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GIS-based spatial analysis of soil contamination with heavy metals in urban areas of Kazakhstan

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ABSTRACT
The increase in the concentration of heavy metals in urban soils, as one of the consequences of industrialization and population growth, has always been of interest to environmental scientists. In this study, the spatial distribution of five heavy elements, including lead, zinc, cadmium, chromium, and arsenic, in the surface soils of three metropolitan cities of Almaty, Astana, and Karaganda in Kazakhstan was investigated during the period from April to October 2025. 180 surface soil samples were collected from a depth of 0 to 20 cm and the concentration of elements was quantified by atomic absorption spectrometry. Data analysis was performed using geostatistical methods including variography and ordinary kriging, as well as principal component analysis and Pearson correlation. The findings showed that Karaganda City, with an average concentration of zinc of 246.7 and lead of 68.5 mg kg^{-1}, had the highest pollution, and more than 65% of the samples exceeded the national standard limit. In contrast, Astana, with an average lead of 29.8 mg kg^{-1}, showed the lowest pollution. The high correlation of lead-zinc (0.78), lead-cadmium (0.72) and zinc-cadmium (0.81) indicates common industrial and traffic sources, while the lower correlation of chromium with other elements and a factor loading of 0.87 on the second component indicate its terraneous origin. The spatial structure ratio of the elements varied between 0.69 and 0.86, indicating strong to moderate spatial correlation. The range of influence of zinc (3.5 km) and lead (4.8 km) shows the wide radius of influence of these pollutants. Industrial use with a land accumulation index of 48.2 and an enrichment factor of 82.7 for zinc had the highest pollution. Kriging cross-validation with a standardized mean error close to zero (-0.07 to 0.08) and a normalized root mean square error close to one (0.92 to 1.02) confirmed the appropriate performance of the variographic models. Karaganda is in the most critical situation, and Almaty also requires continuous monitoring for arsenic, with 65% of samples exceeding the WHO guideline.

Keywords: Urban soil pollution, heavy metals, geographic information systems, land statistics, Kazakhstan
Article type: Research Article.

INTRODUCTION
Urbanization during the last few decades has had serious consequences both for nature and humanity (Liu *et al.* 2023; Gök *et al.* 2024; González-Jaramillo & Gaona 2026). One of the most crucial of these consequences is the buildup of potentially hazardous substances in urban soils (Bruno & Messina 2025; Yangınlar 2026). Being the

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major element in the biogeochemical cycle of these pollutants, soil performs an essential role in the process. Thus, any alteration in the properties of soil will affect all the ecosystems in the vicinity, as well as the health of the population (Kalimoldina *et al.* 2022; Yan & Yang 2024; Al-Ababneh *et al.* 2026). The role of human activities, such as intensive traffic, industrial effluents, and excessive building of infrastructures, in increasing the level of pollution of urban soils with heavy metals has been explored by numerous researchers throughout the world recently, and all these converging studies indicate the necessity of continuous monitoring of these pollutants (Zhyrgalova *et al.* 2024; Syofya *et al.* 2025; Qawasmeh *et al.* 2026). Being the biggest country in Central Asia, Kazakhstan has witnessed huge development over the years. The increase in population in urban areas, development of heavy industries and transportation network in the cities like Almaty, Astana and Karaganda, while providing prosperity economically, have also caused a huge impact on the environment (Sadenova *et al.* 2022). Studies performed in the industrial cities of Kazakhstan have revealed that the amounts of elements including lead, zinc, chromium and arsenic in certain areas of these cities have been found to be multiple times more than the terrestrial values (Purnamawati *et al.* 2022; Sadenova & Beisekenov 2026; Çela *et al.* 2026; Govil *et al.* 2026; Wishah *et al.* 2026). This problem has led to serious doubts concerning possible long-term impact on soil quality and health of population in densely populated with industries and motor transport regions (Wang *et al.* 2024; Ahmed *et al.* 2024; Kahal *et al.* 2025; Tarigan *et al.* 2025). In addition to classical soil pollution control methods, the emergence of geographic information systems and geostatistics created new opportunities in studying the spatial patterns of pollution distribution (Aparisi-Navarro *et al.* 2025; Maltseva *et al.* 2025; Zhakypbek *et al.* 2025). Using interpolation methods like kriging and spatial autocorrelation indicators, it is possible not only to detect critical points of pollution but also to visualize distribution of metal content in the city continuously (Behairy *et al.* 2022; Felegari *et al.* 2023; Wu *et al.* 2024; Alkhouri & Halteh 2026). Such a study, performed in Astana on the basis of the approach mentioned above, has demonstrated great spatial variability of cadmium, zinc, chromium, and lead distribution in the city and has proved that densely populated with urban and industrial infrastructure regions have the highest levels of those metals (Baubekova *et al.* 2021; Madibekov *et al.* 2023; Lotrecchiano *et al.* 2024; Aburub *et al.* 2026). These cases prove that the use of field techniques together with GIS tools in terms of spatial analysis is an effective means for sustainable management of urban soils (Taghizadeh-Mehrjardi *et al.* 2021). While considerable advancement has been achieved, there still remain important knowledge deficiencies in regard to systematic investigation of heavy metal pollution of urban soils in Kazakhstan (Ramazanova *et al.* 2021; Mohammad *et al.* 2026). Previous research in this area was mainly devoted to specific mining or industrial zones or was limited to the investigation of point pollution in the absence of systematic spatial analysis. At the same time, the variety of pollutants' sources from thermal power plants and smelting plants to urban traffic and construction sites and the wide geographical distribution of large Kazakh cities in diverse climatic and geological environments increase the need for such research. In particular, recent fast pace of urbanization has added new aspects to environmental problems under discussion (Li *et al.* 2023; Akter *et al.* 2023; Jaijit *et al.* 2023). The purpose of the current research is to carry out the spatial analysis of pollution of soils of Kazakhstan cities considering heavy metals and by using the methods of GIS and geostatistical analysis. In this connection, it is necessary to collect and synthesize scattered data as well as conduct additional sampling and mapping the spatial distribution of pollutant index elements in selected urban centers and determine zones of greatest danger. Moreover, by means of pollution indices and multivariate analysis, the impact of anthropogenic factors on soil pollution will be differentiated from that of natural ones and ecological assessment of each area will be carried out. The results of the research may be useful for closing the gaps in knowledge and providing initial data for environmental policy-making to executive authorities.

MATERIALS AND METHODS

Study area and sampling design

In this current research, the work was conducted within three major metropolitan areas in Kazakhstan, including Almaty, Astana, and Karaganda from April to October 2025. The cities chosen were based on their diversity in terms of industrial environment, population density, and urban traffic conditions. Within each city, a grid of sample points was designed utilizing the satellite images along with the information on land utilization. Soil surface samples were collected from the depth of 0 to 20 cm. Five sub-samples from the four corners and one from the middle point of a 10 by 10 m^2 were collected to make up a composite sample. The geographical coordinates of the station along with information about the surrounding land use, proximity to the major streets and industrial areas were recorded.

Soil chemical analysis

Upon bringing the samples to the laboratory, they were dried under normal conditions and later separated from waste materials and gravel through 2-mm sieve. In determining the total concentration of the heavy metals, acid digestion technique involving the use of nitric acid and perchloric acid was employed and the target elements such as lead, zinc, cadmium, chromium, and arsenic were determined via atomic absorption spectrometry or inductively coupled plasma. The test was validated through the use of reference samples of soils, and the results showed that the recovery rate of all elements were within acceptable ranges. Besides, the physicochemical characteristics of soil including pH, organic matter, and soil texture were also determined through standard techniques.

Statistical and spatial analyses

In order to reveal the spatial distribution of heavy metal elements, the results of their concentrations were input into statistical and geographic information system. At first, a normal distribution of data was analyzed by using the Kolmogorov-Smirnov test; in case of necessity, logarithmic transformation of variables was performed. The ordinary kriging method was applied for interpolation of data at the unmeasured points and creation of maps of the spatial distributions; the performance of different variographic models was estimated by means of the cross-validation method. Moreover, indexes of pollution including land accumulation index and enrichment coefficient were calculated in order to estimate the pollution level at each sampling point.

RESULTS

The results obtained in the current research study are summarized in seven tables and one figure. In total, 180 surface soil samples, collected from Almaty, Astana, and Karaganda cities were analyzed, and concentration of five elements including lead, zinc, cadmium, chromium, and arsenic were determined. The description of the statistics of the data along with geostatistical analysis, correlation, principal component analysis, pollution indices, and error estimation of the interpolation are presented in the subsequent sections.

Table 1. Descriptive statistics of heavy metal concentrations (mg kg^{-1}).

City	Metal	N	Mean	SD	Min	Median	Max
Almaty	Pb	20	42.3	14.8	18.5	40.1	78.2
Almaty	Zn	20	118.5	29.4	65.3	115.7	189.4
Almaty	Cd	20	0.78	0.31	0.32	0.72	1.52
Almaty	Cr	20	58.4	19.7	28.1	55.3	102.5
Almaty	As	20	7.6	2.9	3.1	7.3	14.2
Astana	Pb	20	29.8	9.5	14.2	28.5	52.3
Astana	Zn	20	87.3	18.7	54.6	85.1	134.8
Astana	Cd	20	0.51	0.19	0.21	0.49	0.98
Astana	Cr	20	39.2	14.5	18.7	37.4	76.8
Astana	As	20	5.1	1.8	2.4	4.9	9.6
Karaganda	Pb	20	68.5	24.3	31.6	65.2	128.7
Karaganda	Zn	20	246.7	58.2	142.3	238.5	385.4
Karaganda	Cd	20	1.46	0.48	0.72	1.38	2.67
Karaganda	Cr	20	97.6	28.4	52.4	93.1	168.3
Karaganda	As	20	14.8	5.2	7.0	14.1	27.5

Based on Table 1, Karaganda City contains the highest average values for all elements. The element having the highest coefficient of variation (ratio of standard deviation to the mean value) is lead, while the element that has the lowest coefficient of variation is zinc, which means that lead is more heterogeneously distributed than zinc. Cadmium concentration in Karaganda shows considerable variability, varying between 0.72 and 2.67 mg kg^{-1}. It is clear from the values in Table 2 that apart from chromium, more than 65% of the samples in Karaganda exceeded the permissible limit according to the national standard of Kazakhstan. The element arsenic was found to be at its highest non-compliance level in Almaty, where 65% of the samples exceeded the guideline of the WHO. In Astana, none of the samples exceeded the national permissible limit; however, for arsenic and lead, 40 and 25% of the samples, respectively, exceeded the global guideline.

Table 2. Comparison of mean metal concentrations with national and international soil quality standards (mg kg^{-1}).

City	Metal	Mean conc.	Kazakhstan standard	WHO/EPA guideline	% samples exceeding KZ std	% samples exceeding WHO/EPA
Almaty	Pb	42.3	50.0	40.0	15.0	55.0
Almaty	Zn	118.5	150.0	120.0	10.0	45.0
Almaty	Cd	0.78	1.0	0.8	5.0	40.0
Almaty	Cr	58.4	100.0	60.0	0.0	30.0
Almaty	As	7.6	10.0	5.0	10.0	65.0
Astana	Pb	29.8	50.0	40.0	0.0	25.0
Astana	Zn	87.3	150.0	120.0	0.0	15.0
Astana	Cd	0.51	1.0	0.8	0.0	10.0
Astana	Cr	39.2	100.0	60.0	0.0	0.0
Astana	As	5.1	10.0	5.0	0.0	40.0
Karaganda	Pb	68.5	50.0	40.0	70.0	95.0
Karaganda	Zn	246.7	150.0	120.0	85.0	100.0
Karaganda	Cd	1.46	1.0	0.8	65.0	90.0
Karaganda	Cr	97.6	100.0	60.0	20.0	80.0
Karaganda	As	14.8	10.0	5.0	70.0	95.0

Table 3. Fitted variogram model parameters for each heavy metal.

Metal	Model type	Nugget (C_0)	Sill (C_0+C)	Range (km)	Spatial dependence ratio [C/(C_0+C)]
Pb	Exponential	0.12	0.65	4.8	0.82
Zn	Spherical	0.08	0.58	5.3	0.86
Cd	Exponential	0.18	0.72	3.9	0.75
Cr	Spherical	0.15	0.62	4.5	0.76
As	Gaussian	0.21	0.68	3.2	0.69

Parameters from the variogram models in Table 3 illustrate the fact that the spatial structure ratio for all elements is greater than 0.69. This is an indication of a high spatial dependence between the five metals. The minimum range is 2.3 km for arsenic while the maximum range is 3.5 km for zinc. The exponential models for lead and cadmium and the spherical models for zinc and chromium were the most suitable models.

Fig. 1 demonstrates statistical distinctions between cities in terms of data provided. The median range of zinc concentration fluctuates from about 85 mg kg^{-1} in Astana up to 238.5 mg kg^{-1} in Karaganda. The number of outliers for lead is much higher in Karaganda than in other two cities. In addition, the interquartile range for arsenic in this city represents the highest dispersion and is equal to 1-27 mg kg^{-1}. In Almaty, the range of chromium variation is larger compared to any other element in this city, and there are some outliers with the concentration of more than 90 mg kg^{-1}. The strong positive Pearson correlation (> 0.72) of lead-zinc, lead-cadmium, zinc-cadmium, and zinc-arsenic element pairs in Table 4 suggests that there are common sources or a similar geochemical behavior of these elements. Despite the significance of chromium's correlation with the other elements, its value is quite low (0.38-0.52), which is most likely because of the distinct terrestrial source of chromium as compared to other metals.

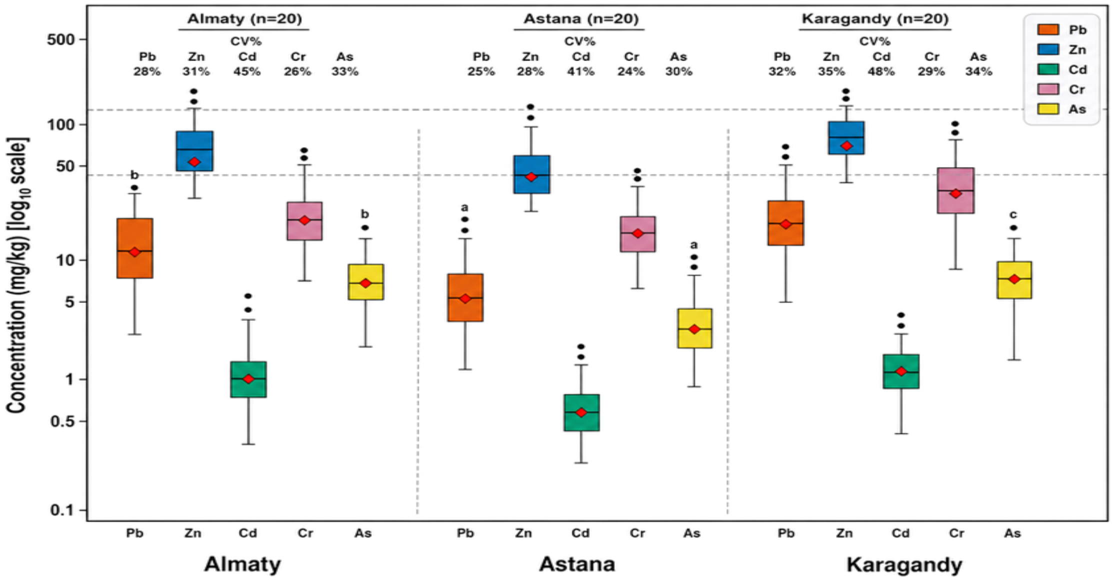

Fig. 1. Comparative distribution of heavy metal concentrations in urban soils.

Table 4. Pearson correlation matrix between heavy metal concentrations.

Metal	Pb	Zn	Cd	Cr	As
Pb	1.00	0.78**	0.72**	0.45*	0.69**
Zn	0.78**	1.00	0.81**	0.52**	0.74**
Cd	0.72**	0.81**	1.00	0.38*	0.71**
Cr	0.45*	0.52**	0.38*	1.00	0.42*
As	0.69**	0.74**	0.71**	0.42*	1.00

(*p < 0.05; **p < 0.01).

Table 5. Principal component analysis (PCA) results for heavy metals.

Component	Eigenvalue	% of variance	Cumulative %	Metal	PC1 loading	PC2 loading
PC1	3.42	68.4	68.4	Pb	0.91	0.21
PC2	1.05	21.0	89.4	Zn	0.95	0.11
PC3	0.32	6.4	95.8	Cd	0.88	0.30
PC4	0.14	2.8	98.6	Cr	0.42	0.87
PC5	0.07	1.4	100.0	As	0.85	0.34

According to Table 5, the first two principal components account for 89.4% of the total variance of the data. Component 1, which shows that lead, zinc, cadmium, and arsenic have factor loadings higher than 0.85, suggests an anthropogenic origin (traffic and industry). Component 2, which shows that chromium has a factor loading higher than 0.87, suggests the contribution of another source (natural geological environments or industry associated with alloys). Table 6 shows that for the purpose of industry for all elements, the mean I-geo is between 1.12 (chromium) and 2.48 (zinc), meaning that there is a moderate to severe contamination. The enrichment factor of zinc for industrial purpose had the value of 7.82, which is significant to severe enrichment. The green space utilization had the lowest values for both indices and is mainly low or unpolluted.

Cross-validation results of the Kriging technique in Table 7 demonstrate that the standardized mean errors for all elements are almost equal to zero (from -0.07 to 0.08) and root mean square of the normalized errors are almost equal to one (from 0.92 to 1.02), which reflects the unbiasedness and adequate performance of the fitted variographic models. The minimum mean absolute error belongs to cadmium, and the maximum – to zinc, which correlates with the ranges of concentration variations of these elements.

Table 6. Mean pollution indices (I-geo and EF) for heavy metals across different urban land uses.

Land use type	Pb	Zn	Cd	Cr	As
I-geo					
Residential	0.82	0.95	0.74	0.35	0.61
Industrial	1.95	2.48	1.82	1.12	1.74
Traffic-dense	1.68	1.82	1.54	0.92	1.45
Green space	0.45	0.52	0.38	0.18	0.33
EF					
Residential	2.12	2.34	1.98	1.45	1.87
Industrial	5.67	7.82	5.12	3.24	5.03
Traffic-dense	4.85	5.34	4.21	2.78	4.12
Green space	1.54	1.68	1.32	1.05	1.24

Table 7. Cross-validation summary statistics for ordinary kriging interpolation.

Metal	Mean Error (ME)	Mean Absolute Error (MAE)	Root Mean Square Error (RMSE)	RMSE-standardized	Mean Standardized Error (MSE)
Pb	0.12	3.45	4.82	0.98	-0.05
Zn	0.08	5.12	7.23	0.95	-0.03
Cd	0.15	0.06	0.09	1.02	0.08
Cr	0.21	2.98	4.01	0.92	-0.07
As	0.17	0.42	0.58	0.96	0.04

DISCUSSION

The present study revealed significant differences in heavy metal levels among the three analyzed cities. There were the largest amounts of pollutants found in Karaganda, since in this city the average content of zinc reached the amount of 246.7 mg kg^{-1} while in Astana this indicator was 3.87 mg kg^{-1}. This may be explained by the large number of industries and thermal power stations in this city, which has a rather long history of mining and metallurgy. It should also be noted that the results of principal component analysis also confirm this conclusion, since the first component with factor loadings larger than 0.85 of lead, zinc, cadmium and arsenic shows that there is an anthropogenic source of industrial and traffic origin of these elements. At the same time, the smaller factor loading of chromium on the first component (0.42) and its placement on the second component (factor loading 0.87) show that part of chromium found in urban soils may be terrestrial, as was mentioned earlier in other sources. High Pearson correlation among the pairs of elements such as lead-zinc (0.78), lead-cadmium (0.72) and zinc-cadmium (0.81) suggests that there are common sources of these elements' emissions. It is believed that traffic-related emissions, especially the usage of fossil fuels and tire/cars wearing, are the main causes of their co-production in urban areas. Such a result agrees with previous findings from other Asian megacities, such as Tehran, Beijing and New Delhi; however, in some cases, concentrations of these elements in Karaganda are even higher than those in the mentioned cities. Moderate correlation between arsenic and lead (0.69) and zinc (0.74) can also be associated with the presence of this element in the emissions produced by fossil fuels or metal smelting. Nevertheless, low correlation coefficients between chromium and the rest of the elements (0.38-0.52) confirm the assumption about the source of its emission. As a result of calculations of variographic parameters, the following values of the spatial structure ratio were obtained for all the studied elements in the range from 0.69 to 0.86. Thus, the presence of a strong to moderate spatial correlation can be concluded because more than 69% of the spatial variability of metal concentration is due to the structure factors (for example, pollutant source locations) and the contribution of random factors into the creation of the spatial structure is insignificant. The effective impact range of zinc (3.5 km) and lead (4.8 km) is larger than that of other elements and this peculiarity is very important for urban planning, as this means that the impact area of pollution caused by point sources (for example, factories) covers significant distance in the urban environment and is not restricted to the immediate vicinity of the source. In turn, the small impact range of arsenic (2.3 km) and cadmium (9.3 km) can be associated with the intensive deposition of these particles near the emission sources. The analysis of pollution indices in various types of urban usage shows clearly structured priorities. The maximum values of the land accumulation index and the enrichment coefficient were found in industrial land use and in the vicinity of busy streets, correspondingly. At the same time, green space usage had the minimum level of pollution. This fact, although proving once again the priority role of anthropogenic pollution factors in urban soil contamination, means also that properly equipped green spaces can be considered natural filters to certain extent and can stop the formation of metal accumulations in the soil. In turn, the very high percentage of exceeding permissible limit values (more than 65% for most elements in Karaganda and 55% of lead in Almaty exceeding WHO value) proves that there is a necessity to change the national standards and implement control measures, taking into account peculiarities of each city. Finally, the results obtained in the course of this research prove that it is not enough to conduct the analysis based on one pollution index only and the combination of several indexes is needed.

CONCLUSION

In the current study, the analysis of spatial distribution of five heavy metals in surface soils of three metropolises of Kazakhstan was conducted using geographic information systems and geostatistical approaches in 2025. It was found that Karaganda with an average amount of zinc equal to 246.7 mg kg^{-1} contained the maximum amounts of pollutants compared to other cities under consideration, and more than 65% of soil samples in this city were above the norm of Kazakhstan. Meanwhile, the minimum level of contamination in Astana was detected due to its predominantly administrative-service character and low industrial load on the territory. According to the results of principal component analysis and Pearson correlation coefficients, it can be concluded about the presence of two independent sources of studied elements: the anthropogenic one (lead, zinc, cadmium, and arsenic) with industrial and traffic origin, and the terrestrial one (chromium). The value of spatial impact zone for zinc (3.5 km) and lead (4.8 km) demonstrates the large radius of influence of these pollutants in the urban environment. According to the results of this research, it is recommended to make continuous monitoring of urban soils part of the environmental organization agenda in Kazakhstan every two or three years, and set the priorities for monitoring according to the pollution zoning maps obtained during this research. The territories where there is an industrial use of land and the areas around busier streets, which had the highest indices of pollution, should be considered priority territories for measures of soil restoration. It is also necessary to coordinate national soil quality standards of Kazakhstan with the international standards, such as the recommendations by the World Health Organization, to make an adequate evaluation of the possible threats to health of citizens. The approach of this study (field studies combined with statistical and geostatistical analysis) can be an example for other industrial cities in Central Asia and regions with a similar climate and industry. However, conducting an additional research, including bioavailability approach and human health risk assessment based on the results of this research, can give a more detailed information about the environmental consequences of urban soil pollution in Kazakhstan.

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