RESEARCH PAPER

# SNOW COVER POLLUTION BY POTENTIALLY TOXIC ELEMENTS IN SMALL AND MEDIUM-SIZED INDUSTRIAL CITIES: CASE OF SVERDLOVSK REGION, RUSSIA

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ABSTRACT. This study aims to develop and validate a method for assessing urban air pollution by analysing undisturbed snow cover in residential areas of small and medium-sized industrial cities in Sverdlovsk Region, Russia: Kachkanar, Serov, Verkhnyaya Pyshma, and Alapaevsk. Snow samples were collected in each city.

The proposed approach is based on the analysis of the most contaminated solid fraction of snow (particles >2 μm and filtrate). This method has shown effectiveness in identifying pollutants and their sources. It is also more cost-efficient and offers better material accessibility than the approach that analyses both dissolved (<0.45 μm) and suspended (>0.45 μm) snow phases. The balanced set of qualitative and quantitative indicators includes the physical and chemical properties of snow, the accumulation intensity of PTEs, the calculation of indices ($I_{geo}$, *EF, PI,* $PI_{sum}$, $PI_{avg}$ *and* $PI_{Nemerow}$), dust load, and geochemical associations.

Snow's physical and chemical properties were influenced by natural conditions. Low mineralisation and suspended solids were mostly composed of calcium and magnesium bicarbonates and sulfates. Snow pH was slightly alkaline in Serov and mildly alkaline in other cities.

Metallurgical and mining cities showed higher pollution according to the indices: elevated V and Fe in Kachkanar, Cr in Serov, Cu and As in Verkhnyaya Pyshma. Kachkanar was the most polluted city ($PI_{sum}$ – 154, $PI_{Nemerow}$ – 12), while Serov and Verkhnyaya Pyshma were also significantly polluted with similar $PI_{sum}$ and $PI_{avg}$ values (66 and 4.2, respectively) and $PI_{Nemerow}$ values (5.1 and 7.2, respectively). Geochemical associations reflected local industrial profiles. Dust load ranged from 27 to 163 mg/m$^2$/day, peaking in Kachkanar.

The collected data indicate current atmospheric pollution in the studied cities. This method proved effective for assessing urban air pollution and is recommended for environmental monitoring in other industrial regions.

KEYWORDS: environmental monitoring, urban area, industrial cities, snow, atmospheric pollution, potentially toxic elements, urban geochemical background

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## INTRODUCTION

Aerosols, particulate matter (PM), metals and metalloids (MMs) in urban air are a negative factor for the environment and human health. Atmospheric pollution increases the risk of respiratory diseases, allergies, lung cancer, cardiovascular and other diseases[1] (Raaschou-Nielsen et al. 2013; Chen et al. 2016). This includes the health effects due to elevated concentrations of PM-related metals (Tiotiu et al. 2020; Lee et al. 2021).

The urban atmosphere constantly contains a mixture of particles of different chemical composition, morphology, and size. The origin of these particles is diverse: erosion, weathering, and abrasion of surfaces (roads, pavements, lawns, etc.) (Piscitello et al. 2021; Pellecchia et al. 2023), vehicle emissions (Jeong et al. 2019; Piscitello et al. 2021; Pellecchia et al. 2023), industries and power plants (Moskovchenko et al. 2021; Zhou et al. 2024), construction works (Guo et al. 2020; Yang et al. 2020), dust storms (Opp et al. 2021; Tariq et al. 2023; Lak et al. 2024), wildfires (Tariq et al. 2023; Kaskaoutis et al. 2024), incineration plants, and

[1] World health statistics 2020: monitoring health for the SDGs, sustainable development goals. Geneva: World Health Organization; 2020.

landfills. Atmospheric pollution due to motor vehicles can be exhaust (fuel combustion) and non-exhaust (abrasion of rubbing elements, for example, brake pads, discs, tyres, road surface, etc.) (Carlsson et al. 1995; Pellecchia et al. 2023; Vijayan et al. 2024). Emissions from manufacturing plants and motor vehicles are the major sources of PM in urban air[2].

During the cold season, the amount of fuel burned for heat production increases, leading to a greater influx of anthropogenic emissions into the atmosphere (Tigeev et al. 2021; Moskovchenko et al. 2022). The snow cover that forms during this period captures various potentially toxic elements (PTEs) from the air and accumulates them layer by layer throughout the season.

PTEs in snow can be present in dissolved and suspended forms, corresponding to the liquid and solid phases respectively. The liquid form can participate in the biochemical cycle, while the solid form accumulates in the environment, becoming part of soils, road dust, and surface sediment (Seleznev et al. 2019; Vlasov et al. 2020). Pollutants migrate from snow into the surrounding environment during melting. This happens, for example, when de-icing agents are used on roads and pavements. The process intensifies significantly over a short period (1-2 weeks) at the end of the cold season.

In northern regions, analysing the composition of snow cover is an effective method for assessing air pollution (Engelhard et al. 2007; Xue et al. 2020; Szwed et al. 2022; Moskovchenko et al. 2021, 2022, 2023). The main objectives of environmental studies of snow cover are as follows: (1) obtaining information on the amount of pollutants in the atmosphere (Kondratev et al. 2017; Szwed et al. 2022; Moskovchenko et al. 2023; Popovicheva et al. 2024) and their deposition (Alves et al. 2019; Kosheleva et al. 2024; Talovskaya et al. 2025); (2) tracing the sources of air pollution, using snow along roads as a marker of vehicle pollution (Kuoppamäki et al. 2014; Moskovchenko et al. 2021, 2022; Vijayan et al. 2024); (3) obtaining information on the physical and chemical properties of snow cover, including soluble and solid forms (Kuoppamäki et al. 2014; Vlasov et al. 2020); (4) understanding the long-range transboundary transport of pollutants (Opp et al. 2021; Tariq et al. 2023); (5) studying the transport of pollutants from nonpoint sources with meltwater runoff in urban areas (Indraratne et al. 2023).

In large or industrial cities in Russia, state air monitoring is often conducted at stationary observation posts. The range of monitored substances in these programmes is limited to common gases (nitrogen dioxide, sulfur dioxide, carbon monoxide, etc.), various hydrocarbons, suspended particles, and heavy metals (Pb, Cd, Cu, Zn, Ni, Cr, Mg, Fe, Mn). The majority of pollutants deposited from the atmosphere are in the solid phase – suspended solids (Vlasov et al. 2020; Tigeev et al. 2021), which are not analysed in this type of monitoring.

The study region for this research is the Sverdlovsk region, a major industrial area of Russia. The region has a well-developed extractive industry, full-cycle ferrous and non-ferrous metallurgy, and mechanical engineering. Most large industrial enterprises in the region are city-forming and are located in small and medium-sized cities known as 'monotowns.' Environmental monitoring in small and medium-sized cities is less frequently represented in scientific literature, and the state monitoring approach does not cover the full range of potential pollutants or include all industrial cities. This may be due to both reduced public attention to cities of this size and the significant costs of environmental control. At the same time, industrial enterprises conduct their own emissions monitoring at emission points, along the perimeter of their territory, and within the sanitary protection zone in accordance with the law and approved internal environmental projects. However, the data from such monitoring are not publicly available and are intended for reporting to government authorities.

The aim of this study is to propose and test a method for assessing urban air pollution by analysing the composition of undisturbed snow cover in residential areas. The proposed method is rapid and low-cost. It includes an optimal set of qualitative and quantitative indicators needed for an adequate assessment of contemporary pollutant deposition in the urban environment from the atmosphere.

The study objects are two phases of snow: the liquid phase with particles <2 μm (filtrate) and the solid phase with particles >2 μm. The total element concentration in both phases was recalculated to reflect the deposition intensity of PTEs and the indices being calculated.

This study examines four small and medium-sized cities in the Sverdlovsk region: the industrial monotowns of Kachkanar, Serov, and Verkhnyaya Pyshma, and the non-industrial city of Alapaevsk, which was used as a background site. The proposed method appears to be applicable to all types of cities that have a stable snow cover during the cold season.

## MATERIALS AND METHODS

### Description of surveyed cities

Four small cities in the Sverdlovsk region, Russia: Kachkanar, Serov, Alapaevsk, and Verkhnyaya Pyshma, with different industrial specialisations, were studied. Table 1 provides a description of the surveyed cities.

In all cities studied, the cold (winter) period of the year lasts five to six months, from mid-October to mid-April. During this period, the average daily air temperature is continuously below 0°C, and precipitation falls as snow. Around mid-April, intensive snowmelt begins, and in one to two weeks, almost the entire snow cover melts. In Serov, the cold period can be longer.

### Snow sampling program

All surveyed cities show a block structure of development. Two main types of development observed are multi-storey buildings (MSB) and detached house development (DHD), each with an adjacent property and a facade area that forms part of the street network. Snow samples were collected exclusively in the residential areas of the cities. A total of 40 snow samples were gathered, with 10 samples from each city. Five sampling sites were chosen in MSB neighbourhoods and five sites in DHD. All sites are spaced apart and represent different city areas with varying stages of development. The sampling grid was irregular and followed the Guidance Document 52.04.186-89[3], with a sampling site density of 1-2 samples per km$^2$. The number of sampling points in this study is comparable to those investigated in other research (e.g., Engelhard et al. 2007; Vlasov et al. 2020; Moskovchenko et al. 2021; Vijayan et al. 2024). Although the sampling grid is irregular, it covers the entire residential area of the city. Other researchers also employ irregular grids to assess the condition of snow cover within urban environments.

[2] Particulate Matter (PM) Basics https://www.epa.gov/pm-pollution/particulate-matter-pm-basics

[3] Guidance Document 52.04.186-89. Air Pollution Control Guideline. https://docs.cntd.ru/document/1200036406.

**Table 1. Brief description of the cities studied**

| City | N E coordinates | Residential area*, km$^2$ | Location | Climate | Industries |
|---|---|---|---|---|---|
| Kachkanar | 58°42′N 59°29′E | 6.3 | Southwest of the Kachkanar Mountain, on the Eastern Side of the Middle Urals in the watershed of the Isa and Vyja Rivers (tributaries of the Tura River). The relief is represented by mountain with large differences in altitude. | Continental climate, the average temperature in January is -15.3 °C, in July is +17.3 °C. The average annual precipitation is 467 mm. | Production of iron ore. One of the largest modern iron ore enterprises in Russia and the only one in the world that produces Fe-V concentrate, sinter and pellets for blast furnace smelting. Ore is mined by drilling and blasting. |
| Serov | 59°36′N 60°34′E | 17.9 | On the border between the Middle and Northern Urals, on the eastern slope of the Ural Mountains in the Western Part of the West Siberian Plain. The Kakva River flows through the city. The relief is mainly represented by flat with large hills in the north of the city. | Continental climate, the average temperature in January is -16.2 °C, in July is +18.0 °C. The average annual precipitation is 493 mm. | The main industry is the ferrous metallurgy and other metallurgy-related industries. |
| Alapaevsk | 57°51′N 61°42′E | 13.6 | Eastern Side of the Middle Urals at the intersection the Trans-Ural Plain and the West Siberian Lowland. The Neiva River flows through the city. The relief is mainly represented by large hills | Continental climate, the average temperature in January is -15.6 °C, in July – +18.7 °C. The average annual precipitation is 496 mm. | In the early 18th century At the end of the 20th century, due to depreciation and reduction of mineral base, the plant significantly reduced production. Since the beginning of the 21th century the metallurgical production has actually ceased. Currently, Alapaevsk has woodworking, food production enterprises. |
| Verkhnyaya Pyshma | 56°58′N 60°35′E | 11.6 | Middle Urals, the Eastern Side of the Ural Mountains, at the headwaters of the Pyshma River. One of the satellite cities of Ekaterinburg megapolis. The relief is hilly. | Continental climate, the average temperature in January is -12.6 °C and in July +18.9 °C. The average annual precipitation is 535 mm. | Since 1854, copper ore has been mining and processing in Verkhnyaya Pyshma. Nowadays the main industry of the city is non-ferrous metallurgy, machine building, and metal processing. |

*Residential area values are taken from Seleznev et al. (2024).

Sampling was carried out at the end of the cold season (March 2024), which is the period of maximum snow accumulation. The location of the studied cities in the Sverdlovsk region, Russia, and the sampling sites is shown in Fig. 1.

The undisturbed snow cover was selected for sampling at the sites. For sites in MSB neighbourhoods, it was usually located on green zones or playgrounds, as these areas are not used during the cold season. For sites in DHD neighbourhoods, sampling points were located on the facade area of the block between the property zone and the street or sidewalk. Snow sampling was conducted away from the vehicular zone, with distances ranging from 2 to 35 metres (average 10 metres).

The undisturbed snow cover sample was collected using a sampling device, following the methodology outlined in Guidance Document 52.04.186-89. The device consists of a plastic tube with a diameter of 10 cm and a piston, which allows for the extraction of the entire snow cover thickness during sampling. The number of undisturbed snow cores collected was determined by the volume of the container, which is 5 litres. The container is sealed and made entirely of polymer materials. Corrosion-resistant equipment was used for sampling. During sampling, the lower part of the core, along with some surface materials (soil, leaves, debris, etc.), was removed from the sample. Contamination of the samples during collection, transportation, and analysis was prevented.

## Sample preparation and analysis

Snow sample preparation was carried out in accordance with Russian Standard 31 861-2012[4]. The collected samples were preserved at –4°C in a laboratory refrigerator. Melting was done at room temperature for 24 hours. After melting, large inclusions, such as pine needles, leaves, and debris, were removed from the samples. The samples were then filtered through ash-free 'blue tape' paper filters with a pore size of 2 μm using a vacuum filtration system based on Büchner funnels and Büchner flasks. As a result, two phases were obtained: the solid phase with particle sizes >2 μm and the filtrate, representing the liquid phase with particle sizes <2 μm. The filtrate was transferred into two containers, one with a volume of 1.5 litres for cation-anion composition determination and another with a volume of 50 ml for metal content determination.

The elements detected in both phases were Al, Ti, V, Cr, Mn, Co, Fe, Ni, Cu, Zn, As, Mo, Cd, Sn, Sb, and Pb. For the liquid phase, the following parameters were measured in the laboratory. Acidity level (pH) (using a Milwaukee PH600

[4] Water. General requirements for sampling (GOST R 31861-2012). https://base.garant.ru/70571468/.

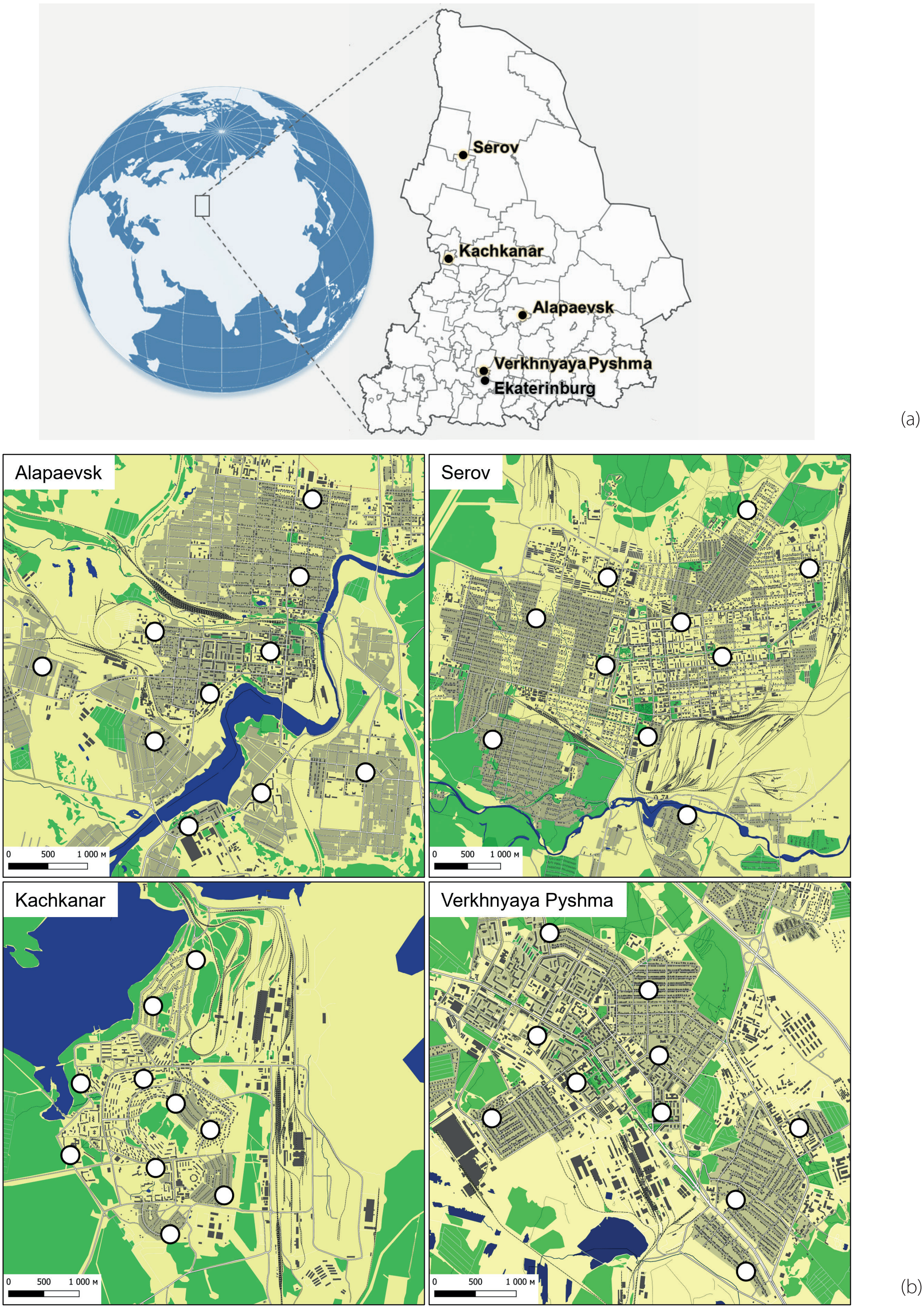


**Fig. 1. Location of (a) Sverdlovsk region, Russia, with the studied cities, and (b) snow sampling sites (white points)**

portable pH-meter) and redox potential (Eh) (using an ORP-200 portable ORP-meter) were determined according to the methods attached to the devices. $Na^{++}$ and $K^{+}$ were determined by flame photometry; $Ca^{2+}$ and $Mg^{2+}$ by complexometric titration; $Cl^{-}$ by titration; $PO_4^{3-}$, $CO_3^{2-}$, and $HCO_3^{-}$ by potentiometric titration; $NO_2^{-}$, $NO_3^{-}$, $NH_4^{+}$, $SO_4^{2-}$, and $SiO_2$ by photometry. The content of PTEs in the liquid phase was determined by inductively coupled plasma mass spectrometry (ICP-MS) using an ELAN 9000 mass spectrometer (Perkin Elmer, USA) according to the certified technique NSAM 480-X. The detection limits for the liquid phase were as follows: Al, Ti, V, Cr, Ni, Cu, Zn, As – <2 µg/L, Mn, Mo, Sn, Pb – <0.2 µg/L, Co, Cd, Sb – <0.1 µg/L.

Filters with suspended solids were dried at room temperature. The elemental analysis of the suspended solids was performed using ICP-MS technique according to the 'Method for measuring elemental content in solid objects' by ICP-MS, PND F 16.1:2.3:3.11-98[5] on an ELAN 9000 mass spectrometer from Perkin Elmer (USA). Solids were prepared for element concentration determination using extraction with three acids ($HNO_3$, $HClO_4$, and HF). The detection limits for suspended solids were as follows: Al, Ti, Fe, Zn – <5 µg/L; V, Cr, Mn, Co, Ni, Cu, As, Mo, Sn, Sb, Pb – <0.1 µg/L; Cd – <0.05 µg/L.

Statistical data processing was performed using STATISTICA 12 and Microsoft Excel. Median Absolute Deviation (MAD) (Reimann et al. 2005) was used as a measure of variability in PTEs deposition intensity. It was calculated using the following formula:

$$MAD = Median\left(\left|x_i - \tilde{x}\right|\right) \quad (1)$$

where $x_i$ is each value of intensity, $\tilde{x}$, is average value of intensity.

### Assessment of pollution in snow cover

To assess the average atmospheric pollution level over the observation period, the accumulation intensity of pollutants in the snow cover was calculated (mg/m² per day). The calculation of accumulation intensity considered the concentration of i PTEs (in the range from 1 to n) in solid phases (>2 µm and filtrate) of the j sample (in the range from 1 to k), the volume of melted water (L), the number of collected cores (pcs.), the sampler area (m²), and the snow cover duration (150 days). The PTEs accumulation intensity in the snow cover is calculated using the following formula:

$$AI_{PTE\ i,j} = \frac{C^{SP}_{Me\ i,j} \times V_{sample\ j}}{N_{cores\ j} \times S_{sampler} \times N_{days}} + \frac{C^{F}_{Me\ i,j} \times V_{sample\ j}}{N_{cores\ j} \times S_{sampler} \times N_{days}} \quad (2)$$

where $AI_{PTEs\ i,j}$ is the $i$ PTE accumulation intensity in the snow cover, mg/m² per day; $C^{SP}_{Me\ i,j}$ and $C^{F}_{Me\ i,j}$ is the concentration of PTEs in solid phase (>2 µm) and filtrate (<2 µm), respectively, mg/L; $V_{sample\ j}$ is the volume of melted water, L; $N_{cores\ j}$ is the number collected cores, pcs.; $N_{days}$ is the snow cover duration (150 days); $S_{sampler}$ is the sampler area, m².

To evaluate pollution levels using the following indices: *Geoaccumulation Index ($I_{geo}$), Single Pollution Index (PI), Enrichment Factor (EF), Sum of Contamination ($PI_{sum}$), and Nemerow Pollution Index ($PI_{Nemerow}$)* – the total concentrations of PTEs in solid phases (>2 µm and filtrate) of the snow sample were used.

The $I_{geo}$ was originally defined by Müller in 1969 to determine metal contamination in sediments by comparing current concentrations with pre-industrial levels (Müller 1986). It can be calculated using the equation:

$$I_{geo} = \log_2\left[C_{i,j} / \left(1.5 \times C_{bg}\right)\right] \quad (3)$$

where $C_{i,j}$ is the measured concentration of the $i$ PTE under study, and $C_{bg}$ is the geochemical background or reference concentration of the element. The factor 1.5 is used to account for possible variations in the background levels of the metal in the environment, as well as minimal anthropogenic influences. Müller (1986) classified $I_{geo}$ into seven classes (Table 2).

The Pollution Index (*PI*) for the single sample j (from a sample set of k=10) was calculated as the ratio of the *i* PTE concentration to the geochemical background for the city (Qingjie et al. 2008):

$$PI_i = \frac{C_i}{C_{bg}} \quad (4)$$

where $C_i$ is the concentration of the *i* PTE in *j* sample, $C_{bg}$ is geochemical background concentration of the *i* PTE.

**Table 2. Interpretation of $I_{geo}$ and *EF* values for pollution level assessmen**

| $I_{geo}$ | | *EF* | |
|---|---|---|---|
| $I_{geo}$ values | Class | *EF* values | Class |
| $I_{geo} \leq 0$ | unpolluted | $EF < 2$ | Deficiency to minimal enrichment |
| $0 < I_{geo} \leq 1$ | from unpolluted to moderately polluted | $2 < EF < 5$ | Moderate enrichment |
| $1 < I_{geo} \leq 2$ | moderately polluted | $5 < EF < 20$ | Significant enrichment |
| $2 < I_{geo} \leq 3$ | from moderately to strongly polluted | $20 < EF < 40$ | Very high enrichment |
| $3 < I_{geo} \leq 4$ | strongly polluted | $EF > 40$ | Extremaly high enrichment |
| $4 < I_{geo} \leq 5$ | from strongly to extremely polluted | | |
| $I_{geo} > 5$ | extremely polluted | | |

[5] Quantitative chemical analysis of soils. Methodology for measurement of metal content in solid objects by inductively coupled plasma spectrometry method PND F 16.1:2.3:3.11-98. https://base.garant.ru/70972096.

The *EF* is a method for quantifying the enrichment of PTEs in a sample relative to a geochemical background. An *EF* is calculated in j sample as follows:

$$EF_i = \frac{\left[C_i / C_{ref\,j}\right]_{sample}}{\left[C_i / C_{ref}\right]_{background}} \quad (5)$$

where $C_i$ is the concentration of the *i* PTE, $C_{ref}\,j$ is the concentration of a reference element in j sample for the purpose of normalisation. Iron (Fe) was used as the reference element.

The $PI_{sum}$ represents the sum of all determined PTEs concentrations expressed as *PI* (Qingjie et al. 2008). The $PI_{sum}$ is calculated using the following formula:

$$PI_{sum} = \sum_{j=1}^{k} \sum_{i=1}^{n} PI_{i,j} \quad (6)$$

where *PI* is the calculated value for *PI*, *n* is the total number of PTEs analysed in this study, and *k* is the number of samples.

Since $PI_{sum}$ is the sum of individual pollution indices (*PI*), the classification of $PI_{sum}$ depends on the number of elements used. To normalise $PI_{sum}$ by the number of elements, the average pollution index ($PI_{avg}$) can be calculated (Qingjie et al. 2008):

$$PI_{avg} = \frac{PI_{sum}}{n} \quad (7)$$

where *n* is the number of total PTEs analysed in this study.

The interpretation of $PI_{avg}$ values is as follows: $PI_{avg} \le 1$ is not polluted (background level), $1 < PI_{avg} < 2$ is slightly polluted, $2 < PI_{avg} < 3$ is moderately polluted, $3 < PI_{avg} < 5$ is seriously polluted, $PI_{avg} > 5$ is very seriously polluted.

The $PI_{Nemerow}$ allows for the assessment of the overall PTE pollution level (Qingjie et al. 2008). The $PI_{Nemerow}$ is calculated using the following formula:

$$PI_{Nemerow} = \sqrt{\frac{\left(PI_{avg}\right)^2 + PI_{i\,max}^2}{2}} \quad (8)$$

where $PI_{i\,max}$ is the maximum *PI* value among the studied PTEs in the sample.

The interpretation of $PI_{Nemerow}$ values is as follows: $PI_{Nemerow} < 0.7$ is safety domain, $0.7 < PI_{Nemerow} < 1.0$ is precaution domain, $1.0 < PI_{Nemerow} < 2.0$ is slightly polluted domain, $2.0 < PI_{Nemerow} < 3.0$ is moderately polluted domain, $PI_{Nemerow} > 3$ is seriously polluted domain (Qingjie et al. 2008).

To evaluate dust load in cities, the total solid content in the collected snow was calculated, taking into account the size of the sampler and the number of collected cores. The formula for calculating dust load over the observation period is as follows:

$$Dust\ Load = \frac{m_{s.s.}}{N_{cores} \times S_{sampler}} \quad (9)$$

where $m_{s.s.}$ is the mass of suspended solids in the snow sample, g; $N_{cores}$ is the number of collected cores, pcs.; $S_{sampler}$ is the sampler area, $m^2$. The daily dust deposition from the atmosphere was estimated for a cold season duration of 150 days.

As a reference concentration (urban geochemical background) for pollution assessment, PTEs concentrations in the snow cover of residential areas in Alapaevsk were used. This choice was made because Alapaevsk has no industrial facilities that could serve as sources of emissions for the studied pollutants. The influence of other air pollution factors typical for urban environments, such as vehicle emissions, dusting of materials, and surface wear, is similar across the studied cities. This fact allows for the assessment of pollution specifically caused by PTEs originating from metallurgical enterprises, extractive industries, and other industrial facilities.

### Identification of pollutant sources

To determine element associations in the snow samples, hierarchical clustering was performed. The measure of connectivity used was the correlation distance (linkage distance) 1 – *r*, where *r* is the Pearson correlation coefficient. This distance reflects the degree of element connectivity, enabling grouping by source of origin. Cluster analysis identifies element associations characteristic for each city. These associations can be natural, reflecting geological processes, or anthropogenic, when elements have a common anthropogenic origin, such as industrial emissions. The Single linkage algorithm was used for clustering, which defines the distance between two clusters as the minimum distance between any two points from different clusters. A disadvantage of this method is that a cluster may include elements that are only weakly connected, or it may form a chain of points, some of which have no significant relationship with each other. However, this method makes it possible to account for even weak associations between elements and is sensitive to extreme values, which is important for identifying geochemical anomalies. Its sensitivity to detecting local connections between points can also be useful in cases of diffuse pollutant input. In urban environments, where pollution is often spatially heterogeneous, this method can reveal important information that other methods may smooth out.

To analyse the distribution of major cations and anions in the snow samples, and their correlation with each other and the mass of suspended solids, statistical processing of their concentrations in meltwater was performed. These parameters offer a better understanding of the geochemical processes occurring in the urban environment.

## RESULT

### Physical and chemical properties of snow

The content of major cations and anions in the snow from the cities is shown in Table 3. The $SiO_2$, $PO_4^{3-}$, and $CO_3^{2-}$ contents are mostly below the detection limit in all cities. $Ca^{2+}$ is the dominant cation in all analysed samples, with concentrations ranging from 61 to 290 μeq/L. This follows the trend: Alapaevsk < Verkhnyaya Pyshma < Kachkanar < Serov. The anionic composition is more variable. $Cl^-$ predominates in Alapaevsk, Verkhnyaya Pyshma, and Serov, with concentrations of 161-369 μeq/L. Bicarbonates ($HCO_3^-$) are dominant in Kachkanar (214 μeq/L). Total mineralisation (the sum of cations and anions) ranges from 439 μeq/L in Alapaevsk to 980 μeq/L in Verkhnyaya Pyshma and Serov, corresponding to slightly to moderately mineralised waters.

Table 4 presents the correlation matrix (Spearman correlation coefficient) of the cation and anion composition, and the mass of suspended solids in snow in the cities.

Table 5 presents the average, maximum, and minimum values of pH and Eh for the snow samples from different cities. On average, pH does not differ significantly between cities (around 7.5), except in Serov, where this value reaches 8.4. The value of Eh varies considerably both within each city and between cities. The

**Table 3. Content of major cations and anions in melted snow in the cities**

| City | Sum of cations, μeq/L | Sum of anions, μeq/L | Cations, μeq/L | | | | Anions, μeq/L | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $Na^{++}+K^{+}$ | $Mg^{2+}$ | $Ca^{2+}$ | $NH_{4+}$ | $Cl^{-}$ | $HCO_{3-}$ | $SO_4^{2-}$ | $NO_{3-}$ | $NO_{2-}$ |
| Alapaevsk | 132 | 307 | 23 | 17 | 61 | 31 | 161 | 113 | 10 | 22 | 0.7 |
| V. Pyshma | 335 | 647 | 101 | 43 | 111 | 80 | 369 | 171 | 60 | 38 | 9.3 |
| Kachkanar | 345 | 419 | 33 | 52 | 239 | 21 | 141 | 214 | 31 | 32 | 0.7 |
| Serov | 392 | 587 | 33 | 44 | 290 | 25 | 262 | 256 | 39 | 29 | 1.5 |

**Table 4. The correlation matrix of cation and anion composition (mg/L), and the mass of suspended solids (Ms.s., g) in snow in the cities**

| | Na | $M_{s.s.}$ | K | Ca | Mg | $NO_3$ | $NO_2$ | $NH_4$ | Cl | $SO_4$ | $HCO_3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Na | 1.00 | 0.27 | **0.51** | 0.39 | 0.33 | **0.68** | 0.26 | 0.36 | **0.71** | 0.41 | 0.27 |
| $M_{s.s.}$ | | 1.00 | 0.30 | **0.71** | **0.78** | 0.36 | 0.19 | -0.34 | -0.19 | **0.55** | **0.62** |
| K | | | 1.00 | 0.28 | 0.26 | 0.34 | 0.16 | 0.46 | 0.30 | 0.42 | 0.48 |
| Ca | | | | 1.00 | **0.84** | 0.49 | 0.28 | -0.35 | 0.20 | **0.73** | **0.71** |
| Mg | | | | | 1.00 | 0.47 | 0.16 | -0.33 | -0.01 | **0.69** | **0.72** |
| $NO_3$ | | | | | | 1.00 | 0.25 | 0.18 | **0.57** | **0.52** | 0.31 |
| $NO_2$ | | | | | | | 1.00 | 0.27 | 0.16 | 0.27 | 0.42 |
| $NH_4$ | | | | | | | | 1.00 | 0.43 | 0.01 | -0.04 |
| Cl | | | | | | | | | 1.00 | 0.38 | 0.10 |
| $SO_4$ | | | | | | | | | | 1.00 | **0.80** |
| $HCO_3$ | | | | | | | | | | | 1.00 |

* The correlation is statistically significant at $p < 0.05$.

highest Eh value is observed in Kachkanar (181.5 mV), while the lowest is in Serov (105.6 mV). Alapaevsk and Verkhnyaya Pyshma have very similar pH and Eh values. The greatest variability in Eh is observed in Kachkanar, where the difference between the minimum and maximum values is 2.7 times, whereas this difference does not exceed 1.5 to 2 times in the other cities.

Table 5 presents the average, maximum, and minimum values of suspended solids concentration in the snow across the cities. The highest concentration of suspended solids is observed in Kachkanar (0.54 g/L), while the lowest is in Alapaevsk (0.09 g/L). Even the lowest concentration of suspended solids in Kachkanar (0.25 g/L) is higher than the maximum in Alapaevsk and Verkhnyaya Pyshma (up to 0.23 g/L) and is close to the value in Serov (0.35 g/L).

### The intensity of PTEs accumulation in the snow cover

Table 6 presents the accumulation intensity of PTEs in snow cover across the cities. Median values of PTEs concentrations (see Eq. 2) with MAD (see Eq. 1) are shown.

### Assessment of snow pollution level

Table 7 presents the median values of $I_{geo}$, *EF*, and *PI*. In Kachkanar, significant pollution for V and Fe is observed based on $I_{geo}$ and *PI*. However, the *EF* value for V is on the threshold of natural enrichment. In Serov, significant pollution of Cr is observed across all indices. In Verkhnyaya Pyshma, significant pollution of Cu and As is observed across all indices.

The following values of $PI_{sum}$, $PI_{avg}$ and mean $PI_{Nemerow}$ were calculated, respectively:

– Kachkanar – 154, 9.8, and 12;
– Serov – 66, 4.1, and 5.1;
– V. Pyshma – 66, 4.2, and 7.2.

Table 8 presents the dust load across the cities. During the cold period, snow cover in the cities accumulates 4.0-24 g/m$^2$ of suspended solids, which corresponds to a daily dust deposition of 27-163 mg/m$^2$.

### Element associations

Element associations with cities (where $r < 0.5$) are shown in Figure 3.

**Table 5. Average pH and Eh values and concentrations of suspended solids in snow samples**

| City | pH (mean / min-max) | Eh (mean / min-max), mV | Suspended solids concentration (mean / st. dev. / min-max), g/L |
|---|---|---|---|
| Alapaevsk | 7.4 / 6.8-7.9 | 137.9 / 103-157 | 0.03 / 0.02 / 0.01-0.06 |
| V. Pyshma | 7.4 / 6.5-7.9 | 141.0 / 102-179 | 0.05 / 0.02 / 0.02-0.06 |
| Kachkanar | 7.7 / 7.3-8.0 | 181.5 / 100-273 | 0.18 / 0.06 / 0.10-0.26 |
| Serov | 8.4 / 7.7-8.8 | 105.6 / 70-157 | 0.07 / 0.05-0.13 |

**Table 6. The PTEs accumulation intensity in the snow cover across the cities (median ± MAD, mg/m² per day)**

| Element | Kachkanar | | Serov | | Alapaevsk | | V. Pyshma | |
|---|---|---|---|---|---|---|---|---|
| | median | MAD | median | MAD | median | MAD | median | MAD |
| Al | 0.0001 | ± 0.00003 | 0.0008 | ± 0.0003 | 0.0001 | ± 0.00002 | 0.0007 | ± 0.0003 |
| As | 0.0030 | ± 0.0005 | 0.0027 | ± 0.0013 | 0.0004 | ± 0.0001 | 0.0031 | ± 0.0008 |
| Cd | 0.0001 | ± 0.0001 | 0.0002 | ± 0.0001 | 0.0001 | ± 0.00005 | 0.0001 | ± 0.00002 |
| Cr | 0.0295 | ± 0.0078 | 0.1601 | ± 0.0611 | 0.0065 | ± 0.0028 | 0.0078 | ± 0.001 |
| Cu | 0.0101 | ± 0.0029 | 0.0302 | ± 0.0169 | 0.0044 | ± 0.0016 | 0.1820 | ± 0.1088 |
| Fe | 75.73 | ± 23.19 | 15.15 | ± 8.12 | 1.66 | ± 0.37 | 2.45 | ± 0.94 |
| Mn | 0.1785 | ± 0.1784 | 0.0980 | ± 0.0972 | 0.0234 | ± 0.0233 | 0.0277 | ± 0.0271 |
| Mo | 0.0001 | ± 0.00005 | 0.0012 | ± 0.0004 | 0.0002 | ± 0.0001 | 0.0008 | ± 0.0002 |
| Ni | 0.0182 | ± 0.0050 | 0.0092 | ± 0.0038 | 0.005 | ± 0.0026 | 0.0065 | ± 0.0012 |
| Pb | 0.0084 | ± 0.0024 | 0.0053 | ± 0.0016 | 0.0026 | ± 0.0005 | 0.0084 | ± 0.0015 |
| Sb | 0.0003 | ± 0.0001 | 0.0002 | ± 0.00005 | 0.0002 | ± 0.00004 | 0.0008 | ± 0.0003 |
| Sn | 0.0003 | ± 0.0001 | 0.0003 | ± 0.0001 | 0.0001 | ± 0.00002 | 0.0004 | ± 0.0001 |
| Ti | 0.9885 | ± 0.9884 | 0.0556 | ± 0.0548 | 0.031 | ± 0.0309 | 0.0655 | ± 0.0649 |
| V | 0.1762 | ± 0.0315 | 0.0068 | ± 0.0012 | 0.0026 | ± 0.0007 | 0.0042 | ± 0.0014 |
| Zn | 0.0289 | ± 0.0108 | 0.0395 | ± 0.0116 | 0.0138 | ± 0.0039 | 0.0262 | ± 0.0079 |

**Table 7. Median values of $I_{geo}$, *EF*, and *PI* in snow samples**

| City | Al | Ti | V | Cr | Mn | Co | Fe | Ni | Cu | Zn | As | Mo | Cd | Sn | Sb | Pb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $I_{geo}$ | | | | | | | | | | | | | | | | |
| Kachkanar | 1.3 | 3.9 | 4.9 | 1.2 | 1.9 | 3.9 | 4.5 | 0.7 | -0.1 | -0.1 | 1.7 | -2.0 | 0.2 | -0.4 | -0.5 | 0.2 |
| Serov | 0.2 | -0.2 | 0.5 | 3.7 | 1.2 | 1.5 | 2.2 | -0.1 | 1.7 | 0.6 | 2.0 | 1.7 | 0.9 | 0.0 | -0.9 | 0.0 |
| V. Pyshma | 0.4 | 0.2 | -0.1 | -0.4 | -0.6 | 0.3 | -0.4 | -0.6 | 4.2 | 0.3 | 2.5 | 1.5 | 0.5 | 0.8 | 1.5 | 0.9 |
| *EF* | | | | | | | | | | | | | | | | |
| Kachkanar | 0.1 | 0.6 | 1.5 | 0.1 | 0.1 | 0.7 | 1 | 0.1 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 |
| Serov | 0.2 | 0.2 | 0.3 | 3.9 | 0.5 | 0.5 | 1 | 0.2 | 0.6 | 0.3 | 0.7 | 0.7 | 0.3 | 0.2 | 0.1 | 0.2 |
| V. Pyshma | 1.6 | 1.4 | 0.9 | 0.9 | 0.7 | 1.2 | 1 | 0.7 | 29.0 | 1.6 | 7.9 | 3.2 | 1.2 | 2.2 | 3.4 | 2.5 |
| *PI* | | | | | | | | | | | | | | | | |
| Kachkanar | 3.6 | 23 | 47 | 3.5 | 5.6 | 23 | 34 | 2.5 | 1.4 | 1.4 | 5.0 | 0.4 | 1.7 | 1.1 | 1.1 | 1.8 |
| Serov | 1.7 | 1.4 | 2.1 | 20 | 3.4 | 4.4 | 7.1 | 1.4 | 4.9 | 2.3 | 5.9 | 5.0 | 2.7 | 1.5 | 0.8 | 1.5 |
| V. Pyshma | 1.9 | 1.7 | 1.4 | 1.1 | 1.0 | 1.9 | 1.1 | 1.0 | 29 | 1.8 | 8.4 | 4.3 | 2.2 | 2.7 | 4.2 | 2.7 |

**Table 8. Dust load in the cities**

| City | Average mass of suspended solids in snow, g/m² per season | Average daily supply of suspended solids in snow, mg/m² per day |
|---|---|---|
| Alapaevsk | 4.0 | 27 |
| V. Pyshma | 9.4 | 63 |
| Kachkanar | 24 | 163 |
| Serov | 13 | 84 |

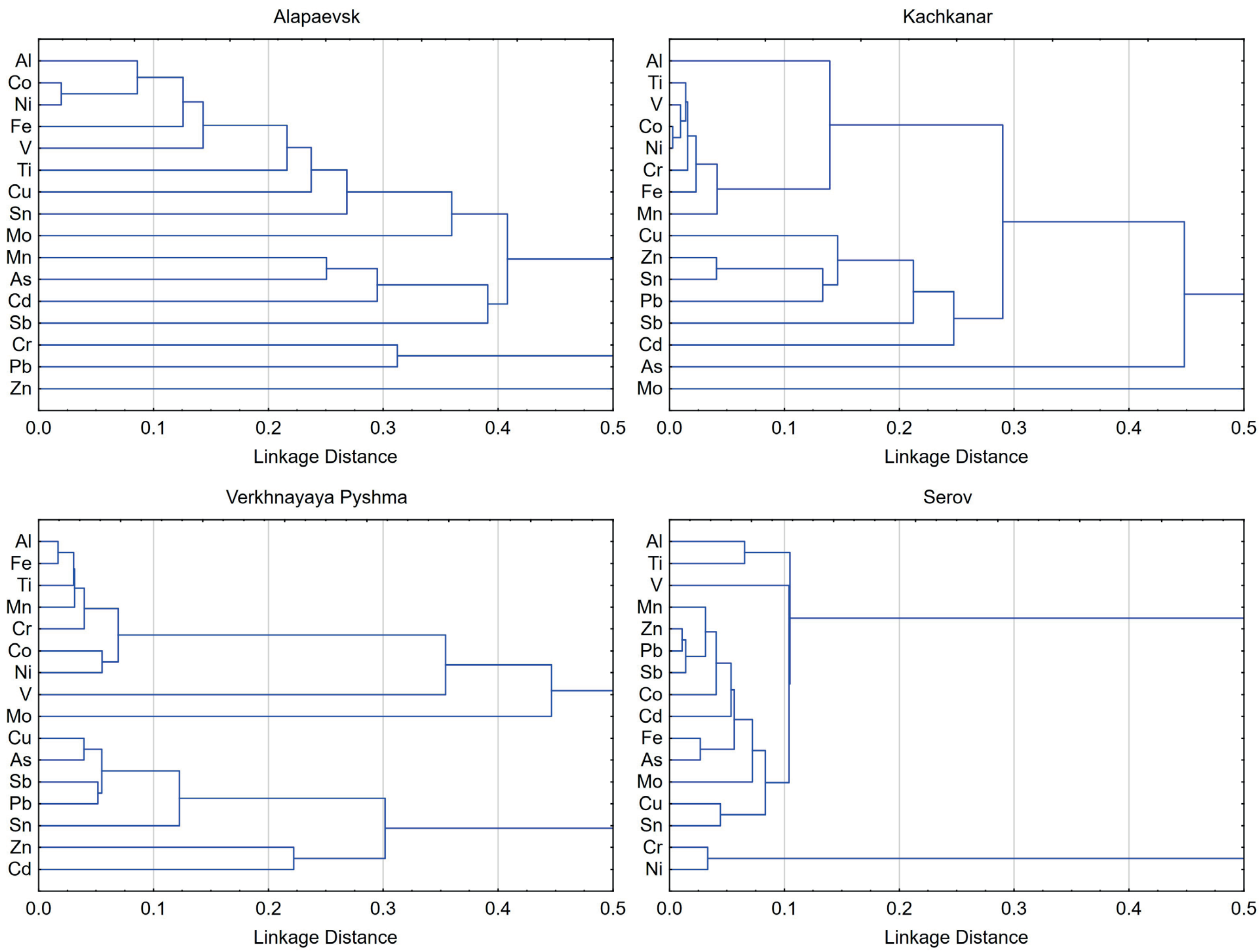


**Fig. 2. The degree of correlation between the sources of input and the migration of anthropogenic elements (Single linkage, 1-*r* , where *r* is Pearson correlation coefficient)**

## Comparison of element concentrations with other studies

Table 9 presents the average concentrations of elements and pH levels in the snow cover of the studied cities, along with concentrations from other studies. The cities being compared have different industrial specialisations, levels of urbanisation, and transport network development. For comparison, only those elements that appear in multiple studies are presented. The total concentration represents the sum of the dissolved and suspended phases. At the same time, the proportion of the dissolved phase (<0.45 µm) is significantly lower than that of the suspended phase in the total concentration (e.g. Grebenshchikova et al. 2016; Vlasov et al. 2020; Moskovchenko et al. 2021). This allows us to compare those results with the findings of the present study.

## DISCUSSION

The study was conducted in small and medium-sized cities with varying industrial specialisations. These cities experience a cold period lasting approximately six months. The cities in the Ural region specialise in the extraction and processing of mineral resources, as well as in manufacturing. Enterprises in these cities produce substantial volumes of metals for the global market (UGMK, Evraz, Kachkanar Mining and Processing Plant). The products from these enterprises are exported to numerous countries worldwide.

The cities studied are of the mono-industry type, where a large proportion of the population is employed by a single company. In small Russian cities, approximately half of the residential area is occupied by detached houses with adjacent private gardens. Here, agricultural activities are common, such as growing berries, fruits, and vegetables, and raising animals for personal consumption (Seleznev et al. 2024). At the same time, residential areas are located very close to industrial sites. For example, in Kachkanar, some residential districts are within the sanitary protection zone of the Kachkanar Mining and Processing Plant quarry (Seleznev et al. 2024). This means that in small cities, the route for pollutants to enter the human body is shorter. About 25% of the population in Russia lives in small cities. Along with other factors, poor healthcare and a lack of social activities affect the population in these cities. Air pollution is a significant environmental issue in small industrial cities.

The study included a set of indicators that maximally accounts for potential pollutants from various industries, as well as natural sources of pollution typical for the region. The set of pollutants is aligned with the set of indicators used in similar studies (Moskovchenko et al. 2023; Vlasov et al. 2020; etc.).

The presence of $Ca^{2+}$, $Cl^-$, $HCO_3^-$, and $SO_4^{2-}$ in snow cover in Kachkanar and Serov can be linked to the metallurgical industry, as these compounds are used as reagents in metallurgical processes. Bicarbonates and sulphates may have a common source, namely emissions from metallurgical and raw material processing industries into the atmosphere. In all studied cities, a deviation from the natural anionic ratio $HCO_3^- > SO_4^{2-} > Cl^-$ was observed. This shift is likely attributable to the application of de-icing

**Table 9. Literature data on the mean concentrations of elements in snow cover (total concentration of elements), μg/L**

| Location | References | pH | Ni | V | Cr | Cu | Pb | Mn | Al | Fe | As | Ti | Cd | Zn | Co |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kachkanar | current study | 7.7 | 21.3 | 224.6 | 32.7 | 10.2 | 8.2 | 186.9 | 2566 | 36491 | 3.0 | 1197.3 | 0.1 | 31.4 | 16.7 |
| Serov | | 8.4 | 14.2 | 8.8 | 422.1 | 45.3 | 8.3 | 141.8 | 1320 | 8545 | 3.5 | 71.1 | 0.2 | 58.6 | 3.0 |
| Alapaevsk | | 7.4 | 9.9 | 4.2 | 14.4 | 16.0 | 4.4 | 45.2 | 792 | 968 | 0.8 | 51.0 | 0.1 | 21.3 | 0.7 |
| V. Pyshma | | 7.4 | 8.4 | 6.3 | 10.9 | 365.4 | 14.3 | 38.9 | 1843 | 1387 | 5.9 | 101.1 | 0.2 | 48.2 | 1.2 |
| Sapporo, Japan | Sakai et al. 1988 | 8.5 | - | - | 9.3 | 37.6 | 34.1 | 513 | - | - | - | - | 0.36 | 53 | - |
| Muroran, Japan | | 6.2 | - | - | 7.8 | 7.2 | 23.9 | 205 | - | - | - | - | 0.22 | 55 | - |
| Asahikawa, Japan | | 5.8 | - | - | 4.0 | 7.2 | 9.0 | 52 | - | - | - | - | 0.08 | 24 | - |
| Lahti, Finland low / high intensity traffic road | Kuoppamäki et al. 2014 | 5.7 / 7.0 | ND / 2.4 | - | 0.26 / 4.3 | 1.3 / 12 | ND / 1.4 | 1.1 / 45 | 210 / 2000 | - | - | - | ND / 0.13 | ND / 3 7 | 0.14 / 2.0 |
| Innsbruck, Austria residential area | Engelhard et al. 2007 | - | - | - | - | 0.02 | 16 | - | - | - | - | - | 3.0 | 0.13 | - |
| Katowice, Poland near the parking lot | Adamiec et al. 2013 | - | 4.2 | 18.0 | 17.0 | 6.3 | 0.86 | 6.4 | - | 392.0 | 4.3 | 5.9 | 4.2 | 25.7 | - |
| Tyumen, Russia | Moskovchenko et al. 2021 | 4.7-6.3 | 31.5 | 2.3 | 24.7 | 11.6 | 4.8 | 32.9 | 847 | 1644 | 0.83 | 54.0 | 0.08 | 34.1 | 1.6 |
| Nizhnevartovsk, Russia | Moskovchenko et al. 2022 | 4.3 | 2.7 | 2.0 | 3.1 | 3.2 | 1.7 | 12.8 | - | 627 | 0.13 | - | 0.02 | 14.5 | 0.41 |
| Moscow, Russia yards with parking lots | Vlasov et al. 2020 | 7.5 | 2.8 | 2.9 | 1.6 | 7.9 | 2.2 | 20.4 | 591 | 748 | 0.12 | 48.9 | 0.82 | 24.9 | 0.38 |
| Vanino, Russia | Lukyanov et al. 2022 | - | 14.7 | 3.8 | 3.5 | 12.5 | 1.2 | 112.7 | - | - | 5.7 | - | - | 58.2 | - |
| Vladivostok, Russia | Kondrat'ev et al. 2017 | 4.9 | 0.64 | 0.69 | - | 2.8 | 0.91 | 36.4 | 90.0 | 53.9 | - | - | 0.11 | 32 | - |
| Svirsk, Russia | Grebenshchikova et al. 2017 | 4.5-7.9 | 2.3 | 3.3 | - | 2.3 | 0.48 | - | - | - | 3.7 | - | 0.07 | 18 | 0.41 |

agents in urban areas, which are predominantly composed of chloride-based compounds. In Verkhnyaya Pyshma, this is further supported by the increased concentration of $Na^{++}$. The concentration of $Na^{++}+K^{+}$ exceeds that of $Mg^{2+}$, indicating a disturbance in the natural ionic ratio, likely associated with urban environmental pollution. The notable discrepancy between cation and anion sums, particularly in Alapaevsk and Verkhnyaya Pyshma, suggests the presence of unidentified ions. The analysed solutions may contain solid particles <2 μm. Vlasov et al. (2020) demonstrated that solid particles <2 μm can contain ions of easily soluble salts, which may affect the results of measuring the concentrations of individual cations and anions.

The mineralization of snow in cities is similar to that in ultra-fresh and fresh waters. However, when comparing mineralization levels between cities, the highest average is observed in Verkhnyaya Pyshma (982 μeq/L), and the lowest in Alapaevsk (439 μeq/L). This suggests that emissions from industrial facilities are within the normal operational limits of the enterprises. The suspended solids in snow are primarily composed of calcium and magnesium bicarbonates and sulphates. Sodium is associated with chloride.

The studied cities exhibit variations in the elemental composition of their emissions. These emissions reflect the industrial specialisation of each city. Kachkanar, with its focus on iron ore extraction, shows a higher concentration of Co-Ni-V-Ti-Cr-Fe-Mn (ranked by element concentration in samples, as presented in Figure 2). The Kachkanar deposit is naturally enriched with Fe and V. In Serov, which specialises in metallurgy, metalworking, and the recycling of secondary metallurgical raw materials, most elements are associated with each other. The exception is a distinct Cr-Ni group, likely linked to steel production, while the other elements are of natural origin. In Verkhnyaya Pyshma, traces of non-ferrous metallurgy are clearly discernible, with the elemental association including Cu-As-Sb-Pb.

In these three cities features a characteristic indicator element originating from stationary sources, its presence connected to the technological production processes occurring within the city. However, Alapaevsk, which lacks heavy industries, shows comparatively low concentrations of PTEs in its snow cover. The Co-Ni association in Alapaevsk might be related to vehicle emissions (Vijayan et al. 2024).

The concentration of PTEs in the atmosphere depends on numerous mechanisms and the characteristics of each area, making the assessment of background concentration problematic (Sakai et al. 1988; Reimann et al. 2005). In this study, PTEs concentrations in a city without heavy industry for decades were chosen as the urban geochemical background. This approach allowed for a comparison of pollution from industrial facilities, mining sites, and other sources. Based on the analysis results, Alapaevsk was the least polluted city among those studied according to all indicators.

The calculated pollution indices identified PTEs typical for the industries of the studied cities, confirming their contribution to overall atmospheric pollution. Kachkanar was the most polluted city ($PI_{sum}$ – 154, $PI_{avg}$ – 9.8, $PI_{Nemerow}$ – 12), while Serov and Verkhnyaya Pyshma were also significantly polluted and had similar $PI_{sum}$ and $PI_{avg}$ values (66 and 4.2, respectively) and $PI_{Nemerow}$ values (5.1 and 7.2, respectively). The *EF* in Verkhnyaya Pyshma shows very high Cu enrichment and significant As enrichment. According to $I_{geo}$, the pollution levels of these elements in Verkhnyaya Pyshma range from moderate for As to extreme for Cu. The detected elemental pollution corresponds to the industrial specialisation of the cities and is likely associated with emissions from local enterprises or atmospheric transport of dust from their industrial sites (for example, from the open-pit mine in Kachkanar).

The mass of deposited dust per unit area varies significantly among the studied cities. Industrial enterprises are the main sources of air pollution during the cold season. The highest dust load is observed in Kachkanar. This is due to the city's proximity to open-pit mining operations, open tailings storage facilities, and the operation of a mining and beneficiation plant. During the sampling stage in Kachkanar, atmospheric pollution was visually noticeable in the snow cover as layers of dark particles. The lowest dust load is observed in Alapaevsk, the city with the least industrial activity among those studied. Verkhnyaya Pyshma and Serov show similar levels of dust load. This is because both cities have developed industrial complexes for mineral processing, although they do not have mining operations. In Serov, the dust load is slightly higher. This may be associated with the open slag storage facility at the ferroalloy plant in the northern part of the city.

The obtained dust load values in the studied cities can be compared to similar estimates in other studies. In the study by Vorobievskaya et al. (2022), conducted in Murmansk, Russia, the dust load ranged from 40 to 65 g/m$^2$, which is more than twice the estimate in Kachkanar. In the study by Moskovchenko et al. (2023), conducted in Nadym, Russia, it was shown that in industrial areas, the dust load is 37 mg/m$^2$ per day, while in residential areas, it is 15 mg/m$^2$ per day. The dust load in residential areas of the studied cities is 2-5 times higher than in the industrial areas of Nadym, and in Alapaevsk, it is close to this value.

The proposed methodology has demonstrated its applicability for a comprehensive assessment of current atmospheric pollution input. The selection of the solid phase with particle sizes >2 µm and the filtrate as research objects proved effective for identifying pollution and its sources. In similar studies of snow cover, two snow phases are typically analysed: dissolved (<0.45 µm) and suspended (>0.45 µm). In many of these studies (Vlasov et al. 2020; Moskovchenko et al. 2021; Vijayan et al. 2024, etc.), the particulate phase is found to be the most contaminated. The role of suspended PTEs in urban areas is significantly increased compared to background regions due to high dust loads, emissions from motor vehicles and industrial facilities, and the use of de-icing salts (Vlasov et al. 2020). Therefore, the present study tested an approach focused exclusively on assessing this phase. This approach helps reduce laboratory costs by decreasing the number of samples analysed. The availability of equipment for isolating the target snow phases (>2 µm and filtrate) makes snow research more accessible in terms of material and financial resources. The results of this study confirmed the effectiveness of this approach.

Overall, the collected data indicate that atmospheric pollution in small industrial cities has a certain impact on the environment. However, the accumulation of pollutants in the snow cover could become a serious issue when they enter water bodies and soil during snowmelt.

## CONCLUSIONS

An assessment was conducted of the current atmospheric input of pollutants into the residential zones of small and medium-sized industrial cities in the Sverdlovsk region, Russia. These cities are located in a temperate climate zone with a cold, prolonged snowy winter. The undisturbed snow cover was used as a geoindicator component of the environment.

The physical and chemical properties of the snow are not anomalous and correspond to the normal operation of the enterprises. Pollutant emissions are due to the normal functioning of the industrial facilities. The solids in the snow are primarily formed by calcium and magnesium bicarbonates and sulphates.

The calculated pollution indices show that industrial facilities in each city are major sources of urban environmental pollution when compared to Alapaevsk, which was chosen as an urban geochemical background. According to $PI_{sum}$, $PI_{avg}$ and $PI_{Nemerow}$, Kachkanar is the most polluted city. Elevated levels of V and Fe are likely connected to the open-pit mine. *EF* values suggest their origin is geogenic rather than anthropogenic. In Serov, Cr pollution is confirmed by all calculated indices and aligns with the city's metallurgical industry profile. In Verkhnyaya Pyshma, there is clearly anthropogenic, extreme Cu pollution and significant As pollution. Moderate pollution of Mo, Sn, Sb, and Pb is also present across all indices. V, Fe, Cr, Cu, and As pollution has been detected. Cluster analysis revealed geochemical associations in the snow cover: in Kachkanar Co-Ni-V-Ti-Cr-Fe-Mn; in Serov Cr and Ni; in Verkhnyaya Pyshma Cu-As-Sb-Pb; and in Alapaevsk Co and Ni. The cities differ in the associations of elements in the depending on their industrial specialisation. The dust load is quite significant and amounts to mg/m$^2$ per day: Kachkanar – 163, Serov – 84, Verkhnyaya Pyshma – 63, Alapaevsk – 27.

A comprehensive environmental monitoring method based on snow cover analysis was used in this study. The method can be successfully applied to other cities.

The proposed method has several limitations and sources of uncertainty:

1. The method is applicable only to regions with a long cold season and stable snow cover.

2. The dissolved form of PTEs is not considered separately in this method.

3. The selected urban geochemical background concentrations may be elevated compared to other possible background values.

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