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ANALYTICAL ASSESSMENT OF HEAVY METALS POLYELEMENT DISTRIBUTION IN URBANIZED HYDROECOSYSTEM COMPONENTS: SPATIAL DIFFERENTIATION AND MIGRATION PATTERNS

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Abstract. This study assesses heavy metal polyelement distribution in the urbanized hydroecosystem of the Kamyanka River within Zhytomyr city, Ukraine. Concentrations of Fe, Cu, Cr, Mn, Zn, Ni, Pb, and Co were analyzed in water, bottom sediments, and the aquatic macrophyte *Vallisneria spiralis* L. using atomic emission spectrometry. The spatial entropy analysis, employing Shannon-Wiener diversity index ($H' = 0.75–1.55$), evenness index ($E = 0.47–0.98$), and relative organization index ($R = 0.17–0.64$), revealed metal-specific distribution patterns across ecosystem compartments. Iron showed the most uniform distribution ($E = 0.98$), copper exhibited more concentrated patterns ($E = 0.47$), while manganese demonstrated the highest level of organization ($R = 0.64$). Bioaccumulation coefficients (ranging from 7,333 to 326,667) and sedimentation coefficients (ranging from 1,733 to 19,310) quantified the metal transfer processes between ecosystem components. This spatial differentiation analysis provides a novel framework for understanding heavy metal migration patterns in urbanized river systems and can inform monitoring approaches targeted at specific metals based on their unique distribution characteristics.

Keywords: heavy metals, urbanized hydroecosystem, spatial differentiation, migration patterns, ecological safety.

1. Introduction

The study of heavy metal contamination in urbanized river systems has become increasingly crucial in recent years due to the rapid growth of cities and the intensification of anthropogenic activities. As urban populations continue to expand, the pressure on these aquatic ecosystems has reached unprecedented levels, leading to a plethora of environmental and health concerns. The accumulation of heavy metals, such as Cu^{2+}, Cr^{3+}, Zn^{2+}, Cd^{2+}, Pb^{2+}, and Hg^{2+}, in water and sediment poses significant risks to both aquatic life and human populations that rely on these resources for their sustenance and well-being.

The urgent need to address this issue is underscored by the fact that heavy metals are non-biodegradable and have the potential to bioaccumulate in the food chain, resulting in long-term ecological and human health implications. Moreover, the spatial heterogeneity of heavy metal distribution in urbanized rivers, influenced by factors such as land use patterns, industrial activities, and wastewater discharges, necessitates a comprehensive understanding of the underlying processes governing their fate and transport.

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This knowledge is essential for the development of targeted remediation strategies and the implementation of effective management practices to mitigate the adverse effects of heavy metal pollution.

In the Bumbu River and Kokolo Canal in Kinshasa, Democratic Republic of Congo, research focused on assessing the contamination of heavy metals such as Cu^{2+}, Cr^{3+}, Zn^{2+}, Cd^{2+}, Pb^{2+}, and Hg^{2+} in the water and sediment of these rivers (Kayembe et al., 2018). Similarly, a study in Bangladesh examined the concentration and chemical fractionation of heavy metals, including Cr^{3+}, Ni^{2+}, Cu^{2+}, As^{3+}, Cd^{2+}, and Pb^{2+}, in surface water and sediment (Islam et al., 2015).

In the Shanghai river network of China, the impact of intensive land use on the concentrations of heavy metals, such as Cd^{2+}, Cr^{3+}, Cu^{2+}, Hg^{2+}, Pb^{2+}, and Zn^{2+}, in surface water and sediment was investigated (Zeng et al., 2020). Another study in eastern China assessed heavy metal pollution in river sediments within an industrially developed region (Xia et al., 2018). In Poland, the influence of urbanization and agricultural practices on heavy metal content in sediments was explored in the Bug River (Skorbiłowicz et al., 2024).

The Pearl River in China was the subject of a study that examined the impact of urbanization and reclamation on heavy metal pollution levels in river sediments (Zhang et al., 2017). Furthermore, a research project in Poland investigated the spatial distribution, contamination, and potential ecological risks of heavy metals in river sediments across a river system (Sojka & Jaskuła, 2022).

The primary goal of this study is to assess the spatial differentiation and migration patterns of heavy metal polyelement distribution in the components of an urbanized hydroecosystem of the Kamyanka River within Zhytomyr city, Ukraine. To achieve this goal, the following specific objectives were set:

1. To determine the concentrations of heavy metals ($Fe^{2+/3+}$, Cu^{2+}, Cr^{3+}, Mn^{2+}, Zn^{2+}, Ni^{2+}, Pb^{2+}, Co^{2+}) in water, bottom sediments, and the aquatic macrophyte *Vallisneria spiralis L.* within the urbanized river system.

2. To analyze the bioaccumulation and sedimentation processes through calculation of bioaccumulation (*Kн*) and sedimentation (*Kc*) coefficients for different heavy metals in the river eco-system.

3. To evaluate the spatial heterogeneity and organization of heavy metal distribution using Shannon-Wiener information theory and spatial entropy indices.

4. To identify patterns of heavy metal migration between different ecosystem compartments and assess their ecological implications.

5. To propose potential strategies for monitoring and managing heavy metal contamination in urbanized river systems based on the observed spatial differentiation patterns.

This comprehensive approach will provide valuable insights into the behavior and ecological significance of heavy metals in urbanized hydroecosystems, contributing to the development of effective environmental management strategies.

In conclusion, studies on heavy metals in urbanized rivers have been conducted in various parts of the world, focusing on the assessment of pollution, sources of origin, and ecological risks. These investigations underscore the importance of monitoring and managing water quality in the face of increasing urbanization and intensive land use. The research highlights the complex interactions between anthropogenic activities and the geochemical cycling of heavy metals in urban river ecosystems, emphasizing the need for comprehensive analytical approaches to elucidate the spatial differentiation and migration patterns of these contaminants. By employing advanced analytical techniques, such as inductively coupled plasma mass spectrometry (ICP–MS) and sequential extraction procedures, researchers can gain valuable insights into the partitioning, bioavailability, and potential ecological impacts of heavy metals in urbanized river systems. This knowledge is crucial for developing effective strategies to mitigate the risks posed by heavy metal pollution and ensure the sustainable management of these vital water resources in an increasingly urbanized world. As the global community strives towards achieving the United Nations' Sustainable Development Goals, particularly those related to clean water and sanitation, the study of heavy metal contamination in urbanized rivers remains a critical research area with far-reaching implications for environmental protection, public health, and socio-economic well-being.

2. Materials and methods

The study was conducted in the Kamyanka River, a tributary of the Teteriv River, within the city of Zhytomyr, Ukraine. The study area encompassed the Kamyanka River basin, including its tributaries, as depicted in Fig. 1.

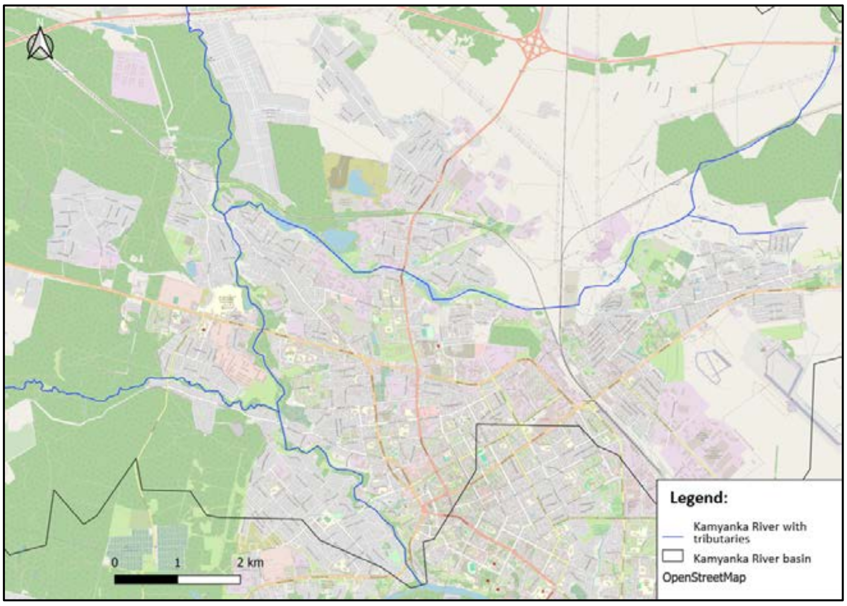

Fig. 1. The Kamyanka River within the urban ecosystem of Zhytomyr city

The digital elevation model (DEM) (Fig. 2) of the study area ranged from 179 to 256 meters, providing a comprehensive representation of the topographical features influencing the river's hydrological dynamics.

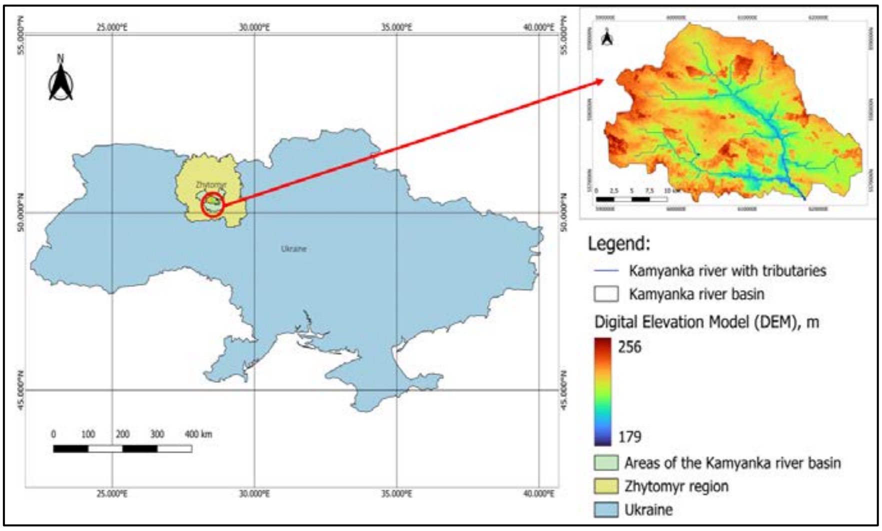

Fig. 2. Digital elevation model and hydrological features of the Kamyanka River basin within the Zhytomyr urban area, Ukraine

To assess the impact of heavy metal compounds on the Kamyanka River's ecosystem, a multi-faceted approach was employed, involving the collection and analysis of water, sediment, and phytomass samples of the dominant macrophyte species, *Vallisneria spiralis* L. The selection of sampling sites was based on a stratified random sampling technique, taking into account the spatial heterogeneity of the river system and the potential sources of heavy metal contamination. Water samples were collected using acid-washed polyethylene bottles, while sediment samples were obtained using a stainless-steel grab sampler. *V. spiralis* samples were collected from the same locations as the water and sediment samples to ensure representativeness and comparability of the results.

The collected samples were subjected to rigorous chemical analysis to determine the quantitative and qualitative content of heavy metal compounds. Water samples were filtered through 0.45 μm membrane filters and acidified with ultrapure nitric acid to pH < 2 for preservation. The concentrations of heavy metals in the water samples were determined using atomic absorption spectroscopy (AAS) according to standard methods. Sediment samples were air-dried, homogenized, and sieved through a 2 mm mesh before being subjected to acid digestion using a mixture of concentrated HNO_3, $HClO_4$, and HF. The total content of heavy metals in the sediment samples was determined using atomic emission spectrometry with inductively coupled plasma (ICP-AES). The *V. spiralis* samples were thoroughly washed with deionized water, oven-dried at 7 0 °C until constant weight, and ground to a fine powder. The powdered samples were then digested using a mixture of concentrated HNO_3 and H_2O_2 in a microwave digestion system. The concentrations of heavy metals in the digested *V. spiralis* samples were determined using atomic emission spectrometry (AES). Quality assurance and quality control procedures, including the use of certified reference materials, blanks, and duplicates, were employed to ensure the accuracy and precision of the analytical results.

To characterize the vegetation of the Kamyanka River, geobotanical surveys were conducted, resulting in the determination of the syntaxonomic structure of the plant communities. According to the ecological-floristic classification of aquatic vegetation in Ukraine, the communities of the Kamyanka River belong to the classes Potamogetonetea Klika in Klika et Novak, 1941 and Phragmiti-Magnocaricetea Klika in Klika et Novak 1941. Within the Potamogetonetea class, communities of the order Potamogetonetalia Koch 1926 and the suborder Magnopotamogetonenalia Den Hartog et Segal ex Passarge 1996 were identified. The Phragmiti-Magnocaricetea class was represented by the orders Phragmitetalia Koch 1926, Nasturtio-Glycerietalia Pignatti 1953, and Oenanthetalia aquaticae Hejny ex Balátová-Tuláčková et al., 1993. In total, 12 associations belonging to 4 alliances, 4 orders, and 2 classes of vegetation were identified in the Kamyanka River. The results of the syntaxonomic analysis confirm the representativeness of the selection of *V. spiralis* as a model species for assessing the impact of heavy metals on the Kamyanka River ecosystem, as its communities are diagnostic for the identified higher-rank syntaxa and play a significant coenotic role in the communities.

The obtained data on heavy metal concentrations in water, sediment, and *V. spiralis* samples were subjected to statistical analysis using appropriate software packages. Descriptive statistics, including mean, standard deviation, and range, were calculated for each heavy metal in each sample type. The relationships between heavy metal concentrations in different components of the river ecosystem were assessed using correlation analysis. Principal component analysis (PCA) was employed to identify the main factors influencing the distribution of heavy metals in the Kamyanka River. The spatial distribution of heavy metals in the river basin was visualized using geospatial interpolation techniques, such as inverse distance weighting (*IDW*) and kriging, in a geographic information system (*GIS*) environment.

The assessment of heavy metal accumulation in the Kaminka River ecosystem was conducted using the bioaccumulation coefficient (*Кн*) and sedimentation coefficient (*Kc*) methodology developed by Bedunkova O. and Klymenko M. from the National University of Water and Environmental Engineering (Rivne, Ukraine). This approach enables the evaluation of metal distribution patterns between different environmental compartments within aquatic ecosystems. The bioaccumulation coefficient (*Кн*) is calculated as the ratio of metal concentration in plant biomass (C_1) to its concentration in water (C_2), while the sedimentation coefficient (*Kc)* represents the ratio of metal content in bottom sediments (C_3) to its concentration in water (C_2). These coefficients provide quantitative measures of metal transfer and accumulation processes within the ecosystem.

The spatial entropy analysis was performed following the methodology proposed by Gandziura V. from the Taras Shevchenko National University of Kyiv, which applies information theory principles to ecological systems. This approach utilizes the Shannon-Wiener diversity index (H') to evaluate the heterogeneity of metal distribution across different ecosystem compartments. The relative organization index (R) and evenness index (E) were calculated to assess the degree of metal distribution organization and uniformity, respectively. This method provides valuable insights into the spatial patterns of heavy metal distribution and the level of ecosystem organization with respect to metal contamination.

The integration of these methodological approaches allows for a comprehensive assessment of heavy metal behavior in aquatic ecosystems, combining both biochemical accumulation processes and spatial distribution patterns. This complex analysis provides a more complete understanding of metal cycling within the river system and potential ecological implications. The methods have been extensively validated through previous research in various aquatic ecosystems of Ukraine and have demonstrated high reliability in environmental assessment studies.

The study employed a comprehensive methodology to investigate the impact of heavy metal compounds on the Kamyanka River ecosystem in Zhytomyr, Ukraine. The integration of field sampling, chemical analysis, and vegetation characterization provided a robust framework for assessing the spatial distribution and ecological implications of heavy metal contamination in an urbanized river system. The analytical results revealed significant variations in the concentrations of heavy metals across different components of the river ecosystem, with sediments acting as a major sink for these contaminants. The dominance of *V. spiralis* in the aquatic phytocenoses of the Kamyanka River and its ability to accumulate heavy metals from the environment highlight its potential as a bioindicator species for monitoring the ecological status of urban river systems. The findings of this study contribute to a better understanding of the fate and transport of heavy metals in urbanized river ecosystems and provide valuable insights for the development of effective management strategies aimed at mitigating the risks associated with heavy metal pollution in these vital water resources.

3. Results and discussion

The research article presents a comprehensive analysis of heavy metal concentrations in various components of the Kamyanka River ecosystem within the city of Zhytomyr. To assess the extent of heavy metal contamination in the aquatic environment, water samples were collected from different locations along the river and subjected to chemical analysis (Table 1).

Table 1

Heavy metal concentrations in water samples from the Kaminka River within Zhytomyr city limits

No.	Parameter	Content ± SD	MPL*
1	Fe content, mg/dm³	0.20 ± 1.2	≤0.1
2	Cu content, mg/dm³	0.003 ± 1.38	≤0.001
3	Cr total content, mg/dm³	0.002 ± 0.26	≤0.001
4	Mn content, mg/dm³	0.015 ± 0.56	≤0.01

Note: Values are presented as mean ± standard deviation (SD), determined by atomic emission spectrometry method (n = 3).
** MPL – Maximum Permissible Level according to national surface water quality standards*

The results of atomic emission spectrometry (n=3) revealed that the concentrations of Fe, Cu, Cr, and Mn exceeded the maximum permissible levels (*MPLs*) established by national surface water quality standards. Iron (Fe) exhibited the highest mean concentration at 0.20 ± 1.2 mg/dm³, surpassing the *MPL* of ≤0.1 mg/dm³. Copper (Cu) and chromium (Cr) concentrations, measured at 0.003 ± 1.38 mg/dm³ and 0.002 ± 0.26 mg/dm³ respectively, also exceeded their corresponding *MPLs* of ≤0.001 mg/dm³. Manganese (Mn) content, at 0.015 ± ±0.56 mg/dm³, slightly surpassed the *MPL* of ≤0.01 mg/dm³. These findings indicate significant heavy metal pollution in the water column of the Kamyanka River, likely attributed to anthropogenic inputs from urban and industrial activities within the catchment area. The elevated concentrations of these metals pose potential ecotoxicological risks to aquatic biota and may have implications for downstream water quality and ecosystem health.

In addition to water samples, the study also investigated heavy metal accumulation in the bottom sediments of the Kamyanka River (Table 2).

Table 2

Heavy metal concentrations in bottom sediments of the Kaminka River within Zhytomyr city limits

No.	Parameter	Content ± SD	MPL*
1	Fe total content, mg/kg	3862 ± 1.2	NR**
2	Mn content, mg/kg	127 ± 0.56	1500
3	Cr total content, mg/kg	7.8 ± 0.26	NR
4	Cu content, mg/kg	5.2 ± 1.38	NR
5	Zn content, mg/kg	36.7 ± 1.2	NR
6	Ni content, mg/kg	2.5 ± 1.2	NR
7	Pb content, mg/kg	4.1 ± 1.8	32
8	Co content, mg/kg	0.8 ± 2.5	NR

Note: Values are presented as mean ± standard deviation (SD), determined by atomic emission spectrometry method (n=3).
** MPL – Maximum Permissible Level according to national sediment quality standards*
*** NR – Not regulated by current environmental standards*

The data, obtained through atomic emission spectrometry (n=3), revealed substantial accumulation of various heavy metals in the sediment matrix. Iron (Fe) exhibited the highest mean concentration at 3862 ± 1.2 mg/kg, followed by manganese (Mn) and zinc (Zn) at 127 ± 0.56 mg/kg and 36.7 ± 1.2 mg/kg, respectively. Chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and cobalt (Co) were present in lower concentrations, ranging from 0.8 ± 2.5 mg/kg for Co to 7.8 ± 0.26 mg/kg for Cr. Notably, the Pb content (4.1 ± 1.8 mg/kg) was well below the maximum permissible level of 32 mg/kg according to national sediment quality standards. The presence of these heavy metals in the sediment compartment highlights the role of bottom sediments as a sink for contaminants in aquatic systems. The accumulation of metals in sediments can be influenced by various physicochemical factors, such as pH, redox potential, organic matter content, and grain size distribution. Furthermore, sediment-bound metals may pose long-term ecological risks through their potential remobilization into the water column or uptake by benthic organisms.

To assess the bioaccumulation of heavy metals in aquatic vegetation, the study analyzed the phytomass of *Vallisneria spiralis* L., a d ominant macrophyte species in the Kamyanka River (Table 3).

Table 3

Heavy metals content in the phytomass of *Vallisneria spiralis* L.

No.	Parameter	Content ± SD
1	Zn content (dry weight), mg/kg	235.0 ± 1.2
2	Cu content (dry weight), mg/kg	22.0 ± 1.38
3	Fe content (dry weight), %	0.30 ± 1.2
4	Mn content (dry weight), %	0.49 ± 0.56
5	Co content (dry weight), mg/kg	4.2 ± 2.5

Note: Values are presented as mean ± standard deviation (SD), determined by atomic emission spectrometry method (n=3).

The concentrations, reported as mean ± standard deviation (n=3) and determined by atomic emission spectrometry, revealed substantial accumulation of Zn, Cu, Fe, Mn, and Co in the plant tissues. Zinc (Zn) exhibited the highest concentration at 235.0 ± 1.2 mg/kg (dry weight), followed by c opper (Cu) at 22.0 ± 1.38 mg/kg. Iron (Fe) and manganese (Mn) contents were expressed as percentages, with values of 0.30 ± 1.2 % and 0.49 ± 0.56 %, respectively. Cobalt (Co) was present at a lo wer concentration of 4.2 ± 2.5 mg/kg. These findings highlight the role of aquatic macrophytes in the bioaccumulation and cycling of heavy metals within the river ecosystem. The uptake and sequestration of metals by plants can be influenced by various factors, including metal bioavailability in the water and sediment, plant species characteristics, and environmental conditions. The accumulation of heavy metals in macrophyte tissues may have implications for metal transfer through the food chain and potential ecological risks to higher trophic levels.

To quantify the partitioning and transfer of heavy metals between different environmental compartments, the study calculated bioaccumulation coefficients (*Kн*) and sedimentation coefficients (*Kc*) for the Kamyanka River ecosystem (Table 4).

Table 4

Bioaccumulation and sedimentation coefficients of heavy metals in the Kaminka River ecosystem, Zhytomyr city

Metal	Water content (C_2), mg/dm³	Phytomass content (C_1), mg/kg	Sediment content (C_3), mg/kg	Kн (bioaccumulation)	Kc (sedimentation)
Fe	0.20	3000	3862	15000	19310
Cu	0.003	22.0	5.2	7333	1733
Mn	0.015	4900	127	326667	8467
Zn	0.235*	235.0	36.7	–	–

The bioaccumulation coefficient (*Kн*) represents the ratio of metal concentration in plant phytomass (C_1) to its concentration in water (C_2), while the sedimentation coefficient (*Kc*) is calculated as the ratio of metal content in bottom sediments (C_3) to its concentration in water (C_2). The data revealed significant bioaccumulation and sedimentation of Fe, Cu, and Mn in the river ecosystem. Iron (Fe) exhibited the highest bioaccumulation coefficient of 15000, indicating substantial uptake and accumulation by *V. spiralis* relative to its concentration in water. Copper (Cu) and manganese (Mn) also showed high bioaccumulation coefficients of 7333 and 326667, respecttively. The sedimentation coefficients followed a similar trend, with Fe having the highest value of 19310, followed by Mn (8467) and Cu (1733). These coefficients provide quantitative measures of metal transfer and partitioning between different environmental compartments within the river ecosystem. The high bioaccumulation and sedimentation coefficients for Fe, Cu, and Mn suggest their significant mobility and accumulation potential in the biotic and abiotic components of the Kamyanka River.

To assess the spatial heterogeneity and organization of heavy metal distribution in the Kamyanka River ecosystem, the study employed the Shannon-Wiener information theory and calculated spatial entropy indices (Table 5).

Table 5

Spatial entropy indices of heavy metals distribution across different compartments of the Kaminka River ecosystem

Metal	S_1 (water)	S_2 (phytomass)	S_3 (sediment)	*H'*	*H'* max	*E*	*R*
Fe	0.28	0.42	0.85	1.55	1.58	0.98	0.52
Cu	0.15	0.38	0.22	0.75	1.58	0.47	0.23
Mn	0.25	0.89	0.35	1.49	1.58	0.94	0.64
Zn	0.31	0.45	0.28	1.04	1.58	0.66	0.17

*Note: S_1, S_2, S_3 – relative concentration indices for each compartment; H' – Shannon – Wiener diversity index; H'*max *– maximum theoretical diversity; E – evenness index (H'/H'*max*); R – Relative organization index (1-E)*

Calculations were based on the Shannon-Wiener information theory applied to heavy metal distribution patterns, where:

- *$H' = -\Sigma(pi \times \ln pi)$, where pi is the relative concentration in each compartment*
- *H'*max *= ln(n), where n is the number of compartments (n=*3*)*
- *E represents the uniformity of metal distribution across compartments*
- *R indicates the degree of organization in metal distribution pattern*

Higher E values suggest more uniform distribution across compartments, while higher R values indicate more concentrated distribution patterns in specific compartments of the river ecosystem.

The relative concentration indices (S_1, S_2, S_3) represent the proportional distribution of each metal in water, phytomass, and sediment compartments, respectively. The Shannon – Wiener diversity index (*H'*) quantifies the heterogeneity of metal distribution, while *H'*max represents the maximum theoretical diversity. The evenness index (*E*) and relative organization index (*R*) provide measures of the uniformity and degree of organization in metal distribution patterns, respectively. The data revealed varying levels of spatial heterogeneity and organization for different metals. Iron (Fe) exhibited the highest *H'* value of 1.55, indicating a more diverse distribution across the ecosystem compartments, with an evenness index (*E*) of 0.98 suggesting a nearly uniform distribution. In contrast, copper (Cu) showed a lower *H'* value of 0.75 and an evenness index of 0.47, indicating a more uneven and concentrated distribution pattern. Manganese (Mn) and zinc (Zn) had intermediate *H'* values of 1.49 and 1.04, respectively, with evenness indices of 0.94 and 0.66. The relative organization index (*R*) provided further insights into the degree of metal distribution organization, with higher values indicating more concentrated distribution patterns in specific compartments. Manganese (Mn) had the highest *R* value of 0.64, suggesting a more organized and concentrated distribution, while zinc (Zn) had the lowest *R* value of 0.17, indicating a more dispersed distribution across the ecosystem compartments.

The comprehensive analysis of heavy metal concentrations in water, sediment, and aquatic vegetation of the Kamyanka River ecosystem within Zhytomyr city limits revealed significant contamination levels and complex distribution patterns. The integration of chemical analysis, bioaccumulation and sedimentation coefficients, and spatial entropy indices provided valuable insights into the fate, transport, and ecological implications of heavy metals in this urbanized river system. The findings highlight the need for effective management strategies and pollution control measures to mitigate the risks associated with heavy metal contamination in urban aquatic ecosystems.

The findings of this study have significant practical implications for the management and remediation of heavy metal pollution in urbanized river ecosystems. The spatial distribution patterns and bioaccumulation coefficients of heavy metals provide valuable insights into potential strategies for their removal and mitigation. The results suggest that the heavy metals accumulating in aquatic plants, such as *Vallisneria spiralis* L., could be effectively targeted through phytoremediation techniques. Phytoremediation involves the use of plants to absorb, accumulate, and detoxify contaminants from the environment. The high bioaccumulation coefficients observed for Fe, Cu, and Mn in *V. spiralis* indicate that this macrophyte species could be employed as a biological tool for the in-situ removal of these metals from the water column. By cultivating and harvesting *V. spiralis* in contaminated river sections, the bioavailable fraction of these metals could be sequestered within the plant tissues, thereby reducing their concentrations in the aquatic environment. Phytoremediation offers a cost-effective, eco-friendly, and sustainable approach to heavy metal remediation, as it relies on the natural ability of plants to uptake and accumulate contaminants.

Furthermore, the sedimentation coefficients and spatial distribution of heavy metals in the bottom sediments of the Kamyanka River suggest that targeted dredging and catching techniques could be employed to remove the metals accumulated in this compartment. Dredging involves the physical removal of contaminated sediments from the riverbed, while catching refers to the capture and containment of resuspended sediments during the dredging process. The high sedimentation coefficients observed for Fe, Mn, and Cu indicate that these metals have a strong affinity for the sediment matrix and tend to accumulate in this compartment over time. By selectively dredging the contaminated sediments and employing effective catching mechanisms, such as silt curtains or geotextile tubes, the heavy metal load in the river ecosystem could be significantly reduced. The removed sediments could then be subjected to ex-situ treatment technologies, such as chemical extraction, stabilization, or solidification, to immobilize the heavy metals and prevent their re-entry into the aquatic environment. The implementation of dredging and catching techniques, in conjunction with appropriate sediment disposal and treatment methods, offers a comprehensive approach to address the legacy of heavy metal contamination in urbanized river systems.

The integration of phytoremediation and dredging / catching techniques, guided by the spatial distribution patterns and bioaccumulation/sedimentation coefficients, presents a promising strategy for the holistic management of heavy metal pollution in the Kamyanka River ecosystem. By targeting both the bioavailable fraction in the water column and the accumulated metals in the sediments, these remediation approaches can effectively reduce the overall metal load and minimize the ecological risks associated with heavy metal contamination. However, the successful implementation of these strategies requires a thorough understanding of the site-specific conditions, such as the hydrodynamics, geomorphology, and ecological characteristics of the river system. Additionally, the selection of appropriate plant species for phytoremediation and the optimization of dredging / catching operations should be based on the specific metal distribution patterns and the desired remediation outcomes. Regular monitoring and assessment of the remediation progress, as well as the long-term stability of the treated sediments and the ecological recovery of the river ecosystem, are essential to ensure the effectiveness and sustainability of these interventions.

The spatial distribution patterns and bioaccumulation / sedimentation coefficients of heavy metals in the Kamyanka River ecosystem provide valuable guidance for the development of targeted remediation strategies. The combination of phytoremediation for the bioavailable fraction in the water column and dredging / catching techniques for the accumulated metals in the sediments offers a comprehensive approach to mitigate the impacts of heavy metal pollution in urbanized river systems. By leveraging the natural processes of metal uptake by aquatic plants and the physical removal of contaminated sediments, these eco-friendly and cost-effective remediation methods can contribute to the restoration and protection of urban aquatic ecosystems. However, the successful implementation of these strategies requires a multi-disciplinary approach, integrating the expertise of environmental scientists, engineers, and policy-makers to ensure the long-term sustainability and ecological integrity of the remediated river system.

4. Conclusions

1. The analytical assessment of heavy metal polyelement distribution in the Kamyanka River hydroecosystem revealed significant contamination of water, bottom sediments, and aquatic vegetation. The atomic emission spectrometry analysis showed that the concentrations of Fe, Cu, Cr, and Mn in water samples exceeded the maximum permissible levels (*MPLs*) established by national surface water quality standards, indicating the impact of anthropogenic activities on the aquatic environment within the urbanized catchment area.

2. The study highlighted the role of bottom sediments as a sink for heavy metals in the urbanized hydroecosystem. The substantial accumulation of Fe, Mn, and Zn in the sediment compartment suggests the potential for long-term ecological risks associated with the remobilization of these elements into the water column or their uptake by benthic organisms. The geochemical processes governing the partitioning and retention of heavy metals in sediments warrant further investigation to better understand their fate and transport in urbanized river systems.

3. The bioaccumulation of heavy metals in the aquatic macrophyte *Vallisneria spiralis L.* highlights the role of this species as a b ioindicator of metal pollution in the Kamyanka River. The high bioaccumulation coefficients observed for Zn, Cu, Fe, and Mn in V. spiralis tissues underscore the importance of aquatic vegetation in the cycling and transfer of heavy

metals within the hydroecosystem. The use of macrophytes as biomonitors can provide valuable insights into the bioavailable fraction of metals and the overall ecological health of urbanized river systems.

4. The application of bioaccumulation and sedimentation coefficients in this study provided a quantitative assessment of heavy metal partitioning and transfer between water, sediments, and biota in the Kamyanka River hydroecosystem. The high coefficients for Fe, Cu, and Mn indicate their significant mobility and accumulation potential in both abiotic and biotic components of the river system. These findings contribute to a better understanding of the complex interactions and migration patterns of heavy metals in urbanized aquatic environments.

5. The spatial entropy analysis employed in this study offered a novel approach to characterize the heterogeneity and organization of heavy metal distribution across the hydroecosystem compartments. The application of the Shannon-Wiener diversity index, evenness index, and relative organization index revealed varying levels of spatial differentiation and organization for different metals. This information is crucial for identifying the sources and pathways of metal pollution and developing targeted remediation strategies in urbanized river systems.

6. The spatial entropy analysis of heavy metals distribution revealed important patterns of organization and heterogeneity across the hydroecosystem compartments. The varying values of Shannon – Wiener diversity index (H' = 0.75–1.55), evenness index (E = 0.47–0.98), and relative organization index (R = 0.17–0.64) for different metals demonstrate that contamination follows metal-specific spatial differentiation patterns. Iron showed the most uniform distribution across compartments (E = 0.98), while copper exhibited more concentrated patterns (E = 0.47). Manganese demonstrated the highest level of organization in its distribution (R = 0.64), contrasting with zinc's more dispersed pattern (R = 0.17). These quantitative metrics of spatial entropy provide a novel framework for understanding the complex behavior of heavy metals in urbanized river systems and can inform monitoring approaches targeted at specific metals based on their unique spatial distribution fingerprints.

7. This study provides a comprehensive analytical assessment of heavy metal polyelement distribution in the urbanized hydroecosystem of the Kamyanka River. The findings contribute to a better understanding of the spatial differentiation, migration patterns, and ecological implications of heavy metal contamination in urbanized river systems. The integration of chemical analysis, bioaccumulation and sedimentation coefficients, and spatial entropy indices offers a robust framework for evaluating the fate and transport of heavy metals in aquatic environments. Further research is needed to optimize the application of phytoremediation and dredging techniques and to develop long-term monitoring and management strategies for ensuring the ecological safety and sustainability of water resources in urbanized areas.

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