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Regional variations and geostatistical mapping of soil contamination by heavy metals in Astana city

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Abstract

Urbanisation and industrial development significantly increase the risk of heavy metal contamination in soil, particularly in rapidly growing cities such as Astana, Kazakhstan. Urban soils accumulate pollutants through traffic emissions, industrial discharges, and construction activities, which may pose risks to ecosystems and human health. Therefore, it is critical to assess the spatial distribution and concentration of hazardous metals to support environmental decision-making and sustainable land management. This study focuses on evaluating the spatial distribution of cadmium (Cd), zinc (Zn), chromium (Cr), lead (Pb), and copper (Cu) in the surface soils of Astana. A total of 25 soil samples were collected from different functional zones of the city. The samples were analyzed using standard laboratory procedures. Spatial interpolation was performed using the kriging method in ArcGIS 10.8 to generate distribution maps. The results demonstrated spatial heterogeneity in heavy metal distribution across the city. Elevated concentrations of Cd, Zn, Cr, and Pb were primarily found in the Esil, Almaty, and Saryarka districts, which correspond to areas of high vehicular traffic, dense urban infrastructure, and industrial activity. Copper displayed a more localized pattern with scattered hotspots. Although all values were within national and international permissible limits, several areas showed levels exceeding natural background values, suggesting anthropogenic influence and the potential for long-term ecological impact. The study highlights key areas of concern and provides an environmental zoning approach that can aid urban planners and environmental authorities in prioritizing mitigation efforts. The integration of GIS-based spatial analysis with contamination assessment proves effective for supporting sustainable urban development and targeted soil remediation in Astana.

Keywords: Environmental zoning, GIS, Heavy metals, Kriging interpolation, Soil contamination.

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1. Introduction

The phenomenon of rapid urbanization represents one of the most significant anthropogenic transformations of the 21st century, fundamentally altering terrestrial ecosystems and biogeochemical cycles across the globe. Contemporary urbanization patterns demonstrate an exponential increase in urbanized territories, with the global average urban development footprint reaching 0.04 hectares per capita, while developed economies exhibit substantially higher values of 0.1 hectares per capita [1]. This spatial expansion is accompanied by intensive technogenic pressures that fundamentally modify natural soil-forming processes and introduce novel contaminant pathways into urban environments.

The demographic transition accompanying urbanization presents unprecedented challenges for environmental sustainability. Historical demographic data reveal a dramatic population trajectory: from approximately 717 million inhabitants in 1750, the global population surpassed 7.8 billion in 2020, with projections indicating a continued expansion to 8.5 billion by 2030 [2]. This population growth is characterized by a pronounced shift in settlement patterns, with urban population percentages increasing from merely 9% in 1900 to 47% in 2000, with projections suggesting that 90% of the global population will reside in urban centers by 2030.

Astana, the capital of Kazakhstan, exemplifies the rapid urbanization dynamics characteristic of emerging economies in Central Asia. The city represents one of the fastest-growing urban centers globally, with its population more than doubling over the preceding 15 years [3]. Demographic projections for this metropolitan area indicate continued exponential growth, with population estimates reaching 1.9 million by 2030 and potentially expanding to 3.5 million by 2050 [4, 5]. This rapid urban expansion is primarily driven by rural-to-urban migration patterns, creating concentrated population densities that intensify anthropogenic pressures on local environmental systems.

The introduction of heavy metals into urban soil systems occurs through multiple anthropogenic pathways, each contributing distinct contamination signatures and spatial distributions. Primary sources include:

Industrial emissions: Manufacturing processes, particularly metallurgical operations, chemical production, and energy generation facilities, release heavy metals through atmospheric deposition, direct discharge, and waste disposal practices.

Transportation systems: Vehicular traffic contributes significantly to heavy metal accumulation through tire wear particles, brake pad degradation, fuel combustion byproducts, and lubricant losses. These contributions create characteristic linear contamination patterns along major transportation corridors.

Agricultural activities: The application of phosphate fertilizers, sewage sludge, and pesticides introduces heavy metals into periurban soils, which subsequently become incorporated into expanding urban boundaries.

Construction and demolition activities involving building materials, particularly those containing lead-based paints, galvanized materials, and treated timber, contribute to localized heavy metal contamination.

Heavy metals exhibit unique environmental behavior characteristics that distinguish them from organic contaminants. Unlike organic pollutants that undergo biodegradation processes, heavy metals persist indefinitely in environmental matrices, undergoing only physical and chemical transformations that alter their mobility, bioavailability, and toxicity [6].

The accumulation of heavy metals in surface soil horizons occurs through several mechanisms:

Atmospheric deposition: Particulate matter containing heavy metals settles on soil surfaces, creating a concentrated contamination layer in the uppermost soil horizons. Surface runoff concentration: Urban surface water systems transport dissolved and particulate-bound heavy metals, concentrating them in specific landscape positions and soil depressions. In-situ accumulation: Direct deposition from point sources creates localized contamination hotspots with elevated heavy metal concentrations.

Once deposited, heavy metals undergo complex chemical transformations that influence their environmental mobility and biological availability [7]. Factors governing these transformations include soil pH, organic matter content, clay mineralogy, redox conditions, and the presence of competing ions [8].

Heavy metals demonstrate pronounced bioaccumulation potential, concentrating in biological tissues at levels substantially exceeding environmental concentrations [9]. This bioaccumulation occurs through multiple exposure pathways:

Direct soil ingestion: particularly significant for children engaged in hand-to-mouth behaviors and outdoor play activities. Dermal contact: absorption through skin contact with contaminated soil particles. Inhalation of resuspended particles: inhalation of wind-blown contaminated soil particles, particularly during dry periods and high wind conditions

[10]. Dietary Exposure: Consumption of vegetables and fruits grown in contaminated urban soils, where heavy metals are transferred from soil to plant tissues through root uptake processes.

The trophic transfer of heavy metals through food webs results in biomagnification, where predator species accumulate higher concentrations than their prey, creating potential human health risks through the consumption of contaminated food products [11].

Lead represents the most toxicologically significant heavy metal in urban environments, with no known safe exposure threshold. Epidemiological studies demonstrate that elevated blood lead concentrations cause measurable delays in children's physical development and produce lasting negative effects on normal brain development processes [12, 13].

Neurotoxicological research indicates that lead exposure during critical developmental periods results in:

- Reduced cognitive function and IQ scores
- Impaired attention and executive function
- Behavioral disorders and hyperactivity
- Learning disabilities and academic performance deficits
- Altered neuroanatomical development

The relationship between environmental lead exposure and biological uptake demonstrates strong spatial correlations, with research establishing exponential relationships between heavy metal concentrations in urban soils and their corresponding levels in human blood [14].

Urban environments typically exhibit contamination by multiple heavy metals simultaneously, creating complex toxicological interactions that may produce synergistic or antagonistic effects [15]. The elements of primary concern in this study include: Silicon (Si). While generally considered non-toxic, crystalline silica particles can cause respiratory inflammation and fibrosis when inhaled [16]. Lead (Pb) - a highly toxic neurotoxin with no safe exposure threshold, particularly dangerous for developing children. Zinc (Zn) - an essential micronutrient in small quantities but toxic at elevated concentrations, causing gastrointestinal distress and immune system suppression [17]. Cadmium (Cd) - a highly toxic heavy metal that accumulates in the kidneys and liver, classified as a human carcinogen with a long biological half-life. Chromium (Cr) - exists in multiple oxidation states with varying toxicity; hexavalent chromium is highly toxic and carcinogenic [18].

Urban soil formation processes differ fundamentally from natural pedogenesis due to the dominant influence of anthropogenic activities. In urban environments, technogenesis becomes the primary soil-forming factor, often overwhelming natural bioclimatic influences that typically control soil development [6].

The complexity of urban soil systems arises from several factors: anthropogenic parent materials, urban soils develop from a mixture of natural materials and anthropogenic substrates, including construction debris, imported fill materials, and industrial waste products. Modified hydrology urban infrastructure alters natural drainage patterns, creating localized zones of enhanced or restricted water movement that influence chemical weathering and contaminant transport [19]. Altered Biological Activity - Urban environments support modified biological communities with altered decomposition rates and nutrient cycling processes [20]. Physical disturbance, frequent excavation, compaction, and surface sealing create complex soil profiles with disrupted horizon development.

The development of cultural layers represents a distinctive characteristic of urban soil systems, where human activities create stratified deposits that preserve historical records of contamination and land use changes [21, 22]. In cities with long historical development, such as Astana's older districts, soils have developed beneath thick cultural layers that may extend several meters in depth [23, 24].

These cultural layers exhibit several important characteristics:

- Preserved contamination signatures from different historical periods
- Varying heavy metal concentrations reflecting changing industrial activities
- Stratified deposits that enable temporal reconstruction of contamination history
- Complex geochemical interactions between historical and contemporary contamination sources

The assessment of heavy metal contamination in urban soils represents a critical component of environmental health protection in rapidly developing cities such as Astana. The complex interactions between multiple contamination sources, varied urban land uses, and diverse exposure pathways require comprehensive, scientifically rigorous assessment approaches that integrate advanced analytical methods with sophisticated spatial analysis techniques [25].

Future research directions should focus on:

- Long-term monitoring programs to track contamination trends over time
- Development of predictive models for contamination distribution under different urban development scenarios
- Investigation of remediation technologies appropriate for urban soil contamination
- Integration of contamination assessment with urban planning and public health protection strategies
- Comparative studies across different urban centers to identify common patterns and region-specific characteristics

This research contributes to the growing body of scientific knowledge addressing environmental contamination in rapidly urbanizing regions, providing essential information for evidence-based environmental management and public health protection strategies.

2. Materials and Methods

In this study, the central part of Astana city was first divided into subregions with distinct characteristics (Esil, Nura, Almaty, Saryarka, and Baikonur), and sampling points were selected to represent these areas. Astana is located at 51°08′ N latitude and 71°26′ E longitude. Preliminary assessments indicated the need to collect samples from **25 locations**. Soil material was collected from the topsoil layer (0–20 cm depth) at the designated points, then labeled and transported to the laboratory. In the laboratory, soil samples were sieved, placed in Petri dishes, and dried at 45 °C for 15 days.

Since soil samples are difficult to homogenize and their elemental composition varies significantly, **six replicates** were prepared for each sample. After drying, the samples were analyzed using an Atomic Absorption Spectrometer (AAS) to determine the concentrations of lead (Pb), chromium (Cr), copper (Cu), zinc (Zn), and cadmium (Cd). The obtained data were first processed using analysis of variance (ANOVA) and Duncan's multiple range test in **SPSS** statistical software.

Subsequently, the concentrations of Pb, Cr, Cu, Zn, and Cd from various sampling locations were transferred into Geographic Information Systems (GIS**)** using ArcGIS 10.8 software. Coordinates and data projections were defined in the initial stage. The spatial data were then modeled using the kriging interpolation method, and pollution maps were generated for each heavy metal [26]**.** The area and percentage coverage for each concentration range on the maps were also calculated using Microsoft Excel.

Sampling and preparation of soil samples to determine the content of elements in the soil according to ISO 17.4.4.02–84 "Nature Protection. Soil. Methods of sampling and preparation of samples for chemical, bacteriological, helminthological analysis." As part of the study, points were identified in the sub-districts of Astana, Almaty, Baikonur, Esil, Nura, and Saryarka.

Samples were taken from the surface layer of the soil (5-20 cm) using the envelope method (from 5 points). By mixing samples from these 5 points, a combined soil sample weighing 1 kg was prepared. The background content of the studied heavy metals in the soil was determined to establish the exact concentrations of elements present. As a control (background) site, 5 test sites were selected within a radius of 10 km from Astana, where there is no anthropogenic load (remote from industrial zones). Five samples were collected from the surface layers of the soil in the background area (0-15 cm) following ISO 17.4.4.02–84 standard.

The concentrations of mobile forms of the elements Si, Pb, Zn, Cd, and Cr in Astana's soil were determined by atomic absorption at the Research Institute of Batysecoproekt LLP's certified laboratory, following the regulatory document m-MVI-80-2008.

3. Results

Elemental concentration changes were evaluated regionally in relation to varying traffic intensities, examining the correlation between traffic density and heavy metal accumulation.

3.1. Change of Cr Element

Chromium (Cr), one of the most toxic and hazardous heavy metals, was analyzed in this study. The variation in Cr concentrations was assessed on a regional basis according to traffic density levels, and the relationship between Cr levels and vehicular load across different zones is presented in Table 1.

According to sanitary and hygienic standards (SanPiN), the maximum permissible concentration (MPC) of total chromium in soil is 6.0 mg/kg, which serves as the benchmark for ecological assessment of soil contamination.

In areas with no traffic, the lowest Cr concentrations were recorded in Zone 1 (5.19 mg/kg) and Zone 4 (5.29 mg/kg), while the highest values were found in Zone 2 (5.48 mg/kg), Zone 3 (5.42 mg/kg), and Zone 5 (5.38 mg/kg).

In low traffic density areas, the minimum Cr concentrations were 5.36 mg/kg in Zones 1 and 2, and 5.45 mg/kg in Zone 5. The maximum values were observed in Zone 4 (5.58 mg/kg) and Zone 3 (5.56 mg/kg).

In medium traffic intensity areas, Cr concentrations ranged from 4.79 mg/kg (Zone 2) to 5.86 mg/kg (Zone 1). Lower values were also noted in Zone 4 (5.52 mg/kg) and Zone 5 (5.42 mg/kg), while the highest concentrations were recorded in Zone 1 (5.86 mg/kg) and Zone 3 (5.75 mg/kg).

In areas with high traffic intensity, Cr concentrations increased further. The minimum values were 5.49 mg/kg (Zone 2), 5.61 mg/kg (Zone 5), and 5.63 mg/kg (Zone 4), while the maximum reached 5.80 mg/kg (Zone 1) and 5.70 mg/kg (Zone 3).

In very high traffic zones, the highest Cr concentration was 6.10 mg/kg in Zone 3, followed by 6.01 mg/kg in Zone 1 and 5.97 mg/kg in Zone 5. The lowest concentrations in this category were 5.52 mg/kg in Zone 2 and 5.78 mg/kg in Zone 4.

When considering regional variation in Cr concentration based on traffic density, the results of Duncan's multiple range test revealed that Zones 1, 3, and 5 were grouped into three homogeneous subsets, whereas the remaining zones formed two groups. The lowest concentration overall (4.79 mg/kg) was recorded in Zone 2, in areas with medium traffic intensity. Notably, no zone fell into the highest homogeneous group in high traffic areas.

According to the results of one-way ANOVA, the concentration of mobile chromium forms differed significantly depending on traffic load ($F = 3.98$; $p = 0.0156 < 0.05$), confirming the influence of vehicular activity on the distribution of Cr in the soil across the study area.

The spatial distribution of chromium (Cr) concentration in the study area is illustrated in Figure 1. The interpolation results show that the highest Cr concentrations were recorded in the southern part of the Esil district, where values reach up to **5.67 mg/kg**. These areas are associated with zones of active urban development and dense transportation infrastructure. The distribution of Cr concentrations over the city territory is as follows:

- 5.64–5.67 mg/kg: the highest concentration zone, covering approximately 12–15% of the study area, primarily located in the southern part of the Esil district;
- 5.60–5.64 mg/kg: around 17%, observed in the central and southwestern Esil and Nura districts;
- 5.55–5.60 mg/kg: approximately 20%, extending across Nura district and western Esil;

- 5.50–5.55 mg/kg: about 18%, covering parts of Almaty, Saryarka, and Nura districts;
- 5.47–5.50 mg/kg: around 15%, mostly in Baikonur and Almaty districts;
- 5.40–5.47 mg/kg: the lowest concentration range, found in 13% of the area, particularly in the northern part of the Baikonur district.

It is notable that the southern part of the Esil district consistently shows the highest Cr values, indicating potential anthropogenic sources such as traffic emissions, construction activities, or historical pollution accumulation. In contrast, lower Cr levels are found in the northern parts of the city, including Baikonur and Saryarka districts, which are characterized by lower urban load and more residential or administrative land use.

Table 1.
Change of Cr element by region.

Area	Density of traffic					
	Notraffic	**Less intense**	**Middle**	**Dense**	**Toodense**	***F* value**
1	5.19aA	5.36aA	5.86aA	5.8aA	6.01bB	4.15
2	5.48aA	5.36aA	4.79aA	5.49aA	5.52bB	3.78
3	5.42aA	5.56aA	5.75aA	5.7aA	6.1bB	4.63
4	5.29aA	5.58aA	5.42aA	5.63aA	5.78bB	2.89
5	5.38aA	5.45aA	5.52aA	5.61aA	5.97bB	3.55
F value	3.98					

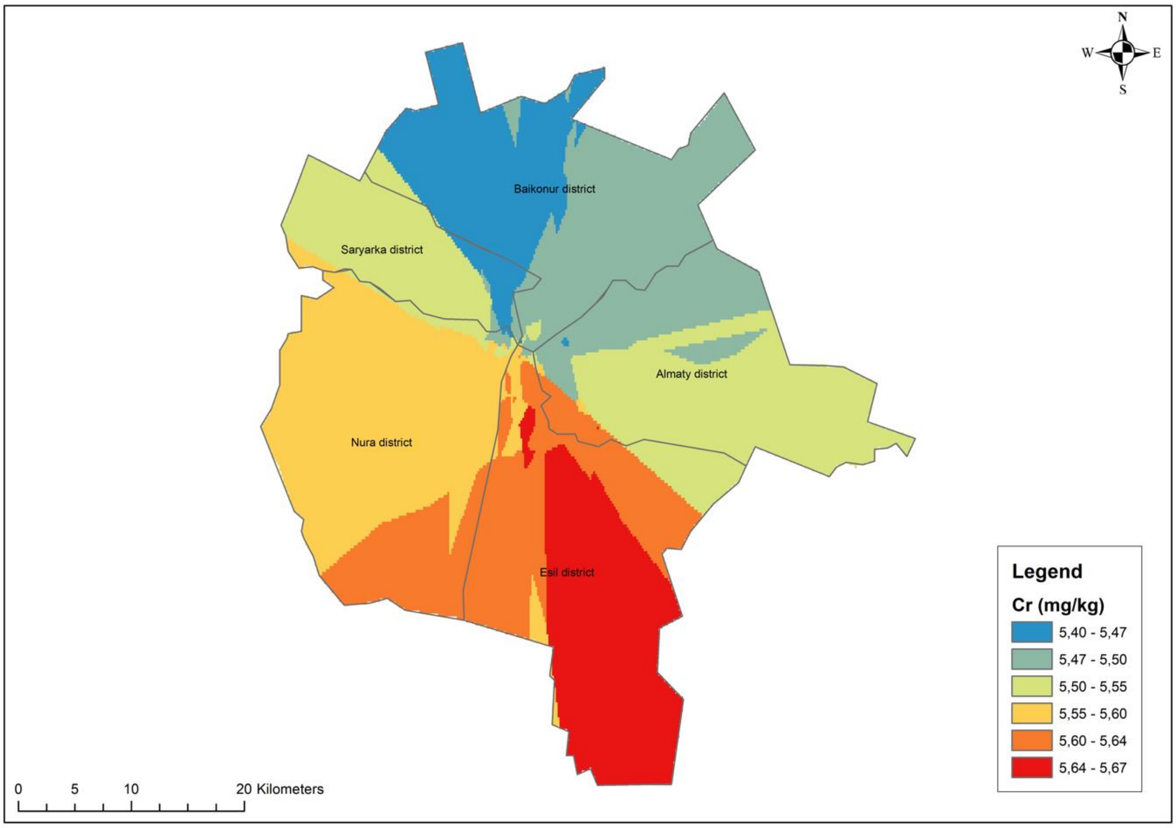

Figure 1.
Variation of Cr concentration.

3.2. Change of Cu Element

Copper (Cu) is an essential micronutrient; however, at elevated concentrations, it becomes toxic and negatively affects microorganisms, plants, and soil processes. Major sources of soil copper contamination include emissions from transportation and industrial activities. The variation in Cu concentration by region and traffic intensity is presented in Table 2.

According to sanitary and hygienic standards, the maximum permissible concentration (MPC) of the mobile form of copper in soil is 3.0 mg/kg. This threshold is used as an indicative value for assessing the ecological bioavailability of heavy metals and their potential toxicity to plants and soil microorganisms.

In areas with no traffic, the lowest Cu concentrations were recorded in Zone 4 (2.43 mg/kg) and Zone 2 (2.46 mg/kg), while the highest values reached 2.64 mg/kg in Zone 5 and 2.49 mg/kg in Zone 3.

In low traffic density areas, the highest Cu concentrations were found in Zone 2 (2.96 mg/kg) and Zone 3 (2.83 mg/kg). The lowest values were recorded in Zone 1 (2.55 mg/kg), Zone 5 (2.72 mg/kg), and Zone 4 (2.74 mg/kg).

In moderate traffic density zones, Cu concentrations decreased to 2.31 mg/kg in Zone 2, with similarly low values in Zone 5 (2.52 mg/kg). The highest levels were observed in Zone 3 (2.72 mg/kg), Zone 1 (2.68 mg/kg), and Zone 4 (2.62 mg/kg).

In high traffic density areas, the maximum values were recorded in Zone 1 (2.88 mg/kg) and Zone 4 (2.81 mg/kg). The minimum concentration was observed in Zone 3 (2.70 mg/kg), while intermediate values were noted in Zone 2 (2.71 mg/kg) and Zone 5 (2.76 mg/kg).

In very high traffic density zones, the highest Cu concentration reached 3.10 mg/kg in Zone 1. This was followed by Zone 3 (2.97 mg/kg) and Zone 5 (2.92 mg/kg), while the lowest values were recorded in Zone 4 (2.64 mg/kg) and Zone 2 (2.78 mg/kg).

According to one-way ANOVA, Cu concentrations varied significantly with traffic intensity ($F = 4.11$; $p = 0.0319 < 0.05$), indicating that increased vehicle density contributes to elevated copper levels in the soil of the studied area.

Figure 2 presents the spatial distribution of copper (Cu) concentrations in the soil across Astana. Unlike other heavy metals, Cu shows a distinctly fragmented distribution pattern, with small high-concentration hotspots scattered throughout the city. The overall concentration levels range between 2.33 and 3.07 mg/kg**.**

The spatial distribution by concentration range is as follows:

- 2.83–3.07 mg/kg: localized hotspots, covering less than 5% of the total area, primarily located in central zones of Almaty, Saryarka, and Baikonur districts.
- 2.74–2.83 mg/kg: about 7–10%, detected in small patches around central and northern parts of the city;
- 2.69–2.74 mg/kg: approximately 12%, scattered in the transitional zones;
- 2.66–2.69 mg/kg: around 15%, found mostly in the surrounding areas of hotspots;
- 2.59–2.66 mg/kg and 2.33–2.59 mg/kg: make up the majority of the area (over 55%), especially in the outskirts of the city, including large parts of Nura, Esil, and Baikonur districts.

Unlike the more uniform patterns observed for Zn and Pb, the Cu concentration map highlights discrete, point-source contamination**,** suggesting that Cu pollution is more likely associated with specific anthropogenic activities (e.g., mechanical workshops, electrical equipment, construction sites) rather than diffuse urban or transport-related emissions.

The lowest Cu values are predominantly recorded in the outer zones of the Esil and Nura districts, where environmental loads are minimal.

Table 2.
Change of Cu element by region.

Area	**Density of traffic**					
	Notraffic	**Less intense**	**Middle**	**Dense**	**Toodense**	***F* value**
1	2.45 aA	2.55aB	2.68 aB	2.88 aB	3.1 bC	4.12
2	2.46 aA	2.96 aB	2.31 aB	2.71 aB	2.78 bC	3.80
3	2.49 aA	2.83 aB	2.72 aB	2.7 aB	2.97 bC	4.44
4	2.43 aA	2.74 aB	2.62 aB	2.81 aB	2.64 bC	3.01
5	2.64 aA	2.72 aB	2.52 aB	2.76 aB	2.92 bC	3.65
F value	4.11					

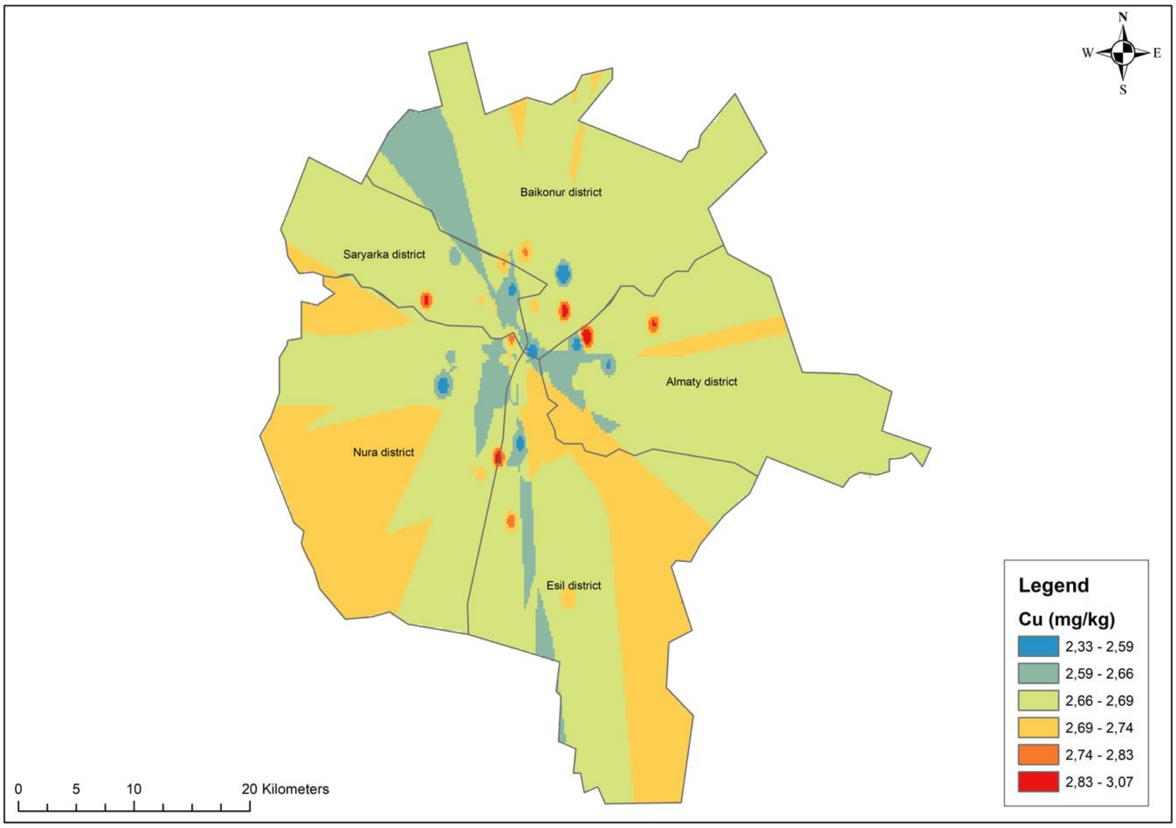

Figure 2.
Variation of Cu concentration.

3.3. Change of Pb Element

The variation in Pb concentration, one of the elements most closely associated with traffic density, across different districts is presented in Table 3. Lead (Pb) is one of the most extensively studied heavy metals due to its known effects on human health and ecosystems, as well as its direct association with traffic intensity. The results of this study showed that variations in Pb concentration across different regions and traffic density levels are statistically significant at the 99.9% confidence level ($p < 0.001$). According to sanitary and hygienic standards, the maximum permissible concentration (MPC) of the mobile form of lead in soil is 6.0 mg/kg, which serves as a reference for evaluating its bioavailability and potential toxicity to living organisms.

In areas with no traffic, the highest Pb concentrations were recorded in Zone 5 (7.51 mg/kg), Zone 2 (7.34 mg/kg), and Zone 4 (7.23 mg/kg). The lowest concentrations were observed in Zone 3 (6.44 mg/kg) and Zone 1 (7.15 mg/kg).

In low traffic density areas, the highest Pb concentrations were found in Zone 5 (7.47 mg/kg) and Zone 2 (7.23 mg/kg), while the lowest were in Zone 2 (6.24 mg/kg), Zone 1 (6.78 mg/kg), and Zone 3 (6.89 mg/kg).

In medium traffic density areas, the Pb concentration dropped to a minimum of 5.32 mg/kg in Zone 3. Other low values were recorded in Zone 1 (6.58 mg/kg) and Zone 4 (6.74 mg/kg), while the highest levels were observed in Zone 5 (7.49 mg/kg) and Zone 2 (6.85 mg/kg).

In high traffic density zones, the maximum concentrations were noted in Zone 5 (7.62 mg/kg) and Zone 1 (7.59 mg/kg). The lowest value was recorded in Zone 3 (6.28 mg/kg), while intermediate levels were found in Zone 2 (7.54 mg/kg) and Zone 4 (7.56 mg/kg).

In very high traffic intensity areas, the highest Pb concentration reached 7.87 mg/kg in Zone 1, followed by 7.85 mg/kg in Zone 3 and 7.60 mg/kg in Zone 5. The lowest values in this category were recorded in Zone 2 (7.27 mg/kg) and Zone 4 (7.34 mg/kg).

Overall, the Pb concentration range was relatively narrow (5.32–7.87 mg/kg), with a clear minimum in Zone 3 and a maximum in Zone 1.

According to one-way ANOVA, differences in the mobile Pb concentrations between traffic density zones did not reach statistical significance at the 95% confidence level ($F = 2.49$; $p = 0.076$). Nonetheless, the data demonstrate a consistent trend of increasing Pb content with increasing traffic intensity.

Duncan’s multiple range test revealed statistically homogeneous groups (see Table below). The lowest Pb concentrations were found in medium traffic areas (Group A), while the highest concentrations were observed in high and very high traffic zones (Group C).

Interestingly, three of the highest Pb values were recorded in areas without traffic, two in low, medium, and high traffic zones each, and only one in the very high traffic zone. Notably, the maximum Pb concentration (7.87 mg/kg) was recorded in Zone 1 (very high traffic), while another prominent value (7.51 mg/kg) was found in Zone 5 (no traffic), suggesting the presence of additional non-traffic-related sources of pollution, such as household or industrial emissions.

In summary, one-way ANOVA results indicate that Pb concentration differences across traffic zones are not statistically significant ($F = 2.38$; $p = 0.1217 > 0.05$). Therefore, the impact of vehicular traffic on Pb accumulation in soil within the study area was not confirmed at the 95% confidence level.

Figure 3 shows the spatial variation in lead (Pb) concentrations across Astana city. According to the kriging interpolation results, the highest Pb levels were observed in the northern and northwestern areas, particularly within the Saryarka and parts of the Baikonur districts, where concentrations reached up to 7.89 mg/kg**.**

The spatial distribution of Pb concentrations by range is as follows:

- 7.55–7.89 mg/kg: approximately 20% of the study area, mainly covering the central and western parts of Saryarka district and small hot spots in Baikonur and Almaty.
- 7.20–7.55 mg/kg: around 22%, extending across most of the Baikonur and Nura districts;
- 6.81–7.20 mg/kg: about 18%, including transitional zones between high and moderate levels;
- 6.39–6.81 mg/kg: approximately 16%, located in the Almaty and Nura districts;
- 5.91–6.39 mg/kg: covering about 14% of the area, mostly in Esil and southeastern Almaty;
- 5.32–5.91 mg/kg: the lowest Pb levels, detected in 10% of the area, primarily within the central and southern part of the Esil district.

Notably, the lowest Pb concentrations are concentrated in the Esil district, which includes newer residential and administrative developments, with more controlled environmental conditions. In contrast, higher Pb values are found in the older urban zones, including industrial or densely trafficked areas of the Saryarka district, suggesting the influence of past and present anthropogenic sources, such as vehicle emissions and urban infrastructure [27]**.**

Table 3.
Change of Pb element by region.

Area	Density of traffic					
	Notraffic	**Less intense**	**Middle**	**Dense**	**Toodense**	***F* value**
1	7.15aA	6.78aA	6.58aA	7.59aA	7.87aA	1.42
2	7.34aA	7.23aA	6.85aA	7.54aA	7.27aA	1.21
3	6.44aA	6.89aA	5.32aA	6.28aA	7.85aA	2.05
4	7.23aA	7.47aA	6.74aA	7.56aA	7.34aA	1.33
5	7.51aA	6.24aA	7.49aA	7.62aA	7.6aA	1.87
F value	2.38					

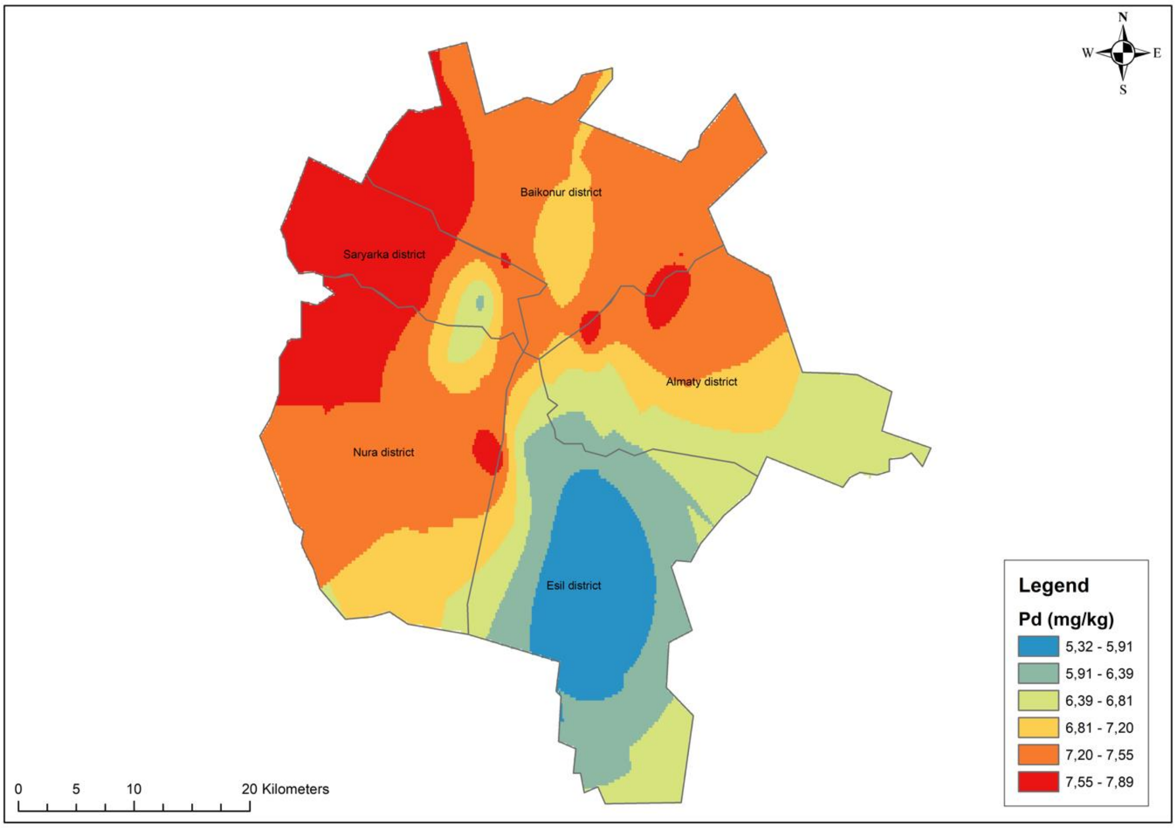

Figure 3.
Variation of Pb concentration.

*3.4. Change of **Cd** Element*

Cadmium (Cd), analysed in this study, is classified as a highly toxic heavy metal with known carcinogenic and mutagenic effects. It has the ability to accumulate in soil and migrate into plants, posing a potential threat to both ecosystems and human health. The variation in Cd concentration across different regions and levels of traffic intensity is presented in Table 4.

The maximum permissible concentration (MPC) for the mobile form of cadmium in soil is 0.2 mg/kg. This threshold reflects the environmentally hazardous fraction of the element capable of migrating through ecosystems and entering food chains.

In areas with no traffic, the lowest Cd concentrations were observed in Zone 4 (1.14 mg/kg) and Zone 5 (1.28 mg/kg), while the highest values were recorded in Zone 3 (1.56 mg/kg), Zone 1 (1.49 mg/kg), and Zone 2 (1.36 mg/kg).

In low traffic density areas, the highest Cd levels were found in Zone 3 (1.66 mg/kg), Zone 2 (1.47 mg/kg), and Zone 4 (1.45 mg/kg). The lowest concentrations were 1.16 mg/kg in Zone 5 and 1.39 mg/kg in Zone 4.

In moderate traffic density zones, Cd concentrations dropped to 1.24 mg/kg in Zone 4, with similarly low values in Zone 2 (1.41 mg/kg) and Zone 5 (1.42 mg/kg). The highest concentrations were observed in Zone 1 (1.62 mg/kg) and Zone 3 (1.49 mg/kg).

In high-traffic areas, the maximum concentrations were found in Zone 1 (1.68 mg/kg) and Zone 3 (1.51 mg/kg), while the lowest value was recorded in Zone 2 (1.20 mg/kg), with intermediate values in Zone 5 (1.25 mg/kg and 1.28 mg/kg).

In very high traffic intensity zones, the highest Cd concentration reached 1.94 mg/kg in Zone 3, followed by 1.83 mg/kg in Zone 1 and 1.32 mg/kg in Zone 5. The lowest values were observed in Zone 4 (1.01 mg/kg) and Zone 2 (1.22 mg/kg).

According to the results of one-way ANOVA, the differences in Cd content across areas with different traffic intensities were not statistically significant ($F = 0.403$; $p = 0.8023 > 0.05$). These findings indicate that vehicular traffic does not exert a strong influence on the spatial distribution of Cd in the studied zones.

An analysis of the tabular data reveals that the highest Cd concentrations were recorded in the Almaty and Esil districts. In these areas, concentrations reached up to 1.62 mg/kg. Additionally, lower values were observed in the peripheral parts of the Saryarka and Nura districts. The highest Cd concentration was detected along Abylai Khan Street in the Almaty district, reaching 1.83 mg/kg.

The spatial variation of Cd concentration across the study area is presented in Figure 4. According to the map, the highest concentrations of Cd are located in the southern and southeastern parts of the city, particularly in the central and eastern zones of the Esil and Almaty districts, where Cd levels range between 1.54 and 1.62 mg/kg.

The distribution of Cd concentrations across the area is as follows:

- Concentrations of 1.54–1.62 mg/kg cover approximately 15% of the total study area.
- Concentrations of 1.48–1.54 mg/kg occupy around 20%.
- Concentrations of 1.41–1.48 mg/kg account for approximately 18%.
- Concentrations of 1.33–1.41 mg/kg are found in ~22% of the area.
- Concentrations of 1.27–1.33 mg/kg cover about 15%.
- The lowest values, 1.20–1.27 mg/kg, were recorded in about 10% of the area.

The lowest Cd concentrations are primarily observed in the northwestern and western parts of the city, specifically in the Saryarka and Nura districts. These areas are characterized by lower traffic density, increased green space, and their location on the urban periphery.

Table 4.
Change of Cd element by region.

Area	Density of traffic					
	Notraffic	**Less intense**	**Middle**	**Dense**	**Toodense**	***F* value**
1	1.49aA	1.47 aA	1.62 aA	1.68 aA	1.83 aA	1.18
2	1.36aA	1.45 aA	1.41 aA	1.20 aA	1.22 aA	1.04
3	1.56aA	1.66 aA	1.49 aA	1.51 aA	1.94 aA	1.59
4	1.14aA	1.39 aA	1.24 aA	1.28 aA	1.01 aA	1.35
5	1.28aA	1.16 aA	1.42 aA	1.25 aA	1.32 aA	1.12
F value	0.403					

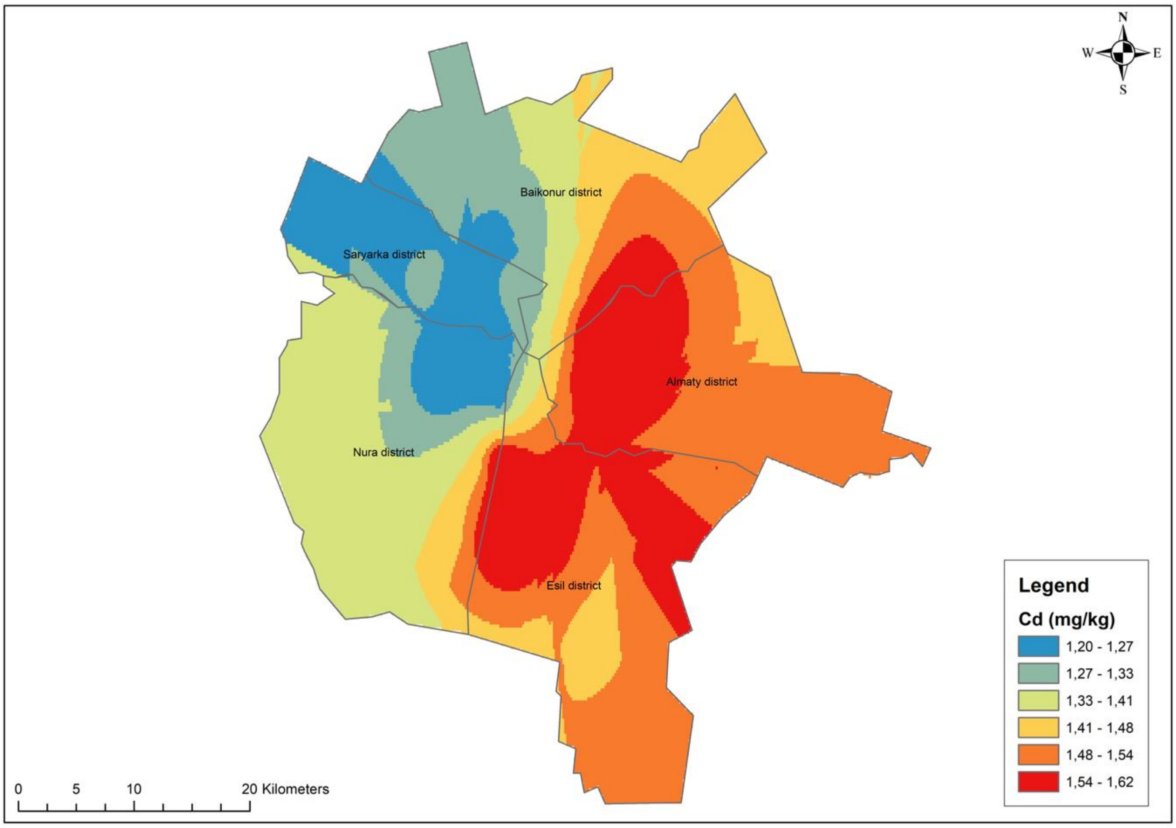

Figure 4.
Variation of Cd concentration.

3.5. Change of Zn Element

Zinc (Zn) is an essential micronutrient required for the proper functioning of living organisms. However, excessive accumulation of Zn in soil can lead to toxic effects, disruption of biochemical processes, and inhibition of soil microflora. The primary sources of Zn input into soil include vehicle exhaust, tire wear, and brake pad abrasion [28]. The variation in Zn concentration by region and traffic intensity is presented in Table 5.

According to sanitary and hygienic standards, the maximum permissible concentration (MPC) for the mobile form of Zn in soil is 23.0 mg/kg. This value serves as a reference for evaluating the metal's bioavailability to plants and microorganisms, as well as for environmental monitoring of soil contamination by heavy metals.

In areas with no traffic, the lowest Zn concentrations were observed in Zone 4 (20.64 mg/kg) and Zone 5 (20.85 mg/kg), while the highest values were recorded in Zone 3 (22.8 mg/kg), Zone 2 (22.4 mg/kg), and Zone 1 (22.2 mg/kg).

In low traffic density zones, the highest concentrations were found in Zone 1 (22.5 mg/kg) and Zone 3 (22.0 mg/kg). The lowest values were recorded in Zone 5 (20.57 mg/kg), Zone 2 (20.79 mg/kg), and Zone 4 (20.81 mg/kg).

In moderate traffic density areas, Zn concentrations dropped to 20.5 mg/kg in Zone 1 and 20.6 mg/kg in Zone 3. The highest concentrations were found in Zone 2 (22.3 mg/kg), Zone 4 (22.1 mg/kg), and Zone 5 (21.34 mg/kg).

In high traffic density zones, the maximum Zn levels were recorded in Zone 2 (21.48 mg/kg) and Zones 1 and 3 (21.4 mg/kg). The lowest value was found in Zone 4 (20.39 mg/kg), with a moderate value in Zone 5 (20.6 mg/kg).

In very high traffic intensity areas, the maximum Zn concentration reached 23.0 mg/kg in Zone 1, followed by 22.9 mg/kg in Zone 3 and 22.8 mg/kg in Zone 5. The lowest values were observed in Zone 4 (21.21 mg/kg) and Zone 2 (21.65 mg/kg).

According to one-way ANOVA, differences in Zn concentration across traffic zones were not statistically significant ($F = 2.33$; $p = 0.1272 > 0.05$). This indicates the absence of a confirmed influence of vehicular activity on Zn accumulation in the soil within the study area.

The spatial distribution of Zn concentration across the study area is shown in Figure 5. According to the interpolation results, the highest Zn concentrations were observed in the southern and southeastern parts of the city, particularly within the Esil and Almaty districts. In these zones, Zn values reached up to 21.93 mg/kg, which represents the upper limit of the recorded concentration range.

The distribution of Zn concentrations over the study area is as follows:

- 21.74–21.93 mg/kg: approximately 20% of the area, mainly in the Esil and southeastern Almaty districts;
- 21.62–21.74 mg/kg: around 22%, covering parts of Almaty and Baikonur districts;
- 21.54–21.62 mg/kg: approximately 18%, extending towards the northern and western parts of Baikonur and central zones;
- 21.46–21.54 mg/kg: about 17%, found in the border zones of Baikonur and Nura districts;

- 21.36–21.46 mg/kg: approximately 13%, mainly within Saryarka and Nura districts;
- 21.16–21.36 mg/kg: the lowest concentration, detected in about 10% of the area, primarily in the western part of the Saryarka district.

It is noteworthy that the highest Zn concentrations correspond to urban zones with dense residential infrastructure, increased traffic load, and active construction, especially in the Esil and Almaty districts. In contrast, lower Zn values are mostly recorded in the northwestern and western parts of the city, where anthropogenic pressure is relatively low.

Table 5.
Change of Zn element by region.

Area	Density of traffic					
	Notraffic	Less intense	Middle	Dense	Toodense	*F* value
1	22.2aA	22.5aA	20.5aA	21.4aA	23bB	3.92
2	22.4aA	20.79aB	22.3aB	21.48aB	21.65bC	4.05
3	22.8aA	22aA	20.6aA	21.4aA	22.9aA	2.64
4	20.64aA	20.81aA	22.1aA	20.39aA	21.21aA	1.83
5	20.85aA	20.57aA	21.34aA	20.6aA	22.8aA	2.15
F value	2.33					

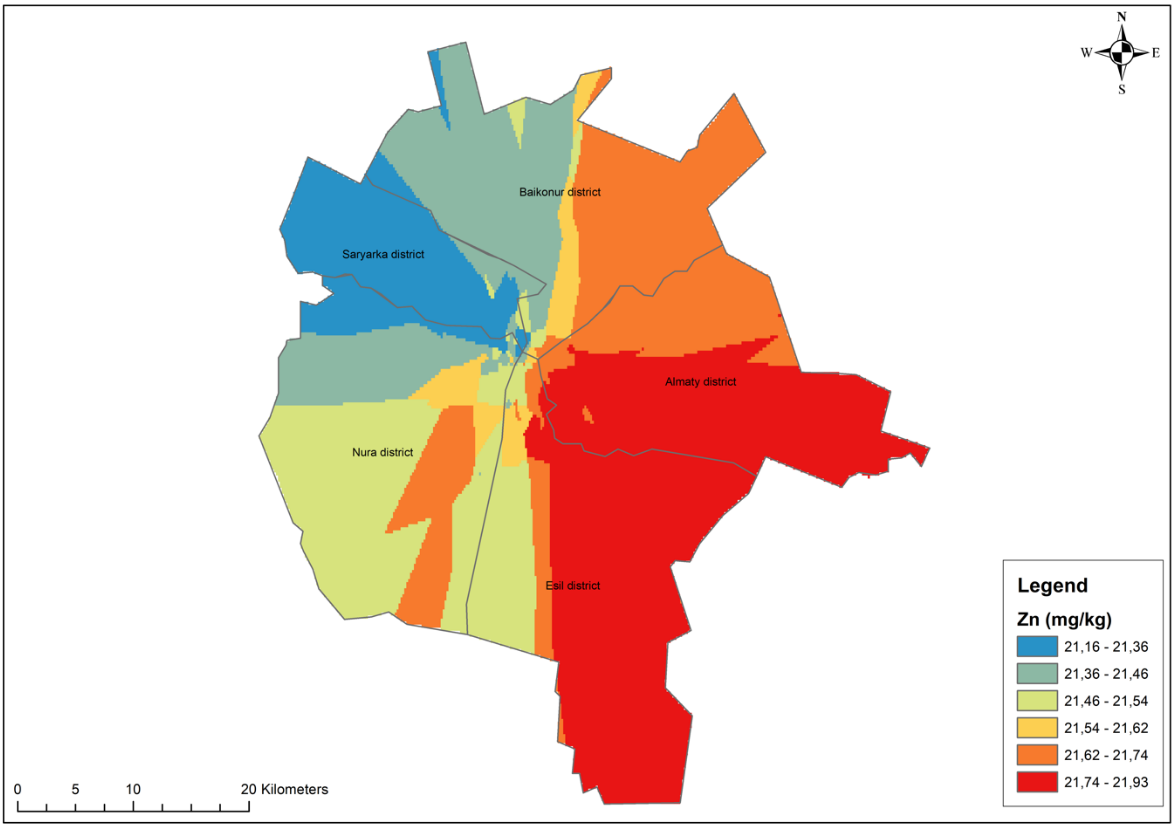

Figure 5.
Variation of Zn concentration.

4. Discussions

The spatial variation of five heavy metals (Cd, Zn, Cr, Pb, Cu) in the urban soils of Astana was assessed using kriging interpolation. The results demonstrated distinct distribution patterns influenced by anthropogenic activities, traffic density, land use, and historical pollution [29].

- Cadmium (Cd) concentrations ranged from 1.20 to 1.62 mg/kg. The highest levels were observed in the southern and southeastern parts of the city, particularly in the Esil and Almaty districts, whereas the lowest concentrations were recorded in the Saryarka and Nura districts.
- · Zinc (Zn) concentrations ranged from 21.16 to 21.93 mg/kg. Zn levels were highest in the Esil and Almaty districts, which correspond to dense urban infrastructure, and lowest in peripheral zones such as Saryarka.
- · Chromium (Cr) showed concentrations between 5.40 and 5.67 mg/kg. The most contaminated areas were in the southern Esil district, while lower levels were typical of the northern and northeastern parts of Baikonur and Saryarka.
- Lead (Pb) concentrations ranged from 5.32 to 7.89 mg/kg. Elevated Pb levels were prominent in the Saryarka and Baikonur districts, likely due to traffic emissions and historical industrial activity. In contrast, the Esil district exhibited relatively low Pb concentrations.

- Copper (Cu) distribution was more localized, with concentrations ranging from 2.33 to 3.07 mg/kg. High Cu levels appeared as isolated hotspots in the districts of Almaty, Baikonur, and Saryarka, indicating point-source contamination.

Based on the spatial distribution of heavy metals, the city was classified into three environmental zones:

- Zone I (High-Risk) – Areas with consistently high concentrations of Cd, Zn, Cr, and Pb. These zones are associated with industrial activity, dense traffic, and construction. Located mainly in the central and southeastern Esil and Almaty districts.
- Zone II (Moderate-Risk) – Transitional areas with moderate levels of pollution, typically surrounding high-risk zones. Found in Baikonur and the peripheral parts of Almaty and Nura.
- Zone III (Low-Risk) – areas with low concentrations of all five metals. These include the outer parts of the Saryarka and Nura districts, suitable for green infrastructure and conservation efforts.

The observed values for most elements remained below international and national permissible limits (e.g., Cd < 3.0 mg/kg, Pb < 6 mg/kg for Kazakhstan soil standards). However, the presence of spatially elevated values, especially in areas of high urban pressure, highlights the need for regular monitoring and targeted mitigation [30].

The spatial patterns observed in this study highlight the significant influence of anthropogenic activities on soil quality. The results can support:

- Informed decision-making in land use planning
- Prioritisation of remediation in high-risk zones
- Sustainable development strategies to reduce urban pollution

The elements in question are among the most prevalent pollutants related to transport activities, with numerous studies noting that environmental concentrations rise with increased traffic [31].

Cadmium (Cd) is a toxic heavy metal that ranks seventh among all heavy metals regarding harm to animals and plants [32, 33]. Lead is classified as a priority heavy metal pollutant by the United States Environmental Protection Agency [34, 35]. Typically, Pb enters the natural environment via industrial production (including mining and smelting), the use of lead-containing products, the combustion of fossil fuels (such as coal and leaded petrol), and mineral fertilizers and wastewater [36]. Cadmium pollution is primarily attributed to factors such as the parent soil material, soil type, water supply systems [37, 38] dust deposition [39] and human activities [40, 41]. Previous studies have demonstrated that mining and smelting metals, electroplating, emissions from vehicles, energy production, fuel production, and the application of fertilizers and pesticides are the principal means by which human activities contribute to Cd pollution [28]. Anthropogenic factors significantly influence the potential contamination of toxic metals [42, 43]. Many studies have indicated that concentrations of Pb, Cd, Cr, Zn, and Cu in urban soils are affected by various factors. For instance:

- A correlation between heavy metal content and the utilisation of fertilisers has been established [27].
- The primary sources of Cr pollution have been identified as the metallurgical industry (55%) and the chemical industry (40%) [44].
- Mineral activity and soil pH are critical factors in the accumulation of heavy metals [45].
- Concentrations vary based on land type: lawns > agricultural lands > artificial gardens > forests > forest-meadow zones [41].
- Four significant sources of soil contamination by heavy metals have been identified: agricultural activities (23.08%), industry (29.10%), natural sources (22.87%), and transport emissions (24.95%) [46].

5. Conclusions

This study evaluated the spatial distribution of five heavy metals (Cd, Zn, Cr, Pb, Cu) in the urban soils of Astana using kriging interpolation and zoning analysis. The findings revealed notable spatial heterogeneity across districts, with distinct contamination hotspots in areas of high anthropogenic activity such as the Esil, Almaty, and Saryarka districts.

Cadmium, zinc, chromium, and lead exhibited elevated concentrations in the southern and central zones of the city, closely associated with traffic density, construction zones, and industrial infrastructure. Copper, in contrast, displayed a more fragmented pattern, forming localized hotspots likely linked to specific point-source pollution.

Based on concentration ranges and spatial patterns, the city was classified into three environmental zones: high-risk, moderate-risk, and low-risk areas. This zoning approach provides a useful framework for urban environmental management by identifying critical zones that require immediate intervention and long-term monitoring.

Although the measured concentrations were below national and international regulatory limits, the presence of pollution clusters indicates potential ecological risk if urban expansion and environmental loads remain unchecked. The results of this study can inform policymakers, urban planners, and environmental agencies to adopt evidence-based measures for sustainable urban development and soil protection.

To improve soil quality and mitigate heavy metal contamination in Astana, the following recommendations are proposed:

1. Establish a regular soil monitoring program in urban districts with high anthropogenic activity, especially Esil, Almaty, and Saryarka.
2. Apply green infrastructure solutions, such as phytoremediation, green belts, and vegetation barriers, in moderate- and high-risk zones.
3. Integrate GIS-based zoning data into urban planning frameworks to prevent development in heavily contaminated areas.

4. Strengthen environmental regulations and enforcement concerning industrial emissions, construction activities, and vehicular traffic in vulnerable districts.
5. Raise public awareness and promote sustainable urban practices through community involvement and educational campaigns.
6. Encourage further research using advanced remote sensing and modeling tools to detect long-term pollution dynamics.

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