Scientific Journal of Latvia University of Life Sciences and Technologies
Landscape Architecture and Art
Volume 26, Number 26
DOI: 10.22616/j.landarchart.2025.26.11

THE LANDSCAPE FOOTPRINT OF POLLUTION: HEAVY METALS IN SNOW ACROSS URBAN LAND USE TYPES

Inga Grīnfelde[1], Inga Straupe[1], Kristaps Siltumēns[1], Oskars Purmalis[2], Māris Bērtiņš[2], Jovita Pilecka-Uļčugačeva[1]

[1]*Latvia University of Life Sciences and Technologies, Latvia*

[2]*University of Latvia, Latvia*

Abstract. Urban landscapes play a critical role in shaping air and water quality, influencing the distribution of heavy metals and other pollutants. This study investigates the spatial and temporal variations of heavy metal concentrations in urban snow water within Jelgava City, Latvia, over three winter seasons (2017–2019). The study examines the relationships between heavy metal accumulation and urban land use categories, including residential, natural, transport, apartment, public, and industrial zones. Snow samples were analyzed for lead (Pb), nickel (Ni), chromium (Cr), and vanadium (V) using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), with statistical analyses performed to determine pollution trends and influencing factors. Results revealed significant spatial and temporal variations in heavy metal concentrations, with Pb exhibiting the highest mean concentration of 7.07 µg/L, followed by Ni (1.93 µg/L), Cr (2.77 µg/L), and V (2.08 µg/L). Maximum recorded values reached 72.26 µg/L for Pb, 40.75 µg/L for Ni, 71.35 µg/L for Cr, and 64.16 µg/L for V, highlighting extreme pollution events. Statistical analysis confirmed significant year-to-year variations for Pb ($p = 0.0047$), Ni ($p = 0.00028$), and Cr ($p = 0.00030$), whereas V remained relatively stable ($p = 0.0696$), suggesting a continuous pollution source. The study also highlights the influence of urban density on heavy metal accumulation, emphasizing the impact of vehicular emissions, heating systems, and industrial activities. The findings underscore the need for integrated urban planning strategies to mitigate heavy metal pollution and improve environmental quality in urban settings.

Keywords: heavy metals, urban snow, urban landscape, air pollution, spatial analysis

Introduction

Urban landscapes are recognized as dynamic systems shaped by complex interactions among built, natural, and socio-economic elements. In the context of growing urbanization, these systems significantly influence environmental quality, particularly air pollution [1–3]. Urban planning decisions, including the distribution of green areas, play a critical role in mitigating pollution. Green infrastructure—such as parks, forests, and water bodies—not only lowers particulate matter levels [4] but also enhances ecological functions such as microclimate regulation, pollutant filtration, and biodiversity support [5; 6]. Conversely, urban areas dominated by impervious surfaces and dense traffic can intensify pollution through increased emissions, resuspension of road dust, and limited dispersion of pollutants [7, 8]. Urban form—particularly the layout of roads, residential density, and industrial zones—can directly affect the distribution and accumulation of airborne contaminants, including heavy metals. Heavy metals such as lead (Pb), nickel (Ni), chromium (Cr), and vanadium (V) are particularly concerning due to their persistence, toxicity, and bioaccumulation potential [9; 10]. These pollutants primarily originate from anthropogenic sources, including vehicle emissions, industrial activities, and fossil-fuel-based heating systems [11–14]. Once deposited on surfaces, heavy metals can be transported via runoff into soil and water systems, increasing ecological and human health risks [15].

Snow, especially in northern urban regions, offers a unique medium for assessing short-term air pollution levels. Acting as a passive sampler, snowflakes capture airborne particles and soluble pollutants during precipitation events and atmospheric deposition, effectively integrating pollution loads over time. This makes snow cover a valuable indicator of urban air quality and a suitable matrix for identifying spatial patterns of heavy metal accumulation [16–18]. Snow's seasonal presence also allows for consistent sampling across urban gradients, particularly during periods of increased emissions from heating systems and reduced pollutant dispersion due to atmospheric stagnation [4–6].

The present study investigates the spatial and temporal distribution of heavy metal concentrations in snow within Jelgava City, Latvia, over three consecutive winter seasons (2017–2019). It aims to identify key pollution sources by analyzing the relationships between heavy metal levels and urban landscape structures, including green areas, transport infrastructure, and residential density. By integrating land use analysis with snow chemistry and statistical assessments, this research highlights how urban planning decisions influence pollution accumulation. Understanding these interactions is essential for designing targeted strategies that enhance urban resilience, reduce pollutant exposure, and support healthier urban ecosystems.

Materials and Methods

Study Area and Sampling Locations

The study was conducted in Jelgava City, Latvia [19], with a focus on assessing spatial variations in pollution accumulation across different urban environments. A total of 20 monitoring points were strategically selected to ensure comprehensive coverage of the city's diverse land use patterns and pollution sources (see Figure 1).

The monitoring points encompassed a wide range of land use categories, including residential areas, natural land, transport infrastructure, apartment building complexes, public spaces, and industrial zones. Each category was evaluated as a percentage of the total land cover within the respective monitoring point, enabling a comparative assessment of how different urban functions influence pollution accumulation.

Evaluation of urban structures

The first stage of the assessment involved analyzing Jelgava City's official territorial plan to determine designated zones and their relative proportions. These zones included residential, natural, transport, apartment, public, and industrial areas.

The territorial plan was imported into a Geographic Information System (GIS) platform, ensuring that all spatial data shared a common coordinate system. Within the GIS environment, a 150-meter-diameter buffer was delineated around each monitoring point, and the proportion of land-use classes within each buffer was then calculated. This initial

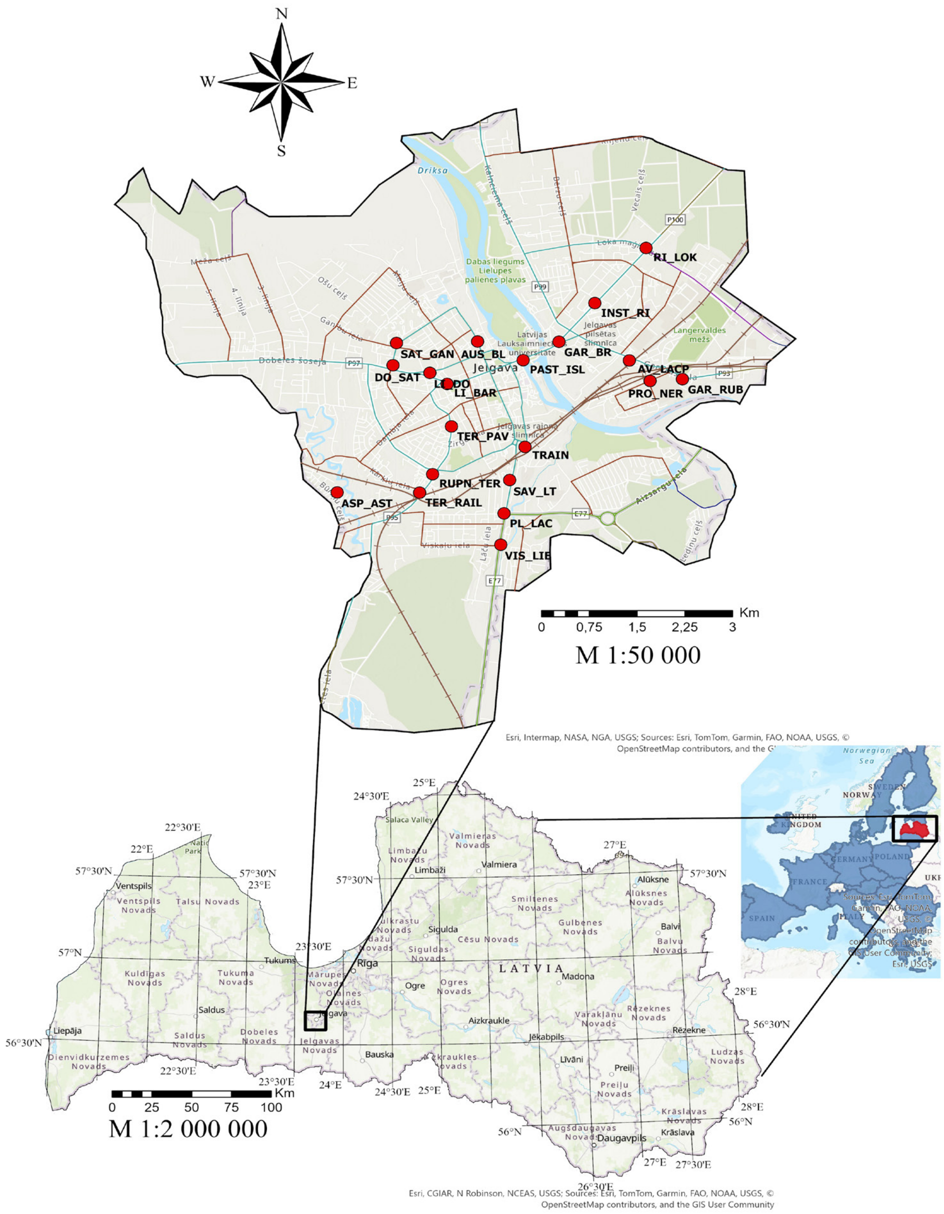

Fig. 1. The area of research and abbreviations of monitoring points [created by authors]

step provided a foundational understanding of the planned urban landscape distribution.

In the second stage, high-resolution satellite imagery was collected and analyzed to cross-check and refine the zoning information derived from the territorial plan. By visually interpreting features such as buildings, roads, and green spaces—supplemented where possible by semi-automated classification techniques—researchers identified any disparities between official designations and observable land-use patterns. For instance, recently developed residential buildings or newly reforested areas might not have been fully captured in the territorial plan. Updated or corrected land-use proportions were then computed within each monitoring point's buffer, enabling a more current and accurate overview of existing conditions.

The third stage consisted of on-site evaluations, aided by 360° panoramic photographs taken at each monitoring point. By physically visiting these locations, the research team confirmed that categorized land uses (residential, natural, transport, apartment, public, and industrial) matched actual conditions. The panoramic images offered a comprehensive perspective, allowing quick detection of mixed-use spaces, transitional zones, or unclassified parcels. Where discrepancies surfaced between the territorial plan, satellite data, and on-site observations, adjustments were made in the GIS database. This final validation step ensured that the resulting dataset captured both the planned and de facto land-use structure, supporting a robust analysis of Jelgava City's urban landscape.

Data Processing and Statistical Analysis

Summary statistics, including mean, median, standard deviation, quartiles, and range, were calculated for each heavy metal to evaluate concentration variability across years and monitoring points.

The temporal trends of metal concentrations were analyzed using four step approach. 1. Descriptive trend analysis, where mean concentrations were plotted across 2017–2019. 2. Quartile-based trend analysis, identifying changes in the distribution of concentrations over time. 3. Statistical comparisons (ANOVA and Kruskal-Wallis tests) were conducted to determine whether significant differences existed between years. 4. Post-hoc pairwise comparisons (Mann-Whitney U test) were performed to identify specific year-to-year differences.

To assess spatial variation in metal concentrations across monitoring points were used extreme analysis approach.

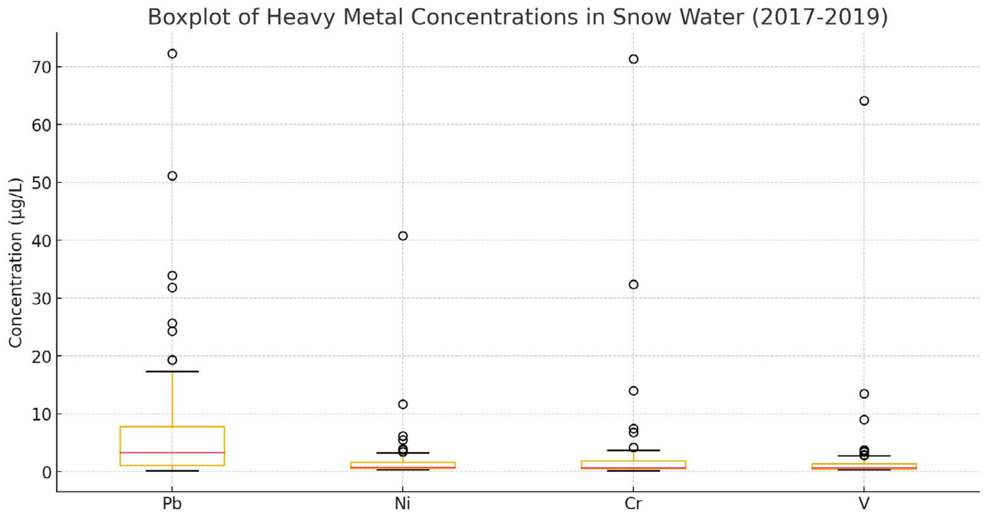

Fig. 2. The concentrations of heavy metals in snow water [created by authors]

Fig. 3 the correlation between proportions of urban structures and heavy metal concentrations a) year 2017; b) year 2018 c) year 2019 (red positiv correlation; green negativ correlation) [created by authors]

Monitoring points with the highest and lowest heavy metal accumulation were identified based on metal concentrations. Urban structure influence was analyzed by correlating heavy metal levels with land use percentages (residential, natural, transport, apartment, public, industrial). Correlation matrices (Pearson correlation and significance testing) were generated to explore relationships between metal concentrations and urban structures across all years and individually for 2017, 2018, and 2019. Heatmaps with statistical significance were used to visualize correlations, with red indicating positive relationships and green indicating negative correlations, while significant values were marked with asterisks ($p < 0.05$).

Results

Descriptive Statistics of Heavy Metals in Snow Water

The analysis of heavy metal concentrations in snow water samples from Jelgava City over the period of 2017–2019 reveals significant variations in their distributions (See Figure 2). Lead (Pb) exhibited the highest mean concentration of 7.07 µg/L, with a median of 3.36 µg/L, indicating a right-skewed distribution. The standard deviation of 11.33 µg/L and variance of 128.43 suggest substantial variability among sampling locations and years. The maximum recorded concentration of Pb reached 72.26 µg/L, while the minimum was 0.19 µg/L. The skewness value of 3.63 and kurtosis of 15.98 further confirm that Pb concentrations are heavily skewed and exhibit a leptokurtic distribution, implying the presence of extreme values.

Nickel (Ni) concentrations displayed a lower mean of 1.93 µg/L, with a median of 0.79 µg/L, suggesting a distribution influenced by a few high outliers. The standard deviation was 4.69 µg/L, and the variance reached 21.99, indicating substantial dispersion. The Ni concentration ranged between 0.40 µg/L and 40.75 µg/L. The skewness (7.49) and kurtosis (61.27) highlight the extreme deviation from normality, with a strong right-skewed pattern.

Chromium (Cr) concentrations showed an overall mean of 2.77 µg/L, with a median of 0.70 µg/L. The wide spread of data is reflected by a standard deviation of 8.72 µg/L and variance of 75.95. The minimum detected concentration was 0.25 µg/L, while the maximum reached 71.35 µg/L. The skewness (6.85) and high kurtosis (51.10) indicate a highly non-normal distribution, dominated by occasional extreme values.

Vanadium (V) concentrations followed a similar trend, with a mean of 2.08 µg/L and a median of 0.70 µg/L. The observed standard deviation was 7.26 µg/L, with a variance of 52.78. The lowest recorded concentration was 0.40 µg/L, while the highest measured value was 64.16 µg/L. Vanadium exhibited the strongest skewness (8.16) and kurtosis (69.83), indicating an extremely right-skewed distribution with highly concentrated extreme values. Overall, the statistical characteristics of all four heavy metals indicate strong right-skewed distributions with high kurtosis, signifying occasional extreme pollution events at certain monitoring points. This suggests that localized pollution sources may have significantly influenced metal accumulation in urban snow during the study period.

The Correlation Between Concentrations and Urban Structures

The correlation analysis between heavy metal concentrations in snow water and urban structure types revealed varying relationships across different years and for total heavy metal loads (See Figure 3). In 2017, apartment area coverage showed the strongest positive correlation with Pb ($r = 0.64$, $p < 0.05$) and V ($r = 0.52$, $p < 0.05$), indicating that increased residential density may contribute to higher metal accumulation. No significant correlations were observed for other land use types. In 2018, no statistically significant relationships were

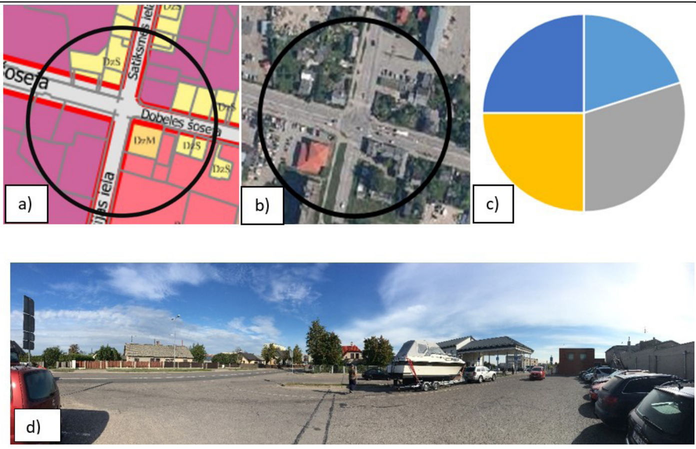

Fig. 4. The monitoring point do_sat with urban structure [created by authors]

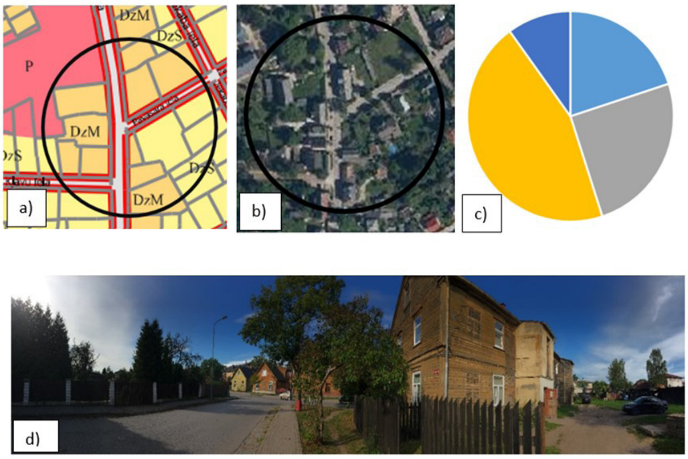

Fig. 5. The monitoring point ter_pav with urban structure sources and mitigation measures [created by authors]

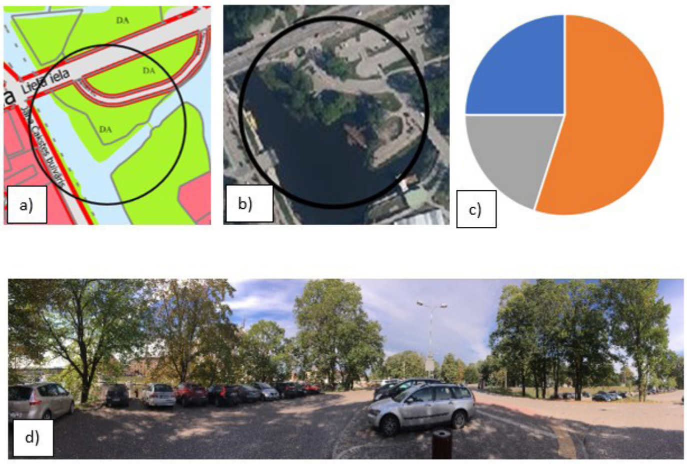

Fig. 6. The monitoring point past_isl with urban structure [created by authors]

found, suggesting a more even distribution of heavy metal contamination without strong urban structure dependencies. In 2019, similar trends to 2017 were observed, with apartment area again demonstrating the most substantial correlations, particularly with Pb and Ni, possibly due to traffic emissions or heating system influences. The total correlation analysis across all years confirmed these findings, as apartment area coverage exhibited consistently positive relationships with Pb ($r = 0.59$, $p < 0.05$) and V ($r = 0.25$, $p < 0.05$), reinforcing the link between residential zones and heavy metal deposition. Other land use types, such as public, natural, and transport areas, generally showed weak or negative correlations, with no significant trends across multiple years. These results highlight the potential impact of urban density and land use patterns on localized heavy metal accumulation in urban snow.

The Trend Over Time

The analysis of heavy metal concentrations in snow water from 2017 to 2019 reveals distinct patterns and trends, supported by both descriptive and statistical approaches. Lead (Pb) exhibited the highest concentrations in 2018, followed by a notable decline in 2019. This trend, along with a decrease in median and upper quartile values, suggests a reduction in pollution from sources such as traffic emissions or industrial activity. Statistical testing confirmed significant temporal variation ($p = 0.0047$), especially between 2018 and 2019. Nickel (Ni) remained relatively stable across 2017 and 2018, with a slight decrease in 2019, and while quartile analysis showed minor fluctuations, statistical results ($p = 0.00028$) indicate dynamic pollution patterns likely influenced by changing environmental factors or emission controls. Chromium (Cr) concentrations were mostly stable, with a moderate rise in the 75th percentile in 2018, followed by stabilization. Statistically significant year-to-year differences ($p = 0.00030$) suggest episodic pollution events or varying deposition processes. In contrast, vanadium (V) displayed a gradual increase across all years, with a more pronounced rise in the upper quartile, indicating growing emissions potentially linked to industrial sources or heavy fuel oil combustion. However, statistical tests did not show significant differences across years ($p = 0.0696$), implying a steady emission source. Overall, these findings point to both declining and emerging pollution trends, highlighting the importance of targeted environmental monitoring, assessment of emission sources, and the development of effective mitigation policies.

The Urban Landscape Structures

Monitoring point 17 (DO_SAT) is characterized by a diverse urban structure, with 20% residential areas, 30% transport infrastructure, 25% apartment buildings, and 25% public spaces, while no industrial areas or natural land cover are present (see Figure 4). This location exhibits high heavy metal accumulation, with Pb (64.19 µg/L) as the dominant pollutant, followed by Cr (74.06 µg/L), V (67.26 µg/L), and Ni (43.22 µg/L). The elevated concentrations of Pb and Cr suggest significant pollution sources, likely linked to high-density traffic, urban runoff, and residential heating emissions. The presence of extensive transport infrastructure and apartment areas may contribute to heavy metal deposition from vehicle exhaust, road dust, and construction activities, while the absence of natural land cover reduces the potential for pollutant retention or filtration. The high public space coverage also suggests possible human exposure risks, emphasizing the need for targeted pollution mitigation measures in this urban environment.

Monitoring point 14 (TER_PAV) is primarily composed of 20% residential areas, 25% transport infrastructure, 45% apartment buildings, and 10% public spaces, with no industrial or natural land cover present (see Figure 5). This location exhibits an extremely high Pb concentration (117.26 µg/L), significantly exceeding the levels of other heavy metals, while Ni (2.76 µg/L), Cr (3.57 µg/L), and V (2.62 µg/L) remain relatively low. The dominant presence of apartment buildings and transport infrastructure suggests that traffic emissions, road surface wear, and residential heating systems may be major contributors to Pb pollution. The lack of natural land cover may reduce pollutant retention capacity, leading to higher heavy metal accumulation in snow. The relatively low concentrations of Ni, Cr, and V indicate that specific Pb-related emission sources, such as historical leaded gasoline residues or localized construction activities, may be influencing this site. Given the high Pb concentration in an area with dense residential and public spaces, potential human exposure risks should be considered, necessitating further investigation into pollution.

Monitoring point 7 (PAST_ISL) is predominantly covered by 55% natural land, 20% transport infrastructure, and 25% public spaces, with no residential, apartment, or industrial areas (see Figure 6). This location exhibits moderate Pb accumulation (48.77 µg/L), while Cr (35.23 µg/L), V (11.75 µg/L), and Ni (8.96 µg/L) show varying levels of concentration. The high percentage of natural land suggests that metal deposition here may result from atmospheric deposition or long-range transport rather than direct urban emissions. However, the presence of transport infrastructure and public areas indicates possible road dust resuspension and human activities contributing to pollution levels. The relatively high Cr concentration may be linked to natural soil composition or erosion processes, while Pb and Ni levels suggest some influence from vehicular emissions and historical contamination. Despite the high percentage of natural land cover, the observed metal concentrations indicate potential contamination sources, warranting further investigation into atmospheric deposition and transport-related emissions in the area.

Monitoring point 1 (GAR_RUB) is characterized by 50% natural land, 30% transport infrastructure, and 20% residential areas, with no apartment buildings, public spaces, or industrial zones. The total heavy metal concentrations at this site are relatively low, with Pb (8.78 µg/L), Ni (2.75 µg/L), Cr (2.75 µg/L), and V (2.3 µg/L). The dominance of natural land cover suggests that this area is less affected by direct urban pollution sources, likely benefiting from vegetative buffering and lower anthropogenic emissions. However, the presence of 30% transport infrastructure may contribute to the detected metal levels through road dust, vehicular emissions, and atmospheric deposition. The comparatively low heavy metal concentrations suggest that this site experiences less industrial or urban influence, with metal deposition likely driven by regional atmospheric transport and occasional runoff from transport surfaces. The findings indicate that GAR_RUB represents a lower pollution risk area, serving as a potential reference point for assessing background contamination levels in urban snow.

Monitoring point 18 (SAT_GAN) is composed of 20% residential areas, 25% transport infrastructure, 15% apartment buildings, and 40% public spaces, with no natural land or industrial zones present. The total heavy metal concentrations at this site are relatively low, with Pb (11.15 µg/L), Ni (3.45 µg/L), Cr (3.50 µg/L), and V (2.51 µg/L). The relatively high proportion of public spaces and transport infrastructure suggests that metal deposition may be influenced by road dust, vehicular emissions, and human activities in public areas. The lack of natural land cover may reduce the site's ability to naturally filter pollutants, allowing heavy metals to accumulate in snow. Overall, SAT_GAN exhibits moderate contamination levels, with transport and public space usage likely playing a role in metal distribution.

Monitoring point 12 (TER_RAIL) is primarily dominated by 90% transport infrastructure and 10% public spaces, with no residential, natural, apartment, or industrial areas present. The total heavy metal concentrations indicate moderate pollution levels, with Pb (10.00 µg/L), Ni (6.25 µg/L), Cr (5.61 µg/L), and V (3.88 µg/L). The overwhelmingly high proportion of transport infrastructure suggests that vehicle emissions, tire and brake wear, road dust resuspension, and railway-related activities are likely the primary sources of heavy metal accumulation. The relatively high Ni and Cr concentrations could be linked to railway operations, metal corrosion, and fuel combustion residues, while Pb levels remain moderate, possibly due to historical pollution from leaded fuels or industrial transport emissions. The absence of natural land cover further reduces the ability of this area to retain and filter pollutants, leading to higher deposition rates in snow. Given its transport-oriented nature, TER_RAIL represents a high-risk zone for metal contamination, particularly influenced by urban mobility and transport-related emissions.

Discussion

The findings highlight pronounced spatial and temporal variations in heavy metal concentrations, with lead (Pb) frequently presenting the highest mean values [20–22]. Urban snow cover, recognized as an indicator of atmospheric pollution [23, 24], often registered elevated Pb near high-traffic roads and residential heating sources, particularly in winter [25–27]. Areas dominated by transport infrastructure (e.g., TER_RAIL) showed increased nickel (Ni) and chromium

(Cr), reflecting substantial vehicular and rail emissions [28, 29]. Descriptive statistics confirmed that Pb and Cr surged after 2017 and stabilized in subsequent years, hinting at shifts in fuel use or regulatory measures [30–32]. By contrast, Ni exhibited year-to-year fluctuations, likely driven by meteorological variability or sporadic industrial activities [33, 34]. Vanadium (V) remained stable, implicating continuous industrial or heavy fuel oil combustion as a persistent source [35–37]. Overall, ongoing monitoring and adaptive strategies are necessary to manage such diverse pollution dynamics [38–43, 31, 44].

Correlation analysis underscores that apartment areas strongly align with Pb and V, suggesting that dense residential zones heighten exposure from vehicular traffic and fossil-fuel heating [31, 45–49]. In contrast, natural and transport zones displayed weaker or negative correlations, indicating potential buffering effects or lesser direct contamination [50–54] Notably, sites with abundant vegetation, such as GAR_RUB, exhibited lower heavy metal loads, echoing evidence that green infrastructure captures airborne pollutants and improves soil conditions [55–60]. As traffic, industrial, and residential sources intensify with urban growth, measures like emissions regulation, expanded green spaces, and improved zoning are essential [61–64]. Continuous, site-specific monitoring [44] can guide targeted interventions to mitigate heavy metal risks and foster healthier urban environments.

Conclusions

This study provides a comprehensive assessment of heavy metal contamination in urban snow water, offering insights into the influence of urban land use patterns on pollutant accumulation. The results indicate that Pb and Cr concentrations increased after 2017, stabilizing in subsequent years, while Ni exhibited significant year-to-year fluctuations, and V remained relatively stable. The highest Pb concentrations were recorded in apartment-dense areas, reaching 117.26 µg/L, while Ni and Cr were most prevalent in transport-heavy zones, with peaks of 43.22 µg/L and 74.06 µg/L, respectively.

The strong positive correlation between apartment areas and Pb ($r = 0.64$, $p < 0.05$) and V ($r = 0.52$, $p < 0.05$) highlights the role of high-density residential zones in pollution accumulation. Transport infrastructure also exhibited a strong association with elevated Ni and Cr levels, emphasizing the impact of vehicular and railway emissions. Conversely, monitoring points with higher proportions of natural land cover demonstrated lower heavy metal concentrations, reinforcing the importance of urban green spaces in mitigating pollution.

The study's findings emphasize the need for targeted pollution management strategies, including stricter traffic regulations, expansion of green infrastructure, and improved urban air quality policies. Future research should focus on long-term monitoring and expanding the dataset to include additional pollutants and meteorological influences. These efforts will support more effective urban sustainability strategies aimed at reducing heavy metal contamination and protecting public health in urban environments.

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Authors

Inga Grinfelde, Ph.D., Mg.paed. Associated professor, Expert in hydrology, Academic and research experience for more than ten years, currently working at the Institute of Landscape Architecture and Environmental Engineering, Latvia University of Life Sciences and Technologies. Her main research interests include air pollution, soil contamination, and environmental quality assessment.
E-mail: inga.grinfelde@lbtu.lv
ORCID ID: https://orcid.org/0000-0002-3220-1777

Inga Straupe, Dr. silv., Professor, leading researcher, she is a professor and leading researcher at the Institute of Forestry, Latvia University of Life Sciences and Technologies. She has extensive academic and research experience in the fields of forest ecology, biodiversity conservation, and vegetation dynamics. Her scientific work focuses on forest ecosystem structure and functioning, the effects of human activity and climate change on forest vegetation, invasive plant species, and habitat protection.
E-mail: inga.straupe@lbtu.lv
ORCID ID: https://orcid.org/0000-0002-2098-7194

Kristaps Siltmens, Mg.sc.env., Research Assistant at the Scientific Laboratory of Forest and Water Resources, Latvia University of Life Sciences and Technologies. His research focuses on environmental sustainability, waste management, circular economy solutions, and innovative material development.
E-mail: kristaps.siltumens@lbtu.lv
ORCID ID: https://orcid.org/0009-0004-9803-7764

Oskars Purmalis, Dr. geogr., Associate Professor, Faculty of Science and Technology, University of Latvia with extensive experience in water quality, limnology, soil chemistry, and environmental pollution research. His work focuses on the geochemistry of aquatic ecosystems, humic substances, and the sustainable management of natural resources, including the control and utilization of invasive plant species.
E-mail: oskars.purmalis@lu.lv
ORCID ID: https://orcid.org/0000-0001-9167-0613

Maris Bertins, Mg.sc., Researcher, environmental and analytical chemist, he is a researcher at the Faculty of Chemistry, University of Latvia, where he has been working since 2018. His scientific expertise lies in environmental and analytical chemistry, materials science, and isotopic analysis. His research explores the elemental composition and isotopic signatures in environmental samples, as well as the development of innovative materials for environmental and biomedical applications.
E-mail: maris bertins@lu.lv
ORCID ID: https://orcid.org/0000-0002-0504-4163

Jovita Pilecka-Uļčugačeva, Ph.D., Assistant Professor, environmental engineer. Academic and research experience for more than ten years, currently working at the Institute of Landscape Architecture and Environmental Engineering, Latvia University of Life Sciences and Technologies. Her main research interests include air pollution, soil contamination, and environmental quality assessment.
E-mail: jovita.pilecka@lbtu.lv
ORCID ID: https://orcid.org/0000-0001-5556-0345

Kopsavilkums

Pētījumā analizētas smago metālu (Pb, Ni, Cr, V) koncentrācijas sniega ūdenī Jelgavā trīs ziemas sezonās (2017–2019), sasaistot piesārņojumu ar pilsētvides zemes izmantojumu. Izvietojām 20 monitoringa punktus dažādos apbūves tipos un katram 150 m rādiusā noteicām zemes izmantošanas proporcijas, bet metālus noteicām ar ICP-OES. Kopumā reģistrējām izteiktas telpiskās un laika svārstības: vidēji visaugstākais bija Pb (7,07 µg/L), kam sekoja Cr (2,77 µg/L), V (2,08 µg/L) un Ni (1,93 µg/L), ar atsevišķiem ekstrēmiem pīķiem (piem., Pb līdz ~72 µg/L). ANOVA/Kruskal–Wallis testi apstiprināja nozīmīgas gada starpības Pb, Ni un Cr ($p < 0,01$), kamēr V saglabājās statistiski stabils ($p = 0,0696$), norādot uz pastāvīgu emisiju avotu. Korelāciju matrica parādīja ciešākās pozitīvās saites starp daudzdzīvokļu apbūves īpatsvaru un Pb/V, savukārt transporta teritorijās biežāk pieauga Ni un Cr. Vietās ar lielāku dabas teritoriju īpatsvaru metālu līmeņi bija zemāki, apliecinot zaļās infrastruktūras buferfunkciju. Rezultāti izgaismo pilsētas struktūru, satiksmes un siltumapgādes sistēmu ietekmi uz metālu uzkrāšanos. Pētījums sniedz pierādījumus integrētas pilsētplānošanas un emisiju pārvaldības pasākumu nepieciešamībai (satiksmes regulējums, zaļo zonu paplašināšana, siltumapgādes modernizācija), lai mazinātu smago metālu slogu un uzlabotu pilsētvides kvalitāti.