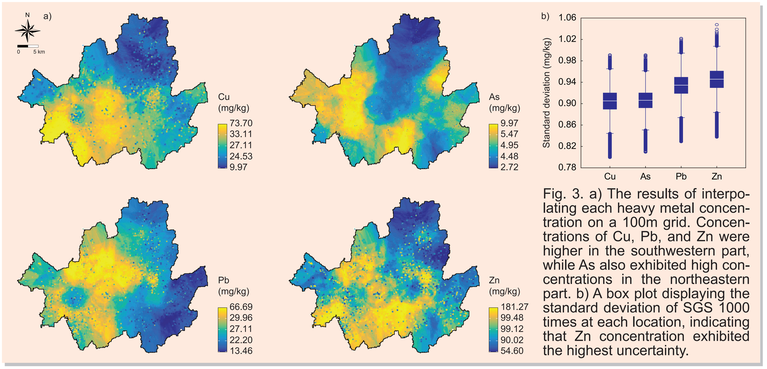


Fig. 3. a) The results of interpolating each heavy metal concentration on a 100m grid. Concentrations of Cu, Pb, and Zn were higher in the southwestern part, while As also exhibited high concentrations in the northeastern part. b) A box plot displaying the standard deviation of SGS 1000 times at each location, indicating that Zn concentration exhibited the highest uncertainty.

Demographic map: Vulnerable class distribution

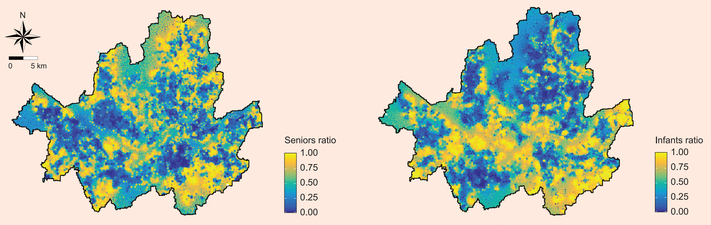


Fig. 4. A demographic map showing the distribution of the ratio of the seniors population (aged 65 and above) and infants (up to 5 years old) relative to the total population. The elderly are living with relatively higher rates in the peripheral areas of Seoul, while a higher ratio of infants with young couples live in newly developed apartments preferentially at central (alongside the Han River) and southeastern parts.

Hazard index analysis

Table 1. Parameters used for calculating the hazard index.

Parameters	Seniors	Infants
IR (kg/day)	0.10	0.20
EF (day/yr)	350	350
ED (years)	30	6
SA (cm^2)	0.57	0.28
AF ($mg/cm^2 \cdot day$)	0.07	0.20
ABS	1.00 E-03	1.00 E-03
BW (kg)	60.40	15.30

Elements	RfD (mg/kg·day)
Cu	4.00 E-02
As	3.00 E-04
Pb	1.40 E-04
Zn	3.00 E-01

IR: Ingestion Rate, EF: Exposure Frequency, ED: Exposure Duration, SA: exposed Skin surface Area, AF: Adherence Factor, ABS: Dermal Absorption Factor, BW: Body Weight, RfD: Reference dose

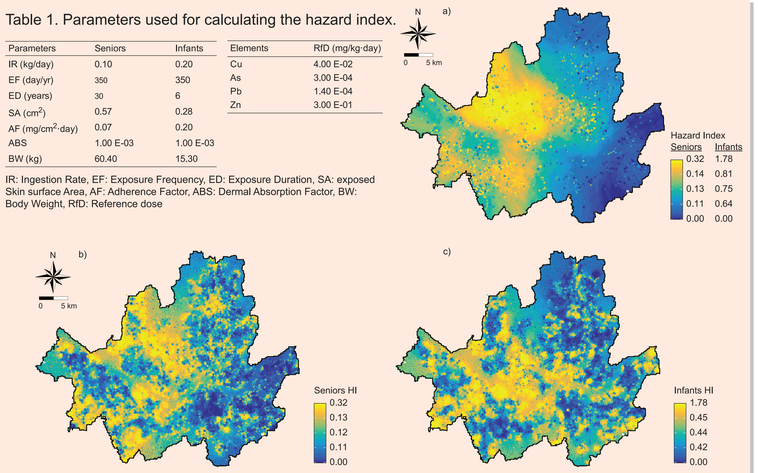


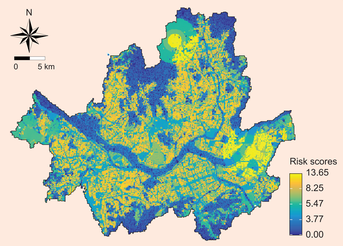
Fig. 5. a) Spatial distribution of calculated hazard index for seniors and infants. b) Spatial distribution of hazard index combined with seniors population ratio. The scale of original hazard index in a) was preserved. c) Spatial distribution of hazard index combined with infants population ratio.

Human health risk assessment

Table 2. Parameters used for calculating exposure route scores for human health risk.

	Groundwater	Surface water	Air	Direct contact
Source	Potential hazard map	Potential hazard map	Potential hazard map	Potential hazard map
Pathway	Lithology of unsaturated zone	Slope Flooding risk	Particulate mobility	
	Infiltration	Surface water flow rate		
Receptor	Distance of site to drinking water supply	Surface water use Minimum distance from surface body	Land use at site Distance to the nearest residential area	Land use at site Distance to the nearest residential area

Fig. 6. Overall human health risk assessment map in study area. The highest score is 13.65, which indicates that health risk at Seoul is overall low.



Summary and conclusion

1. Higher concentrations of Cu, As, Pb, and Zn were found to be mainly controlled by land use in Seoul. The four metals, especially Cu and Pb, were higher in the industrialized, western parts. Higher zinc concentrations in soil seemed to occur in highly traffic areas at southern part. Arsenic enrichment in soil occurs locally, including northeastern green zones, indicating geological influences.
2. The living space of the seniors and infants in Seoul are quite different: seniors preferentially in northern old towns and less developed peripheral green zones, while infants preferentially alongside the Han River and in southeastern, new towns.
3. The hazard index, combining all four metals, shows the higher risk in the northwest. For infants, the hazard index exceeding 1, indicates potential adverse health effects. The results of risk analysis indicates higher hazard indices for the seniors in the west and for infants in central Seoul.
4. Overall the health risk map points to the north and east as highly vulnerable areas. This study suggests that land use, exposure pathways, and the distribution of vulnerable populations should be carefully considered to comprehensively assess the risk of metals-contaminated soil.

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