



Article

Seasonal and Spatial Assessment of Heavy Metal Contamination in Groundwater in the Republic of Kosovo

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Abstract

Groundwater is vital to subsurface ecosystems and to maintaining water supplies for human and environmental needs. Heavy metal pollution of water bodies poses a significant threat to environmental health and human well-being. In this paper, a detailed spatiotemporal analysis of heavy metal pollution at a network of 35 sampling sites is presented for the summer, autumn, and winter seasons. The water samples were analyzed based on the concentration ($\mu\text{g/L}$) of eight priority metals, such as Lead (Pb), Mercury (Hg), Cadmium (Cd), Arsenic (As), Chromium VI (Cr-VI), Copper (Cu), Zinc (Zn), as well as Iron (Fe). Measuring contamination levels, identifying space hotspots, and explaining seasonal variations were the key tasks. The results show that Fe, Zn, and Cu concentrations are consistently high across seasons, with mean values ranging from 234.3 to 253.2 $\mu\text{g/L}$ (Fe), 163.2 to 175.6 $\mu\text{g/L}$ (Zn), and 107.0 to 109.2 $\mu\text{g/L}$ (Cu), indicating a widespread geogenic or diffuse source. The most significant seasonal deviation was observed in the fall when there were unusually high levels of Cd and Hg, with mean concentrations reaching 0.476 $\mu\text{g/L}$ and 0.312 $\mu\text{g/L}$, respectively, suggesting a strong seasonal contamination event or mobilization process. The spatial analysis showed that the locations (e.g., L6, L8, L10, L28, L29) exhibited common hotspots for different metals, with maximum concentrations reaching up to 793.3 $\mu\text{g/L}$ (Fe), 602.3 $\mu\text{g/L}$ (Zn), and 508 $\mu\text{g/L}$ (Cu). Principal Component Analysis (PCA) effectively separated seasonal trends and classified metals into anthropogenic (Pb, Cd, Hg, Cr (VI)) and geogenic/diffuse (Fe, Zn, Cu) groups. The health risk assessment indicated no significant non-carcinogenic risk, although children are more vulnerable, while arsenic levels in winter approached the upper acceptable carcinogenic limit (up to 1.1×10^{-4}).



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Overall, the study highlights the importance of multi-seasonal monitoring by capturing temporally abrupt contamination events and provides a novel integrated framework that combines seasonal analysis, spatial hotspot identification, and multivariate techniques, distinguishing it from conventional single-season or non-integrated studies.

Keywords: heavy metal contamination; spatio-temporal analysis; seasonal variability; water quality assessment; Principal Component Analysis

1. Introduction

Water resources management is always challenging due to various factors, including climate change, population growth, and increasing pollution levels [1–3]. Although numerous research findings are available and being implemented in practice, much remains to be done to achieve sustainable water resource management. However, the problems experienced today were not as prevalent in the past. Therefore, the solution-seeking process must be upgraded to account for the ongoing acculturation of problems affecting water resources.

Supply of safe drinking water is a fundamental human right and a significant United Nations initiative. This was recognized decades ago; nevertheless, many people still lack access to safe drinking water. This is not only due to ever-increasing demand but also to rising pollution levels. Cities become metropolises while many suburbs become cities. Therefore, the demand for safe drinking water significantly increased [4]. However, increasing urbanization and industrialization, along with contamination of water sources by agents such as pesticides and pharmaceuticals, drive pollution levels.

Water pollution is directly related to human health [5–7]. It can cause both acute infectious diseases [8,9], including Cholera, Hepatitis, and Typhoid, and long-term diseases such as cancers [10], neurological disorders [11], and reproductive issues [12]. Therefore, the direct and indirect health costs are of concern. It is increasing at an alarming rate. Therefore, water is essential to life and closely linked to a country's economic development [13]. Thus, quantitative and qualitative knowledge of water resources, obtained through monitoring, provides information on the possibility of large-scale use [14]. The quality of surface waters and ground waters is deteriorating due to untreated urban wastewater discharges into receiving environments (rivers, etc.), the flow of wastewater from urban landfills, and inputs from industrial and agricultural areas where there is increasing discharge of oil, chemical fertilizers, pesticides, and heavy metals [15–23]. Heavy metal pollution in aquatic environments is a widespread problem worldwide, driven by increased industrialization, urbanization, and agricultural production [24–26]. Of specific interest are metals like Lead (Pb), Mercury (Hg), Cadmium (Cd), and Arsenic (As), which are highly toxic, persistent in the environment, and accumulate and magnify through the food web, which is extremely dangerous to ecological wellbeing and human health [27,28]. Other constituents, such as Copper (Cu), Zinc (Zn), and Iron (Fe), although necessary at low doses, may be toxic at high doses. The environments and mechanisms that transport these contaminants are key to the successful development of environmental management and remediation methods [29–31]. The distribution of heavy metals is not homogeneous; it is a complex mixture of point and non-point sources of pollution, regional geology, and new hydro-climatological conditions [32,33]. Therefore, there is a need to establish large-scale monitoring systems to record the spatial heterogeneity and seasonal variations that cannot be assessed without an inclusive monitoring process. The research paper is a reasonable attempt to investigate heavy metal concentrations at 35 locations, with samples collected in summer, autumn, and

winter. This seasonal way of working is crucial, since the hydrologic cycles and temperature changes, as well as changes in seasons in anthropogenic processes, could greatly affect the speciation of metals, solubility, and transport processes greatly [34]. The heavy metal contamination poses serious threats, but advanced treatment technologies exist for its removal. In addition, the effective application of these methods requires understanding the spatial, seasonal, and speciation patterns of metals in real water bodies. In the present study, the seasonal and site-specific profiles of eight metals (Pb, Hg, Cd, As, Cr (VI), Cu, Zn, Fe) directly inform treatment selection and design for specific contamination scenarios [35–37].

One such case is that in autumn or winter, when rainfall increases, surface runoff can increase, mobilizing pollutants from land sources, whereas in summer, it can be lower, resulting in the accumulation of pollutants [38]. The contamination map will be characterized in detail in this study, and a total of eight metals (Pb, Hg, Cd, As, Cr (VI), Cu, Zn, Fe) will be examined [39].

As part of our ongoing groundwater monitoring program in the Republic of Kosovo, we previously published a study that evaluated groundwater quality using physicochemical and microbiological parameters, Water Quality Index (WQI) models, and multivariate statistical analyses to assess its suitability for drinking purposes and identify the major factors influencing overall water quality [35]. The present study builds directly upon that investigation but addresses a distinctly different research objective. Rather than evaluating general groundwater quality, this study focuses specifically on the spatial and seasonal dynamics of eight priority heavy metals, identifies contamination hotspots using Principal Component Analysis (PCA), and evaluates potential carcinogenic and non-carcinogenic health risks associated with heavy metal exposure. Consequently, the present work complements the previous investigation by providing a detailed assessment of heavy metal contamination and its environmental and public health implications, thereby substantially extending the understanding of groundwater quality in the Republic of Kosovo.

Despite numerous studies on heavy metal contamination, many investigations are limited to single-season assessments or lack integrated spatial and multivariate analyses to identify sources [33,34]. In particular, the combined understanding of seasonal variability, spatial hotspot dynamics, and inter-metal relationships remains insufficient in many regions. Moreover, several studies emphasize that the effectiveness of heavy metal removal technologies such as adsorption, membrane filtration, and advanced oxidation processes strongly depends on the accurate characterization of contaminant distribution, seasonal variability, and source mechanisms [30,31]. However, such integrated information is often lacking in conventional studies. This study addresses these gaps by integrating multi-seasonal sampling with spatial analysis and Principal Component Analysis (PCA) to provide a comprehensive assessment of heavy metal contamination. The approach enables not only the identification of pollution hotspots but also the differentiation between anthropogenic and geogenic sources, thereby offering improved insights into environmental monitoring and management.

Unlike many existing studies and extending our previously published investigation, which assessed groundwater quality using physicochemical, microbiological, and WQI approaches, the present study focuses specifically on the spatial and seasonal dynamics of heavy metal contamination in groundwater. This complementary investigation expands the earlier work by incorporating an extensive heavy metal dataset, multi-seasonal monitoring, multivariate source identification using PCA, spatial hotspot analysis, and human health risk assessment. A key novelty of this study lies in capturing abrupt seasonal contamination events, particularly the pronounced increase in Cd and Hg concentrations during autumn, which are often overlooked in conventional monitoring programs. Furthermore, the integrated evaluation of seasonal variability, spatial hotspot identification, source apportion-

ment, and carcinogenic and non-carcinogenic health risks provides a more comprehensive understanding of groundwater contamination dynamics in the Republic of Kosovo.

The paper is designed to meet four objectives, namely:

1. To measure and describe the concentration of the eight targeted heavy metals.
2. To analyze the spatial distribution of the contaminants for the identification of pollution hotspots.
3. To analyze seasonal variations in metal concentrations and assess the influence of temporal factors on environmental contamination.
4. To examine the relationships among metals using multivariate statistical analysis (PCA) in order to identify potential common sources and hotspot patterns.

2. Materials and Methods

2.1. Study Area

The territory of the Republic of Kosovo is located in the central part of the Balkan Peninsula (Figure 1), between the coordinates $41^{\circ}50'58''$ – $43^{\circ}15'42''$ in latitude, and $20^{\circ}01'02''$ – $21^{\circ}48'02''$ in longitude [40]. It has an area of 10,905.25 km² and a population of 1,586,659.00 [41]. Its catchment area is 11,645 km² and is divided into five river basins that discharge into three seas: the Adriatic, the Black Sea, and the Aegean Sea. Water flows range from 61.7 m³/s (Drini i Bardhë catchment), 36.4 m³/s (Ibri catchment), 10.13 m³/s (Morava e Binçës catchment), 8.4 m³/s (Lepenc catchment) to 5.25 m³/s (Plava catchment) [42]. According to the Ministry of Environment, Spatial Planning, and Infrastructure [43], about 79% of the population has access to the public water supply system, and about 65% to the public sewage system, while the average daily water consumption per capita is reported to be 86.67 L/day [42]. It is characterized by hilly–mountainous relief with elevations ranging from 340 m to 1057 m [44] and a continental climate [45]. The average annual air temperature ranges from 24.6 °C (in summer) to −10 °C (in winter), while the average yearly precipitation is 700 mm [42]. The study area has a complex and diverse geological structure [46,47] and is represented by Paleozoic, Mesozoic, and Quaternary rocks. From a hydrogeological point of view, the carbonate rocks and alluviums [47] that spread on both sides of the river valleys have good hydrogeological properties, allowing groundwater storage. The research was carried out at a network of 35 sampling sites (L1–L35), strategically selected to illustrate a range of potential environmental pressures in the study area (Figure 1). The selection of sampling locations was guided by the need to ensure spatial representativeness of different hydrogeological units, land-use patterns, and potential sources of contamination, including urban, agricultural, and industrial influences. Sites were distributed across the major river basins and groundwater systems to capture both impacted and relatively less-impacted areas. This approach allows for a comprehensive assessment of spatial variability and enhances the reliability of hotspot identification. Furthermore, the use of replicate sampling during key seasons improves the robustness and representativeness of the dataset. The sampling was conducted seasonally to elucidate the temporal dynamics of summer, autumn, and winter. In the summer and winter campaigns, triplicate water samples were collected at each site to obtain robust data and assess intra-site variation. Single samples were collected during the autumn campaign. All samples were placed in pre-cleaned polyethylene bottles, processed according to the standard procedure for heavy metal analysis, and transported to the laboratory under refrigeration.

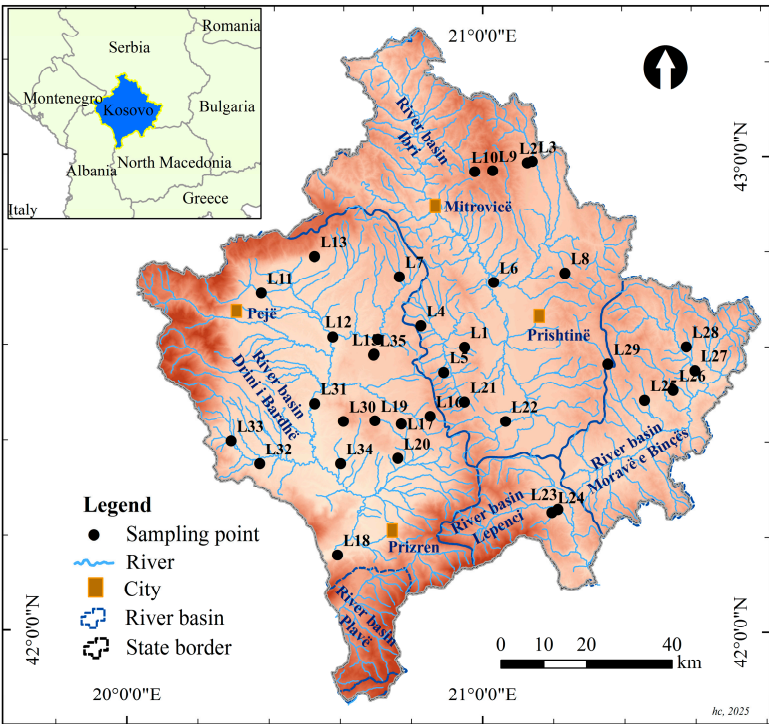


Figure 1. Location map illustrating the spatial distribution of the 35 sampling locations (L1–L35) across the study area.

The study area is the same as that investigated in our previous groundwater quality assessment because it represents an important hydrogeological region requiring continued environmental monitoring. While the earlier study focused on physicochemical and microbiological water quality parameters, the present investigation extends the monitoring program by evaluating seasonal heavy metal contamination, spatial hotspot distribution, and associated human health risks using an expanded sampling network and additional analytical techniques.

2.2. Analysis of Data and Procedures of Analysis

Eight heavy metals, Lead (Pb), Mercury (Hg), Cadmium (Cd), Arsenic (As), Chromium VI (Cr-VI), Copper (Cu), Zinc (Zn), and Iron (Fe) were analyzed by standard laboratory methods, which would have been either Inductively Coupled Plasma Mass Spectrometry (ICP-MS) or Atomic Absorption Spectrometry (AAS), the two methods being susceptible to trace metals [48,49]. All the concentrations are expressed in micrograms per liter (ug/L). The detailed workflow is depicted in Figure 2 and is discussed below:

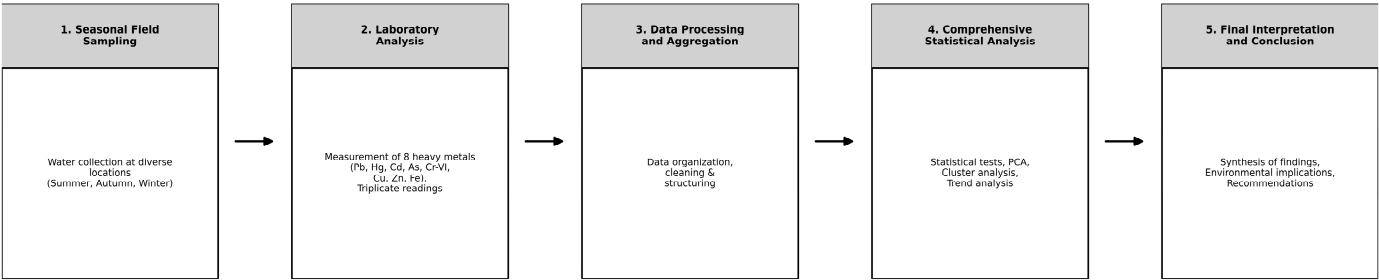


Figure 2. Methodological workflow.

1. Seasonal Field Sampling: It involves the collection of water samples from 35 locations in the summer, autumn, and winter seasons to study the temporal dynamics. All samples were carefully preserved in pre-cleaned polyethylene bottles and refrigerated

during transport to the laboratory to maintain their integrity [50,51]. Table 1 consists of the seasonal schedule information for the Summer, Autumn, and Winter seasons.

Table 1. Seasonal Schedule.

Location	Summer Date	Autumn Date	Winter Date
L1–L5	10 August 2024	8 November 2024	14 January 2025
L6–L10	11 August 2024	9 November 2024	15 January 2025
L11–L15	12 August 2024	10 November 2024	16 January 2025
L16–L20	13 August 2024	11 November 2024	17 January 2025
L21–L25	14 August 2024	12 November 2024	17 January 2025
L26–L30	15 August 2024	13 November 2024	18 January 2025
L31–L35	17 August 2024	15 November 2024	19 January 2025

2. Laboratory Analysis: Water samples were analyzed to study the concentration of eight priority heavy metals using high-sensitivity analytical methods, such as Inductively Coupled Plasma Mass Spectrometry (ICP-MS) or Atomic Absorption Spectrometry (AAS). All the results were standardized and reported in micrograms per liter ($\mu\text{g/L}$) [52].

3. Data Processing and Aggregation: The raw data generated from the laboratory analysis were processed, considering the data cleaning and structuring. Statistical methods, such as the Mean and Standard Deviation, were calculated for the summer and winter seasons. This aggregation process transformed the raw analytical outputs into a structured dataset that is suitable for statistical analysis [53]. The heavy metals concentration in the study area is portrayed in Table 2.

4. Methodology for Carcinogenic and Non carcinogenic risk assessment: For calculating the carcinogenic and non-carcinogenic indices, the average concentrations across three seasons were used. For the assessment of health risk, the USEPA standard exposure parameters were used. For adults, the following were used: IR = 2 L/day, BW = 70 kg, EF = 350 days/year, ED = 30 years, while for children, IR = 1 L/day, BW = 15 kg, EF = 350 days/year, ED = 6 years.

$$CDI = \frac{C \times IR \times EF \times ED}{BW \times At} \quad (1)$$

where

CDI = Chronic daily intake dose, IR = Ingestion rate, C = Concentration of Heavy Metals (HMs), EF = Exposure frequency, ED = Exposure duration and BW = Body weight [54,55].

AT = Average time for non-carcinogenic exposure of 40 years and carcinogenic exposure of 70 years.

The non-carcinogenic risk index, represented by Hazard Quotient (HQ), is calculated using

$$HQ = \frac{CDI}{RfD} \quad (2)$$

Here, RfD is the Oral Reference Dose for HMs. In this equation, for HQ values less than 1, the generated risk will be insignificant and within safe limits. For HQ values greater than 1, the risk level is significant and exceeds the threshold [55].

Carcinogenic risk is calculated only for metals with accepted carcinogenic factors, including Arsenic (As) and Chromium (Cr).

Table 2. Concentration of heavy metals in the study area, average values, standard deviation, minimum, and maximum values.

Site ID	Pb (Sumeer)	Pb (Au-tumn)	Pb (Win-ter)	Hg (Sumeer)	Hg (Au-tumn)	Hg (Win-ter)	Cd (Sumeer)	Cd (Au-tumn)	Cd (Win-ter)	As (Sumeer)	As (Au-tumn)	As (Win-ter)	Cr (Sumeer)	Cr (Au-tumn)	Cr (Win-ter)	Cu (Sumeer)	Cu (Au-tumn)	Cu (Win-ter)	Zn (Sumeer)	Zn (Au-tumn)	Zn (Win-ter)	Fe (Sumeer)	Fe (Au-tumn)	Fe (Win-ter)
L1	0.115	0.27	0.253	0.046	0.18	0.236	0.136	0.27	0.173	0.103	0.9	0.33	0.133	0.24	0.133	29	21	29	45.3	55	45.3	192.6	250	192.6
L2	0.086	0.23	0.17	0.01	0.08	0.136	0.03	0.28	0.29	0.03	0.06	0.23	0.07	0.16	0.106	14.3	11	178.6	33.6	34	188	184.6	197	512.6
L3	0.84	0.46	0.5	0.36	0.3	0.276	0.20	0.8	0.34	0.05	0.08	0.33	0.23	0.32	0.713	49.6	62	24.6	61.6	71	124.3	77.3	87	160
L4	0.096	0.37	0.286	0.013	0.27	0.43	0.05	0.16	0.26	0.08	0.19	0.206	1.196	0.18	1.42	61.3	63	87.6	27.6	25	129	52.6	56	218.3
L5	0.086	0.66	0.48	0.023	0.34	0.476	0.09	0.17	0.173	0.14	0.17	0.416	0.103	0.2	0.753	28.6	50	10	180.6	190	599.6	177	210	628
L6	0.956	0.39	0.316	0.563	0.2	0.23	0.866	1.13	0.2	0.4	0.72	0.33	1.596	1.71	0.253	125.3	260	210.3	581	520	214.6	523.6	631	159
L7	0.136	0.08	0.066	0.126	0.2	0.21	0.143	0.24	0.36	0.01	0.04	0.103	0.743	0.88	0.436	7.33	6	4.33	19	22	21.3	105.3	110	15
L8	1.506	1.27	0.96	0.55	0.41	0.116	1.11	0.33	0.443	0.263	0.36	0.196	0.616	0.75	0.543	210.3	200	18.6	214.6	251	90	159	160	163.6
L9	0.036	0.18	0.17	0.06	0.33	0.25	0.003	0.8	0.11	0.023	0.07	0.373	0.086	0.16	0.246	10	23	438.3	599.6	140	294.3	628	713	380
L10	1.476	0.82	0.843	0.773	0.1	0.12	1.166	1.17	0.61	1.02	1.04	0.08	1.08	1.7	0.706	508	415	10	170.6	139	70.6	191.3	220	68.6
L11	0.056	0.36	0.42	0.06	0.18	0.21	0.006	0.12	0.91	0.076	0.17	0.44	0.066	0.13	0.396	30	21	109.6	56.6	74	94	155	225	116.3
L12	0.31	0.5	0.48	0.14	0.22	0.26	0.533	0.74	0.84	0.29	0.41	0.43	0.42	0.52	0.453	129.3	142	150.6	376	411	90.3	513.6	620	121.6
L13	0.003	0.18	0.153	0.023	0.44	0.23	0.053	0.1	0.34	0.113	0.16	0.24	0.15	0.25	0.426	9.66	6	374	175.3	130	547	344.3	441	546.3
L14	0.483	0.77	0.82	0.296	0.26	0.37	0.326	0.51	0.62	0.356	0.33	0.576	0.136	0.3	0.23	438.3	427	43	294.3	281	35	380	361	59
L15	0.166	0.63	0.71	0.1	0.11	0.23	0.296	0.9	0.206	0.27	0.4	0.55	0.4	0.24	0.21	11	13	45.6	53.33	51	38.6	68.6	80	58.3
L16	0.046	0.19	0.176	0.05	0.08	0.25	0.08	0.15	0.233	0.04	0.2	0.066	0.033	0.08	0.18	10	10	112.6	70.6	64	237.6	68.6	87	291.3
L17	0.186	0.3	0.236	0.166	0.23	0.336	0.143	0.12	0.176	0.096	0.15	0.28	0.073	0.13	0.173	7.66	10	11.3	17.3	21	49.3	31.3	41	37
L18	0.046	0.06	0.046	0.043	0.42	0.156	0.016	0.4	0.163	0.016	0.05	0.136	0.093	0.09	0.173	11.3	13	34	49.3	42	67.6	37	33	63
L19	0.15	0.11	0.14	0.163	0.13	0.33	0.36	0.41	0.39	0.093	0.08	0.04	0.44	0.55	0.25	374	332	28.6	547	633	180.6	546.3	500	177
L20	0.84	1.33	1.223	0.296	0.24	0.433	0.436	1	0.283	0.41	0.8	0.353	0.276	0.31	0.553	178.6	216	14	188	184	33.6	512.6	571	184.6
L21	0.016	0.1	0.166	0.073	0.33	0.313	0.023	0.22	0.18	0.106	0.3	0.133	0.18	0.43	0.303	23.3	30	129.3	37.3	42	376	59.6	64	513.6
L22	0.343	0.19	0.176	0.156	0.42	0.24	0.186	0.27	0.286	0.076	0.11	0.21	0.35	0.52	0.413	149.3	111	19.6	90.3	111	185.6	121.6	140	355
L23	0.696	0.52	0.64	0.25	0.18	0.096	0.186	0.2	0.11	0.183	0.35	0.05	0.613	0.74	0.21	43	60	30	35	41	56.6	59	61	155
L24	0.126	0.31	0.283	0.163	0.09	0.126	0.033	0.41	0.19	0.186	0.17	0.176	0.09	0.09	0.036	4.33	6	420	21.3	12	602.3	15	23	793.3
L25	0.086	0.02	0.023	0.07	0.28	0.066	0.09	0.11	0.05	0.073	0.1	0.04	0.03	1	0.06	19.6	10	62.6	185.6	170	27.6	355	331	52.6
L26	0.14	0.13	0.12	0.04	0.16	0.093	0.183	0.19	0.136	0.143	0.16	0.05	0.453	0.56	0.27	24.66	28	7.33	124.3	130	19	160	170	105.3
L27	0.296	0.43	0.44	0.193	0.31	0.156	0.38	0.56	0.216	0.183	0.22	0.116	0.286	2.5	0.153	141.6	164	9.66	177.3	215	175.3	196.6	172	344.3
L28	0.673	0.33	0.356	0.453	0.53	0.186	1.13	1.8	0.586	0.953	1.25	0.506	1.92	2.3	1.246	257	315	23.3	318.6	351	37.3	413	452	59.6
L29	1.053	1.24	1.613	0.686	1.33	1	0.986	0.92	1.563	0.756	0.88	0.956	0.69	1.11	1.896	420	400	257	602.3	560	318.6	793.3	763	413

Table 2. Cont.

Site ID	Pb (Sumeer)	Pb (Au-tumn)	Pb (Win-ter)	Hg (Sumeer)	Hg (Au-tumn)	Hg (Win-ter)	Cd (Sumeer)	Cd (Au-tumn)	Cd (Win-ter)	As (Sumeer)	As (Au-tumn)	As (Win-ter)	Cr (Sumeer)	Cr (Au-tumn)	Cr (Win-ter)	Cu (Sumeer)	Cu (Au-tumn)	Cu (Win-ter)	Zn (Sumeer)	Zn (Au-tumn)	Zn (Win-ter)	Fe (Sumeer)	Fe (Au-tumn)	Fe (Win-ter)
L30	0.11	1.43	1.356	0.05	0.16	0.876	0.086	0.09	0.44	0.066	0.09	0.52	0.203	0.56	1.043	34	36	116	72	78	149	63	61	221.6
L31	0.046	0.36	0.33	0.023	0.08	0.086	0.106	0.3	0.25	0.143	0.05	0.246	0.03	0.08	0.336	52.3	41	52.3	116.6	115	116.6	120.6	123	120.6
L32	0.356	0.06	0.093	0.34	0.58	0.1	0.233	0.31	0.123	0.173	0.17	0.07	0.11	0.25	0.24	116	100	7.66	149	141	17.3	221.6	218	31.3
L33	0.48	0.16	0.183	10.95	0.33	0.5	0.596	0.74	0.353	0.623	0.94	0.49	0.41	0.52	0.92	112.6	122	49.6	237.6	164	61.6	291.3	270	77.3
L34	0.35	0.24	0.233	0.113	0.56	0.28	0.403	0.46	0.25	0.273	0.32	0.493	0.716	0.85	0.99	87.6	80	508	129	134	170.6	218.3	240	191.3
L35	0.143	0.14	0.293	0.35	0.88	0.69	0.19	0.31	0.353	0.26	0.29	0.406	0.34	0.44	0.563	18.6	21	125.3	90	110	581	163.6	182	523.6
Mean	0.358	0.423	0.421	0.508	0.312	0.288	0.310	0.476	0.348	0.231	0.336	0.291	0.410	0.59	0.486	107.0	109.2	107.2	175.6	163.2	172.7	234.3	253.2	231.7
SD	0.398	0.37	0.37	1.80	0.24	0.20	0.339	0.384	0.284	0.247	0.322	0.20	0.44	0.60	0.41	134.5	127.8	133.8	170.6	155.02	171.5	192.3	204.9	193.4
Min	0.003	0.02	0.023	0.01	0.08	0.06	0.003	0.09	0.05	0.01	0.04	0.04	0.03	0.08	0.036	4.33	6	4.33	17.3	12	17.3	15	23	15
Max	1.506	1.43	1.61	10.9	1.33	1	1.16	1.8	1.563	1.02	1.25	0.95	1.92	2.5	1.89	508	427	508	602.3	633	602.3	793.3	763	793.3

The calculation was made according to the formulas:

$$CR = CDI \times CSF$$

CSF = Cancer slope factor

The amount is calculated by summing the CR values for each chemical substance under study. According to USEPA guidelines, the acceptable CR limit is from 10^{-4} to 10^{-6} . Based on this, CR amounts below 10^{-6} pose insignificant and dismissible carcinogenic risk, while the CR amounts above 10^{-4} is unacceptable [55].

5. Statistical Analysis: Descriptive statistics provided a general overview of the data, whereas the comparative visualizations (boxplots and bar charts) were used to compare metal concentrations across seasons and locations. To explore inter-metal relationships and potential familiar sources, a correlation matrix was generated. Also, PCA was applied to reduce the dataset's dimensionality and visualize the complex relationships among seasons, sampling locations, and heavy metals [56].

6. Interpretation and Conclusion: It involves the synchronization of results from statistical analysis and integration with their broader environmental implications. The results were interpreted using existing pollution science to examine the observed spatial hotspots, seasonal anomalies, and metal groups. It helps to draw evidence-based conclusions about the aquatic environment and provides recommendations for sustainable environmental management.

3. Results and Discussion

The comparative study shows that substantial spatial and temporal variation provides vital information about the aquatic environment. The results of the statistical study, along with their environmental implications, help clarify pollution issues on a larger scale. One limitation of this study is the partial unavailability of autumn data for certain metals (As, Cr (VI), Cu, and Zn). However, complete datasets for summer and winter allow reliable assessment of spatial patterns and overall contamination characteristics, while interpretations of seasonal variability in these metals are made with caution.

3.1. General Concentration Profiles and Seasonal Dynamics

The metals were found to have extremely different concentrations. The most common metals were iron, Zinc, and Copper, which were highest in summer and winter and had a higher mean of 100 µg/L. Conversely, Lead, Mercury, Cadmium (during summer/winter), and Arsenic were at significantly lower concentrations, generally less than 1 µg/L [57]. This overall trend implies a natural occurrence of geogenic or diffuse-source metals (Fe, Zn, Cu) at a base with less significant amounts of more toxic and, in many cases, point-source contaminants [58].

The most remarkable conclusion is a seasonal anomaly characterized by dramatic changes in November (Figures 3 and 4). The mean levels of Cadmium and Mercury were ten times higher in autumn than in summer and winter. This extreme peak can be attributed to seasonal hydrological processes, particularly increased surface runoff and first-flush effects during autumn, which enhance the transport of contaminants from agricultural and industrial areas into groundwater systems. In addition, reduced groundwater storage during the post-monsoon period (October–November) may decrease dilution capacity, leading to higher observed concentrations. Seasonal variations in physicochemical conditions, such as pH and redox potential, may further promote the release and mobilization of metals from sediments [59]. This is well demonstrated using the boxplots in Figure 3, where the distributions of Cd and Hg during the autumn months are completely separated

from the distributions during the summer and winter months, which are concentrated around zero [60]. Here, seasonal monitoring is extremely important; research conducted during summer or winter would have been ineffective in detecting this severe episode of contamination [61].

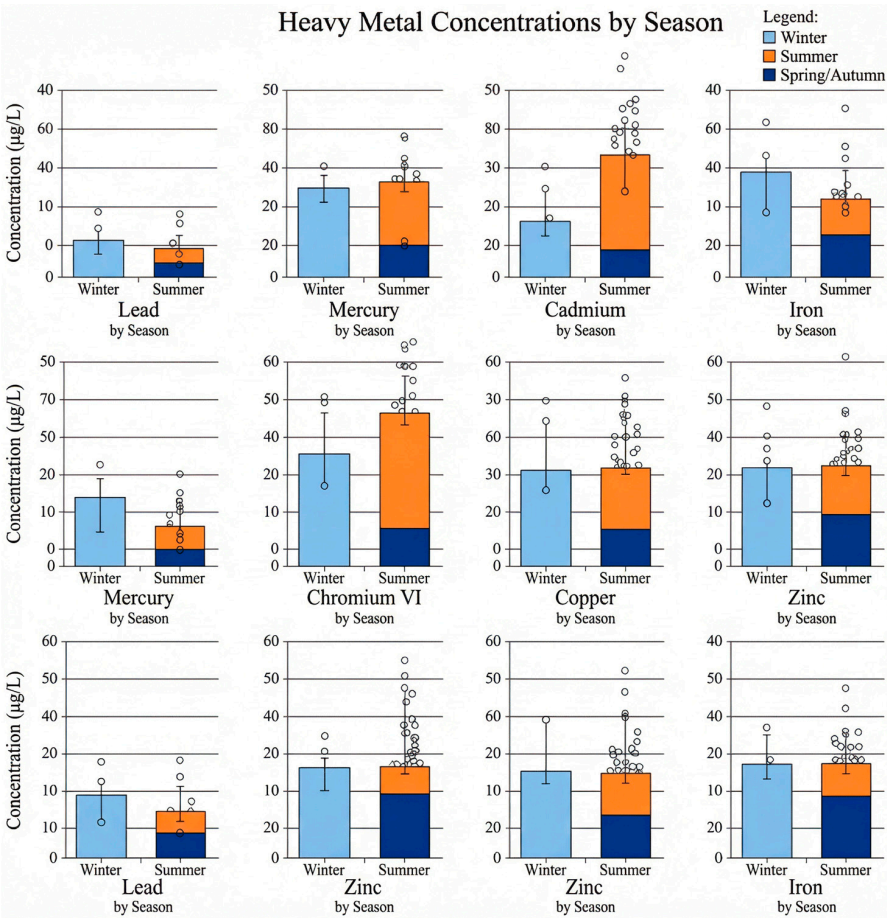


Figure 3. Boxplot comparison of heavy metal concentrations (µg/L) across summer, autumn, and winter.

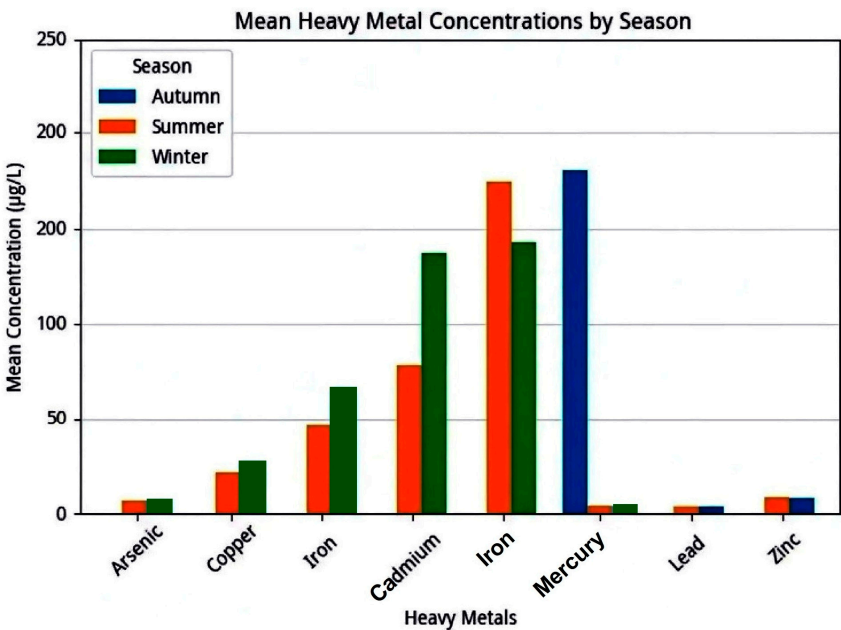


Figure 4. Bar chart of mean heavy metal concentrations by season.

3.2. Spatial Distribution and Hotspot Identification

The main feature of the dataset of all metals was significant spatial variability. Distinct spatial clusters of elevated metal concentrations were observed across the study area. As Figure 5, which displays the concentrations of the three most common metals (Fe, Zn, Cu), indicates, places like L6, L9, L10, L19, L28, and L29 often had the highest concentrations across several seasons. An illustration is at location L29, where Fe, Zn, and Cu had the highest concentrations at 827 µg/L, 692 µg/L, and 451 µg/L, respectively. The consistently high concentrations at specific locations suggest the influence of localized pollution sources, potentially associated with industrial activities, municipal wastewater discharge, or legacy contamination [62]. Figure 6 further breaks down the spatial heterogeneity of four important metals using violin plots, showing not only the median concentration of each element but also the shape of the data distribution at each location. Wides of some locations (e.g., L29 of Zn, L10 of Cu) indicate high variability and extreme values, further confirming that they are hotspots warranting specific investigation and remediation.

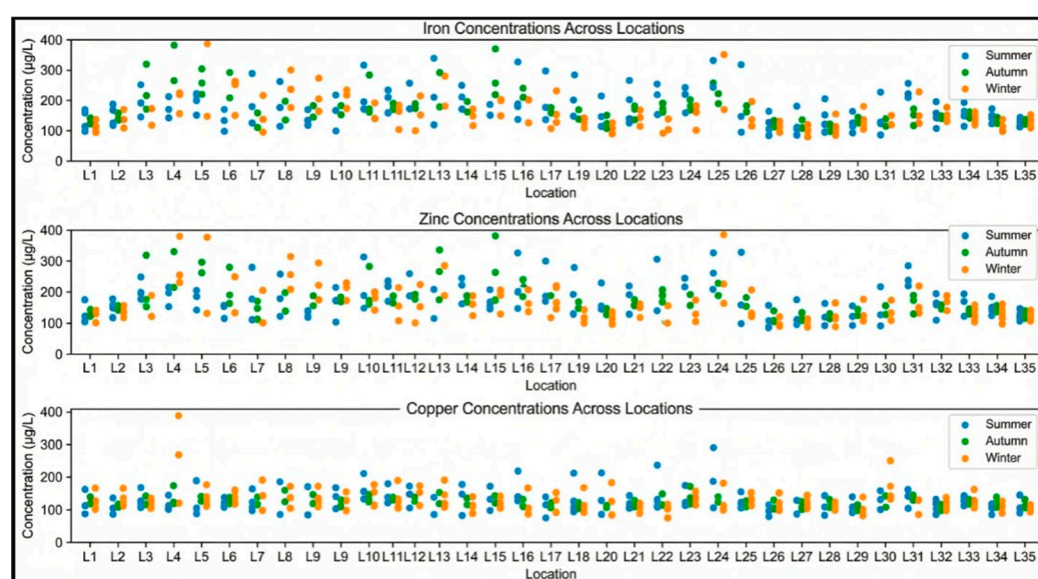


Figure 5. Spatial distribution of high-concentration metals.

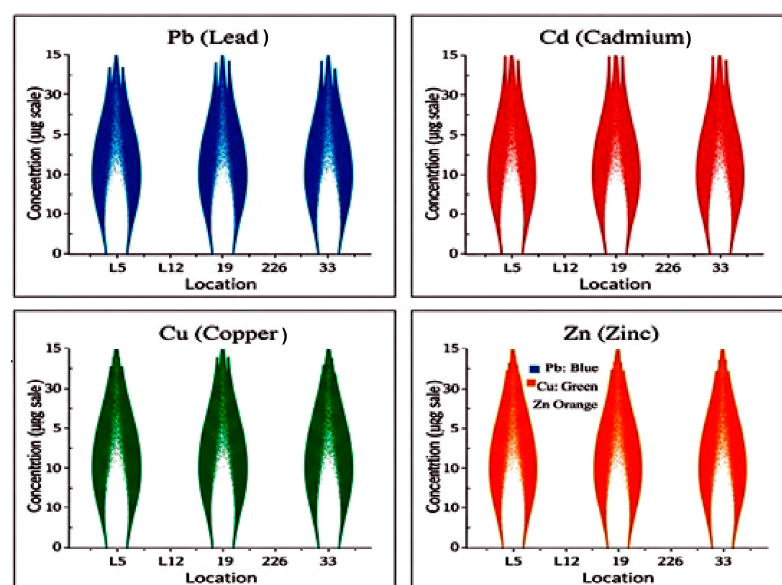


Figure 6. Violin plots showing the distribution of concentrations (log scale) for Pb, Cd, Cu, and Zn at selected high-concentration locations.

3.3. Inter-Metal Relationships and Source Apportionment

A correlation analysis of the summer data, the most complete dataset, was conducted to explore potential sources of contamination (Figure 7). The heatmap indicates several strong positive correlations. For example, there is a significant correlation among Pb, Hg, Cd, and Cr (VI). This pooling suggests that these metals may originate from human activities, such as industrial emissions, mining, or atmospheric deposition associated with fossil fuel combustion [63]. On the other hand, Fe, Zn, and Cu exhibit lower correlations with the former group but show some correlations among themselves, which may reflect another group of sources, perhaps a combination of geogenic weathering and diffuse pollution from urban or agricultural runoff [64].

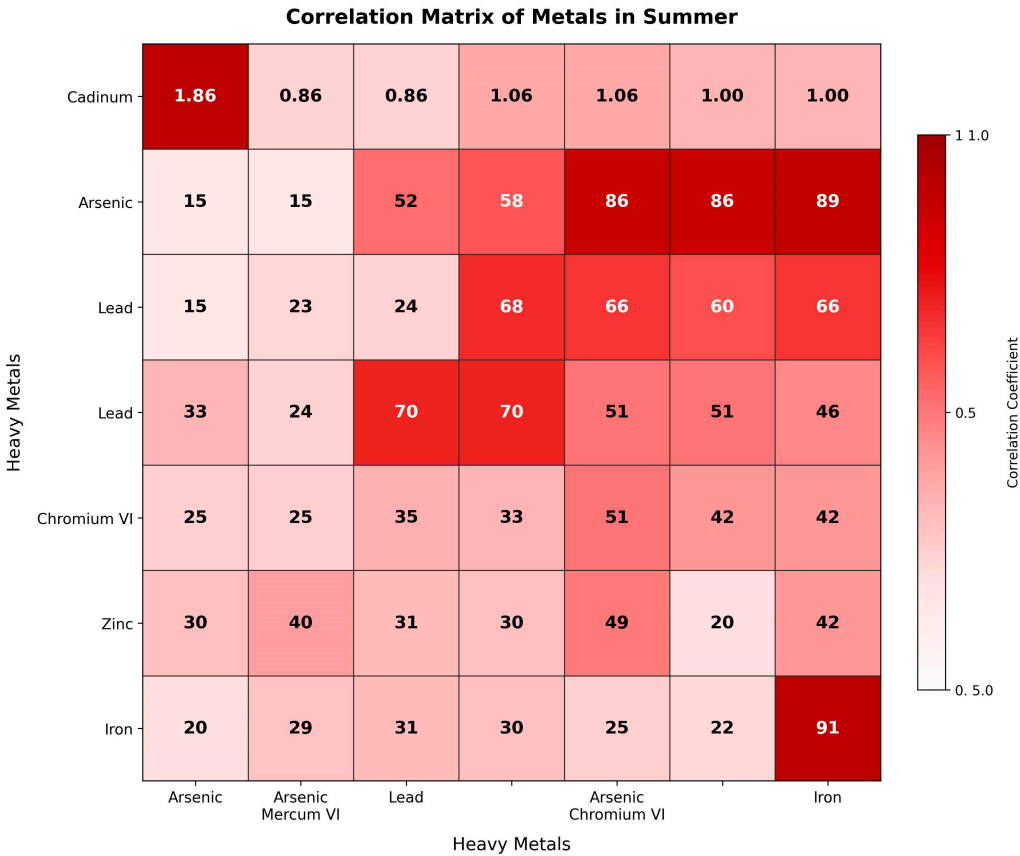


Figure 7. Correlation heatmap.

Principal Component Analysis (PCA), a dimensionality-reduction method in machine learning, was used to further investigate these relationships (Figure 8). The PCA biplot provides an excellent representation of the data. The two major components (PC1 and PC2) had a considerable amount of cumulative variance [65]. The plot shows a clear separation of samples by season, with autumn samples distinct from those of summer and winter, partly due to higher Cd and Hg levels. Moreover, the loading vectors of the metals confirm the correlation analysis: Pb, Cd, Hg, and Cr(VI) are grouped together and point in the same direction, supporting the hypothesis of a standard, probably industrial, origin. Another, looser cluster includes Fe, Zn, and Cu, and implies that they are sensitive to various environmental factors [66].

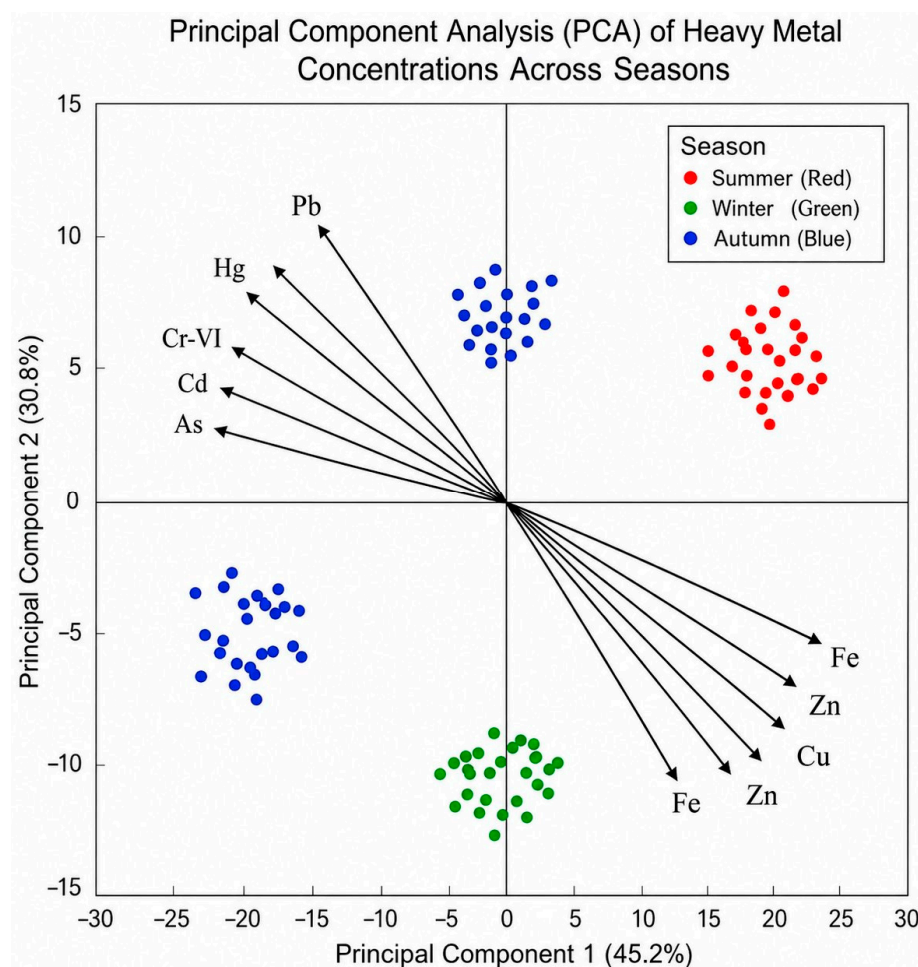


Figure 8. Principal Component Analysis (PCA).

3.4. Implication, Limitations, and Future Work

The study shows that Fe, Zn, and Cu consistently occur at high concentrations. Although these metals are less toxic than others, they may still adversely affect aquatic life. Their elevated levels also indicate continuous and widespread inputs into the river system [53]. The identification of specific hotspots (e.g., L29, L6, L10) is useful for regulatory bodies in allocating investigative and enforcement resources. It is especially significant that the Cd and Hg levels spike in the fall, as these elements are extremely toxic and can even cross the food chain, posing a direct threat to human health when consumed in fish [67]. One limitation of this study is the partial unavailability of autumn data for selected metals (As, Cr (VI), Cu, and Zn). The absence of complete autumn data limits a full seasonal comparison; therefore, conclusions regarding seasonal dynamics are drawn primarily from metals with complete datasets, while interpretations for other metals remain indicative. Nevertheless, the available data provide reliable insights into spatial patterns and overall contamination characteristics. Future studies should ensure complete seasonal datasets to better understand whether the observed autumn anomalies represent broader contamination behavior across all metals [68]. In addition, a more intensive source apportionment study, using either isotopic analysis or receptor modeling, is encouraged to clearly identify the sources of pollution within the identified hotspots. To achieve predictability in water quality management, long-term monitoring is necessary to track trends, assess the effectiveness of adopted mitigation measures, and understand the seasonality of contamination, enabling the development of predictive models [69,70].

3.5. Seasonal Assessment of Heavy Metal Pollution and Human Health Risk from Groundwater Drinking Water

From the assessment of non-carcinogenic risk, the results show that across all three seasons, the general risk index values for adults ranged from 0.174 to 0.271, while for children they ranged from 0.408 to 0.633. These results indicate that the values are below the safety limit ($HI < 1$), and that exposure to heavy metals through groundwater consumption does not pose a significant non-carcinogenic risk. However, higher values of the general risk index (HI) are observed in children than in adults, as children have lower body weight and consume more water relative to body mass. Regarding the hazard quotient (HQ), our results show that copper and arsenic are the largest contributors to non-carcinogenic risk, while other metals contribute only a small portion to the total risk. The non-carcinogenic risk (HQ and HI) and Carcinogenic risk (CR) have been given in Tables 3 and 4 respectively.

Table 3. Assessment of non-carcinogenic risk (HQ and HI) from heavy metals for the three seasons investigated in the studied groundwater drinking water area.

Heavy Metal	Summer		Autumn		Winter	
	HQ (Adult)	HQ (Children)	HQ (Adult)	HQ (Children)	HQ (Adult)	HQ (Children)
Hg	0.046	0.108	0.013	0.031	0.026	0.061
Cd	0.007	0.017	0.010	0.023	0.009	0.021
As	0.107	0.249	0.036	0.084	0.132	0.309
Cr (VI)	0.006	0.014	0.008	0.019	0.007	0.016
Cu	0.073	0.171	0.091	0.213	0.073	0.171
Zn	0.024	0.055	0.016	0.038	0.030	0.070
HI	0.263	0.614	0.174	0.408	0.271	0.633

Table 4. Carcinogenic risk (CR) assessment for the three seasons investigated in the study area for groundwater drinking water.

Season	CR As (Adult)	CR As (Children)	CR Cr (VI) (Adult)	CR Cr (VI) (Children)
Summer	8.7×10^{-5}	4.1×10^{-5}	7.7×10^{-7}	3.6×10^{-7}
Autumn	2.9×10^{-5}	1.4×10^{-5}	5.3×10^{-7}	2.5×10^{-7}
Winter	1.1×10^{-4}	5.0×10^{-5}	9.1×10^{-7}	4.3×10^{-7}

According to the carcinogenic risk index, the risk values for arsenic ranged from 1.4×10^{-5} to 1.1×10^{-4} , while for chromium, they ranged from 2.5×10^{-7} to 9.1×10^{-7} ; all values obtained are within the acceptable ranges according to USEPA recommendations. However, the arsenic values recorded during the winter season, which are close to the upper limit, are of concern, indicating potential long-term concern.

4. Contribution to Sustainable Development Goals (SDGs)

This section discusses the contribution of the current research to the United Nations Sustainable Development Goals (SDGs) (Figure 9). The results offer practical insights into groundwater quality, pollution sources, and health hazards, thereby promoting evidence-based environmental management.

The paper has a direct impact on SDG 6 (Clean Water and Sanitation) by identifying spatial hotspots and seasonal contamination patterns, which can inform targeted monitoring and remediation plans. To illustrate, feedback on high-risk locations (e.g., L6, L10, L29) enables prioritization of treatment interventions and aids in selecting suitable technologies for removing heavy metals. Research has shown that enhanced adsorption-based and composite materials can be successfully used to remove heavy metals and co-contaminants from water, offering efficient and scalable treatment methods [71,72]. In this way, the cur-

rent examination can give a scientific foundation of maximizing such treatment strategies at location-specific scales.

Heavy Metals Research Contribution to Sustainable Development Goals

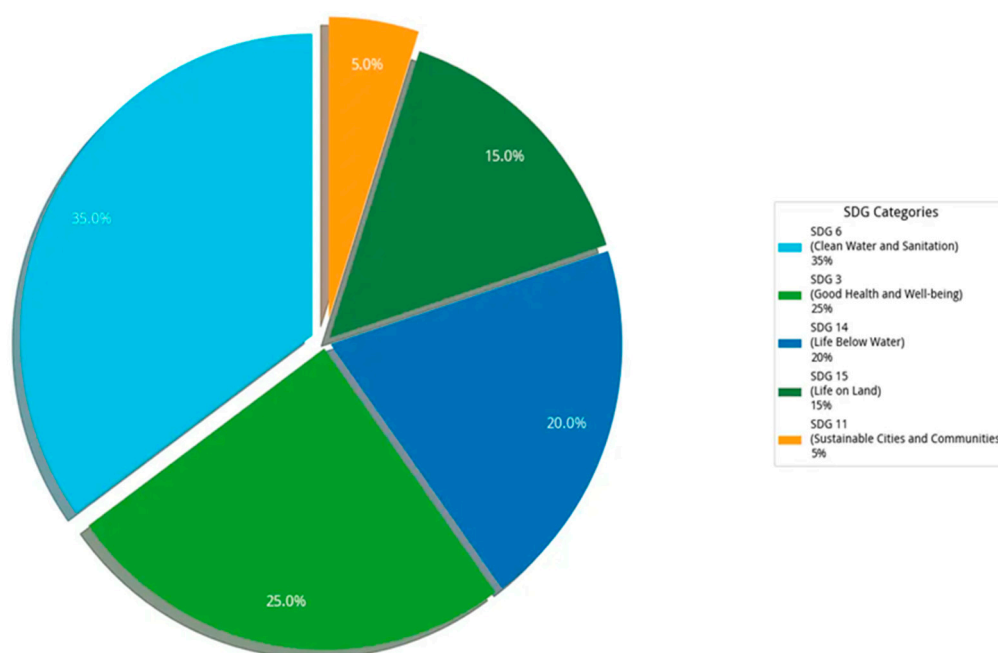


Figure 9. Contribution towards SDGs.

The research also impacts SDG 3 (Good Health and Well-being) by helping evaluate the non-carcinogenic and carcinogenic risks of groundwater intake. The findings, especially the high susceptibility of children and the proximity of arsenic levels to acceptable standards, offer important information for public health planning and safe drinking water management.

Moreover, revealing the seasonal patterns of pollution and contamination hotspots underscores the threat to aquatic life, aligning with SDG 14 (Life Below Water). The research is also relevant to SDG 15 (Life on Land) as it correlates contamination patterns with sources of land-based pollution, thereby providing a basis for regulating runoff and mitigating environmental degradation [73,74].

5. Conclusions

The present study shows widespread chronic contamination, with elevated Fe, Zn, and Cu levels, and identifies persistent high-risk hotspots (L6, L8, L10, L28, and especially L29) where metal concentrations reached extreme values, indicating point-source pollution. A pronounced increase in Cd and Hg concentrations was observed during autumn, indicating a significant seasonal contamination event and highlighting the importance of multi-seasonal monitoring. The PCA results further identified two main groups of metals: Pb, Hg, Cd, and Cr (VI), which are associated with anthropogenic sources, and Fe, Zn, and Cu, which are linked to diffuse or geogenic sources. These findings collectively support the study objectives related to quantification, spatial distribution, and seasonal assessment. It provides evidence-based solutions for decision-makers by establishing a crucial environmental baseline for future assessments and by offering a robust methodological framework that can be applied globally to evaluate and manage heavy metal pollution in river systems.

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References

1. Almulhim, A.I.; Cobbinah, P.B. On Urban Sustainability: Urbanization and Climate Change Collision. *Sustain. Dev.* **2026**, *34*, 979–995. [\[CrossRef\]](#)
2. Makanda, K.; Nzama, S.; Kanyerere, T. Assessing the Role of Water Resources Protection Practice for Sustainable Water Resources Management: A Review. *Water* **2022**, *14*, 3153. [\[CrossRef\]](#)
3. Xia, J.; Dong, Y.; Zou, L. Developing Socio-Hydrology: Research Progress, Opportunities and Challenges. *J. Geogr. Sci.* **2022**, *32*, 2131–2146. [\[CrossRef\]](#)
4. Salehi, M. Global Water Shortage and Potable Water Safety; Today’s Concern and Tomorrow’s Crisis. *Environ. Int.* **2022**, *158*, 106936. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Lin, L.; Yang, H.; Xu, X. Effects of Water Pollution on Human Health and Disease Heterogeneity: A Review. *Front. Environ. Sci.* **2022**, *10*, 880246. [\[CrossRef\]](#)
6. Babuji, P.; Thirumalaisamy, S.; Duraisamy, K.; Periyasamy, G. Human Health Risks Due to Exposure to Water Pollution: A Review. *Water* **2023**, *15*, 2532. [\[CrossRef\]](#)
7. Fida, M.; Li, P.; Wang, Y.; Alam, S.M.K.; Nsabimana, A. Water Contamination and Human Health Risks in Pakistan: A Review. *Expo. Health* **2023**, *15*, 619–639. [\[CrossRef\]](#)
8. Shayo, G.M.; Elimbinzi, E.; Shao, G.N.; Fabian, C. Severity of Waterborne Diseases in Developing Countries and the Effectiveness of Ceramic Filters for Improving Water Quality. *Bull. Natl. Res. Cent.* **2023**, *47*, 113. [\[CrossRef\]](#)
9. Dharwal, M.; Parashar, D.; Shehu Shuaibu, M.; Garba Abdullahi, S.; Abubakar, S.; Baba Bala, B. Water Pollution: Effects on Health and Environment of Dala LGA, Nigeria. *Mater. Today Proc.* **2022**, *49*, 3036–3039. [\[CrossRef\]](#)
10. Asefa, E.M.; Damtew, Y.T.; Ober, J. Pesticide Water Pollution, Human Health Risks, and Regulatory Evaluation: A Nationwide Analysis in Ethiopia. *J. Hazard. Mater.* **2024**, *478*, 135326. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Bochynska, S.; Duszewska, A.; Maciejewska-Jeske, M.; Wrona, M.; Szeliga, A.; Budzik, M.; Szczesnowicz, A.; Bala, G.; Trzcinski, M.; Meczekalski, B.; et al. The Impact of Water Pollution on the Health of Older People. *Maturitas* **2024**, *185*, 107981. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Begum, M.R.; Ehsan, M.; Ehsan, N. Impact of Environmental Pollution on Female Reproduction. *Fertil. Reprod.* **2022**, *4*, 49–57. [\[CrossRef\]](#)
13. Çadraku, H.S.; Selimi, F.; Xhafaj, J. The Institutional and Legal Framework of the Water Sector in Kosovo throughout Different Periods. *Proc. Inst. Civ. Eng. Water Manag.* **2025**, *178*, 143–156. [\[CrossRef\]](#)
14. Çadraku, H. Quantitative and Qualitative Characterization of the Curreli Spring Groundwater, Golesh Massif, Kosovo. *IFAC-PapersOnLine* **2022**, *55*, 36–41. [\[CrossRef\]](#)
15. Abazi, A.M.S.; Durmishi, B.H.; Sallaku, F.S.; Çadraku, H.S.; Fetoshi, O.B.; Ymeri, P.H.; Bytyçi, P.S. Assessment of Water Quality of Sitnica River by Using Water Quality Index (WQI). *Rasayan J. Chem.* **2020**, *13*, 146–159. [\[CrossRef\]](#)
16. Abazi, A.S.; Sallaku, F.; Bytyqi, P.; Spahiu, M.H.; Millaku, F. Heavy Metal Concentrations along the Banks of the Sitnica River and in Four Types of Herbaceous Plants. *J. Ecol. Eng.* **2018**, *19*, 1–9. [\[CrossRef\]](#)
17. Bytyçi, P.; Shala-Abazi, A.; Zhushi-Etemi, F.; Bonifazi, G.; Hyseni-Spahiu, M.; Fetoshi, O.; Çadraku, H.; Feka, F.; Millaku, F. The Macrophyte Indices for Rivers to Assess the Ecological Conditions in the Klina River in the Republic of Kosovo. *Plants* **2022**, *11*, 1469. [\[CrossRef\]](#) [\[PubMed\]](#)

18. Bytyqi, P.; Czikkely, M.; Shala-Abazi, A.; Fetoshi, O.; Ismaili, M.; Hyseni-Spahiu, M.; Ymeri, P.; Kabashi-Kastrati, E.; Millaku, F. Macrophytes as Biological Indicators of Organic Pollution in the Lepenci River Basin in Kosovo. *J. Freshw. Ecol.* **2020**, *35*, 105–121. [\[CrossRef\]](#)
19. Etemi, F.Z.; Bytyçi, P.; Ismaili, M.; Fetoshi, O.; Ymeri, P.; Shala-Abazi, A.; Muja-Bajraktari, N.; Czikkely, M. The Use of Macroinvertebrate Based Biotic Indices and Diversity Indices to Evaluate the Water Quality of Lepenci River Basin in Kosovo. *J. Environ. Sci. Health Part A* **2020**, *55*, 748–758. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Fetoshi, O.; Koto, R.; Sallaku, F.; Çadraku, H.; Rizani, S.; Bytyçi, P.; Nuha, D.; Durin, B.; Durmishi, B.; Haziri, V.; et al. Assessments of Heavy Metal Contaminants in the Drenica River and Bioremediation by *Typha Angustifolia*. *Hydrology* **2024**, *11*, 140. [\[CrossRef\]](#)
21. Demokrati, N.; Hasalliu, R.; Fetoshi, O.; Bytyçi, P.; Bytyçi, A.; Mestani, M.; Durmishi, B.; Blakaj, S.; Kutlllovci Zogaj, D. Assessment of the water quality of wells used for drinking water of Pristina district, Kosovo. *Ecol. Balk.* **2024**, *16*, 87–95.
22. Nuraj, A.; Hasalliu, R.; Bytyçi, P.; Durmishi, B.; Haziri, S.S.; Ajazi, F.; Haziri, V. Application of Water Quality Index for Assessment of Surface Water, Dukagjini Region, Kosovo. *Ecol. Balk.* **2023**, *15*, 68–76.
23. Zhushi Etemi, F.; Çadraku, H.; Bytyçi, A.; Kuçi, T.; Desku, A.; Ymeri, P.; Bytyçi, P. Correlation between Physical and Chemical Parameters of Water and Biotic Indices: The Case Study the White Drin River Basin, Kosovo. *J. Water Land Dev.* **2020**, 229–241. [\[CrossRef\]](#)
24. Aziz, K.H.H.; Mustafa, F.S.; Omer, K.M.; Hama, S.; Hamarawf, R.F.; Rahman, K.O. Heavy Metal Pollution in the Aquatic Environment: Efficient and Low-Cost Removal Approaches to Eliminate Their Toxicity: A Review. *RSC Adv.* **2023**, *13*, 17595–17610. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Bytyçi, P.; Fetoshi, O.; Durmishi, B.; Zhushi-Etemi, F.; Cadraku, H.; Ismaili, M.; Shala-Abazi, A. Status Assessment of Heavy Metals in Water of the Lepenci River Basin, Kosova. *J. Ecol. Eng.* **2018**, *19*, 19–32. [\[CrossRef\]](#)
26. Saravanan, P.; Saravanan, V.; Rajeshkannan, R.; Arnica, G.; Rajasimman, M.; Baskar, G.; Pugazhendhi, A. Comprehensive Review on Toxic Heavy Metals in the Aquatic System: Sources, Identification, Treatment Strategies, and Health Risk Assessment. *Environ. Res.* **2024**, *258*, 119440. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Assey, G.E.; Mogusu, E. Effects of Persistent Organic Pollutants on Environment, Health and Mountains: A Review. *J. Environ. Eng. Sci.* **2024**, *19*, 1–8. [\[CrossRef\]](#)
28. Shekhar, C.; Khosya, R.; Thakur, K.; Mahajan, D.; Kumar, R.; Kumar, S.; Sharma, A.K. A Systematic Review of Pesticide Exposure, Associated Risks, and Long-Term Human Health Impacts. *Toxicol. Rep.* **2024**, *13*, 101840. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Pandey, M.; Thakur, R.R.; Nandi, D.; Bera, D.K.; Beuria, R.; Kumari, M.; Kasawnea, A.M.; Zhran, M. Geospatial Monitoring of Environmental Sustainability: A Remote Sensing-Based Approach for Assessing Mining-Induced Impacts in Eastern India. *Results Eng.* **2025**, *26*, 104692. [\[CrossRef\]](#)
30. Sánchez-Castro, I.; Molina, L.; Prieto-Fernández, M.-Á.; Segura, A. Past, Present and Future Trends in the Remediation of Heavy-Metal Contaminated Soil-Remediation Techniques Applied in Real Soil-Contamination Events. *Heliyon* **2023**, *9*, e16692. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Ugrina, M.; Jurić, A. Current Trends and Future Perspectives in the Remediation of Polluted Water, Soil and Air—A Review. *Processes* **2023**, *11*, 3270. [\[CrossRef\]](#)
32. An, J.; Zha, X.; Wang, H.; Deng, L.; Yang, Y.; Wang, Y.; Di, J.; Zhao, W. Analysis of Influencing Factors of Heavy Metals and Non-Point Source Pollution in Typical Areas of Tethys Himalayan Tectonic Domain. *Water* **2024**, *16*, 291. [\[CrossRef\]](#)
33. Dixit, P.R.; Akhtar, M.S.; Thakur, R.R.; Chattopadhyay, P.; Kar, B.; Bera, D.K.; Chand, S.; Shahid, M.K. Exploring Seasonal Changes in Coastal Water Quality: Multivariate Analysis in Odisha and West Bengal Coast of India. *Water* **2024**, *16*, 2961. [\[CrossRef\]](#)
34. Faurat, A.; Yessimova, D.; Satybaldiyeva, G.; Kuantbayev, A.; Utarbayeva, A.; Kaliyeva, A.; Akhmetov, K.; Khan, S.M.; Ahmad, Z.; Rakhmanov, S. Assessing the Spatial Distribution and Sources of Heavy Metal Pollution in the Snow Cover: A Case Study from Pavlodar, Northeastern Kazakhstan. *PLoS ONE* **2025**, *20*, e0322300. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Zogaj, F.; Blazhevskaya, T.; Sallaku, F.; Thakur, R.R.; Çadraku, H.; Rathnayake, U.; Nandi, D.; Knights, V.; Pavlovskaya, G.; Bytyçi, P.; et al. Assessment of groundwater quality in some regions of Kosovo based on Physico-Chemical and microbiological parameters. *Limnol. Rev.* **2026**, *26*, 16. [\[CrossRef\]](#)
36. Motovilov, Y.G.; Fashchevskaya, T.B. Simulation of Spatially-Distributed Copper Pollution in a Large River Basin Using the ECOMAG-HM Model. *Hydrol. Sci. J.* **2019**, *64*, 739–756. [\[CrossRef\]](#)
37. Namieśnik, J.; Rabajczyk, A. The Speciation and Physico-Chemical Forms of Metals in Surface Waters and Sediments. *Chem. Speciat. Bioavailab.* **2010**, *22*, 1–24. [\[CrossRef\]](#)
38. Erena, S.H.; Worku, H. Dynamics of Land Use Land Cover and Resulting Surface Runoff Management for Environmental Flood Hazard Mitigation: The Case of Dire Daw City, Ethiopia. *J. Hydrol. Reg. Stud.* **2019**, *22*, 100598. [\[CrossRef\]](#)
39. Alam, M.J.; Haque, M.M.; Chowdhury, M.A.Z.; Hossain, M.A.; Khatun, M. Heavy Metals Contamination in Water, Soil, and Fishes of Bangshi River (Bangladesh): A Growing Threat to Aquatic Life and Human Health. *J. Public Health Community Med.* **2025**, *4*, 145. [\[CrossRef\]](#)

40. ISP. *Spatial Plan of Kosovo 2010–2020+*; Institute for Spatial Planning, Ministry of Environment and Spatial Planning: Pristina, Republic of Kosovo, 2010; Volume 1.
41. ReKos. *Regjistrimi i Popullsisë, Ekonomive Familjare Dhe Banesave Në Kosovë 2024 Të Dhënat e Para Finale*; ASK: Pristina, Republic of Kosovo, 2024.
42. AMMK. *Status Report of Water in Kosovo 2020*; AMMK: Pristina, Republic of Kosovo, 2020.
43. MESPI. *Rishikimi i Strategjisë Shtetërore Për Ujëra 2023–2027 Dhe Plani i Veprimet 2023–2025*; Ministry of Environment, Spatial Planning and Infrastructure: Pristina, Kosovo, 2023.
44. KCA. *Geoportal, Topographic Map of Kosovo (Scale 1:25,000)*; Kosovo Cadastral Agency: Pristina, Kosovo, 2025.
45. Pllana, R. *Climate of Kosovo (in Albanian: Klima e Kosovës)*; Kosovo Academy of Sciences and Arts: Pristina, Kosovo, 2015.
46. Elezaj, Z.; Kodra, A. *Geology of Kosovo (Book in Albanian and English)*; Dugagjini: Pristina, Kosovo, 2008.
47. ICM. *Independent Commission for Mines and Minerals*; Geological Map Kosovo, Scale 1:200,000; ICM: Pristina, Kosovo, 2006.
48. Cieřlik, I.; Cieřlik, E.; Cieřlik, I.; Topolska, K.; Szczurowska, K.; Migdał, W.; Gambuř, F. Changes in the Content of Heavy Metals (Pb, Cd, Hg, As, Ni, Cr) in Freshwater Fish after Processing—The Consumer’s Exposure. *J. Elem.* **2017**, *23*, 247–259. [\[CrossRef\]](#)
49. Fajri, P.Y.; Putri, N.E.; Agustina; Desminarti, S. Analysis of Heavy Metals on Various Refilled Drinking Water Depots Circulated in Limapuluh Kota Regency, West Sumatera Province by Inductively Coupled Plasma (ICP) Methods. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1182*, 012065. [\[CrossRef\]](#)
50. Brennan, S.R.; Fernandez, D.P.; Zimmerman, C.E.; Cerling, T.E.; Brown, R.J.; Wooller, M.J. Strontium Isotopes in Otoliths of a Non-Migratory Fish (*Slimy sculpin*): Implications for Provenance Studies. *Geochim. Cosmochim. Acta* **2015**, *149*, 32–45. [\[CrossRef\]](#)
51. Jolaosho, T.L.; Rasaq, M.F.; Omotoye, E.V.; Araomo, O.V.; Adekoya, O.S.; Abolaji, O.Y.; Hungbo, J.J. Microplastics in Freshwater and Marine Ecosystems: Occurrence, Characterization, Sources, Distribution Dynamics, Fate, Transport Processes, Potential Mitigation Strategies, and Policy Interventions. *Ecotoxicol. Environ. Saf.* **2025**, *294*, 118036. [\[CrossRef\]](#) [\[PubMed\]](#)
52. Ni, M.; Yan, S.; Li, T.; Zhou, Z.; Liu, X.; Zhang, S.; Wang, G.; Xu, X.; Pu, Y.; Jia, Y.; et al. Identifying Priority Control Factors for Heavy Metal Pollution in Urban Agricultural Soils of the Chengdu Plain: An Integrated Multi-Model Approach. *Ecotoxicol. Environ. Saf.* **2025**, *303*, 118945. [\[CrossRef\]](#) [\[PubMed\]](#)
53. Sanusi, I.O.; Adepoju, A.A.; Abdulrahman, B.D. Heavy Metal Contamination, Human Health Impact, and Remediation Techniques in Water Bodies: A Review. *Discov. Environ.* **2025**, *3*, 268. [\[CrossRef\]](#)
54. Kaur, L.; Rishi, M.S.; Siddiqui, A.U. Deterministic and Probabilistic Health Risk Assessment Techniques to Evaluate Non-Carcinogenic Human Health Risk (NHHR) Due to Fluoride and Nitrate in Groundwater of Panipat, Haryana, India. *Environ. Pollut.* **2020**, *259*, 113711. [\[CrossRef\]](#) [\[PubMed\]](#)
55. Fallahizadeh, S.; Hosseini Gousheh, S.N.; Hossaini Motlagh, A.; Zarei, M.; Rahimi, N.; Sadat, S.A. Health Risk Assessment of Heavy Metals in Drinking Water Reservoirs of Yasuj Iran Using Monte Carlo Simulation and Sensitivity Analysis. *J. Food Compos. Anal.* **2025**, *148*, 108398. [\[CrossRef\]](#)
56. Madjar, R.M.; Vasile Scăteanu, G. An Overview of Heavy Metal Contamination in Water from Agriculture: Origins, Monitoring, Risks, and Control Measures. *Sustainability* **2025**, *17*, 7368. [\[CrossRef\]](#)
57. Abbas, M.T.; Wadaan, M.A.; Ullah, H.; Farooq, M.; Fozia, F.; Ahmad, I.; Khan, M.F.; Baabbad, A.; Ullah, Z. Bioaccumulation and Mobility of Heavy Metals in the Soil-Plant System and Health Risk Assessment of Vegetables Irrigated by Wastewater. *Sustainability* **2023**, *15*, 15321. [\[CrossRef\]](#)
58. Ziegler Rivera, F.R.A.; Prado Pano, B.; Guédron, S.; Mora Palomino, L.; Ponce de León Hill, C.; Siebe Grabach, C. Impact of the Change in Irrigation Practices from Untreated to Treated Wastewater on the Mobility of Potentially Toxic Elements (PTEs) in Soil Irrigated for Decades. *J. Soils Sediments* **2023**, *23*, 2726–2743. [\[CrossRef\]](#)
59. Zhang, T.; Yu, Y.; Lu, Y.; Tang, H.; Chen, K.; Shi, J.; Ren, Z.; Wu, S.; Xia, D.; Zheng, Y. Bridging Biodegradable Metals and Biodegradable Polymers: A Comprehensive Review of Biodegradable Metal–Organic Frameworks for Biomedical Application. *Prog. Mater. Sci.* **2026**, *155*, 101526. [\[CrossRef\]](#)
60. Ramakrishnaiah, C.R.; Sadashivaiah, C.; Ranganna, G. Assessment of Water Quality Index for the Groundwater in Tumkur Taluk, Karnataka State, India. *J. Chem.* **2009**, *6*, 757424. [\[CrossRef\]](#)
61. Yan, F.; Qiao, D.; Qian, B.; Ma, L.; Xing, X.; Zhang, Y.; Wang, X. Improvement of CCME WQI Using Grey Relational Method. *J. Hydrol.* **2016**, *543*, 316–323. [\[CrossRef\]](#)
62. Singh, B.J.; Chakraborty, A.; Sehgal, R. A Systematic Review of Industrial Wastewater Management: Evaluating Challenges and Enablers. *J. Environ. Manag.* **2023**, *348*, 119230. [\[CrossRef\]](#) [\[PubMed\]](#)
63. Wei, H.; Yu, H.; Zhang, G.; Pan, H.; Lv, C.; Meng, F. Revealing the Correlations between Heavy Metals and Water Quality, with Insight into the Potential Factors and Variations through Canonical Correlation Analysis in an Upstream Tributary. *Ecol. Indic.* **2018**, *90*, 485–493. [\[CrossRef\]](#)
64. Sabat, M.; Jabali, Y.; Millet, M.; Khoury, D. Spatio-Temporal Assessment and Source Identification of Heavy Metals in the Abou Ali River, North Lebanon. *Environ. Chall.* **2025**, *21*, 101349. [\[CrossRef\]](#)

65. Gebeyehu, A.; Hammenhag, C.; Ortiz, R.; Tesfaye, K.; Geleta, M. Characterization of Oilseed Crop Noug (*Guizotia abyssinica*) Using Agro-Morphological Traits. *Agronomy* **2021**, *11*, 1479. [[CrossRef](#)]
66. Hui, K.; Hu, W.; Xi, B.; Yuan, Y.; Lu, H.; Tan, W. Source Analysis of Heavy Metals in Groundwater of Centralized Drinking Water Sources and Seasonal Variations of Health Risks in Wuzhou City, Pearl River Delta, China. *Environ. Chem. Ecotoxicol.* **2026**, *8*, 392–407. [[CrossRef](#)]
67. Saw, S.; Mahato, J.K.; Singh, P.K. Suitability Evaluation of CCME-WQI and GWQI for the Modeling of Groundwater and Human Health Risk Assessment of Heavy Metals—Eastern India. *Resarche Square* **2021**. [[CrossRef](#)] [[PubMed](#)]
68. Gallinat, A.S.; Primack, R.B.; Wagner, D.L. Autumn, the Neglected Season in Climate Change Research. *Trends Ecol. Evol.* **2015**, *30*, 169–176. [[CrossRef](#)] [[PubMed](#)]
69. Barad, S.; Thakur, R.R.; Nandi, D.; Bera, D.K.; Sahu, P.C.; Mishra, P.; Samal, K.P.; Durin, B. Hydrogeochemical and Geospatial Insights into Groundwater Contamination: Fluoride and Nitrate Risks in Western Odisha, India. *Water* **2025**, *17*, 1514. [[CrossRef](#)]
70. Westgarth-Smith, A.R.; Leroy, S.A.G.; Collins, P.E.F.; Harrington, R. Temporal Variations in English Populations of a Forest Insect Pest, the Green Spruce Aphid (*Elatobium abietinum*), Associated with the North Atlantic Oscillation and Global Warming. *Quat. Int.* **2007**, *173–174*, 153–160. [[CrossRef](#)]
71. Yuan, B.; Huang, X.; Yang, S.; Yang, Y.; Lin, Z.; Semiat, R.; Chen, J.P. Development of a magnetic calcium-alginate hydrogel-sphere encapsulated with Fe–Mn–Zr ternary metal composite for heavy metal adsorption. *Sep. Purif. Technol.* **2023**, *306*, 122531. [[CrossRef](#)]
72. You, X.; Liu, M.; Chen, X.; Li, Y.; Yang, Y. Mechanistic insight into the simultaneous removal of Cr (VI) and phosphate by a novel versatile bimetallic material. *J. Environ. Chem. Eng.* **2024**, *12*, 114446. [[CrossRef](#)]
73. Alcamo, J. Water quality and its interlinkages with the Sustainable Development Goals. *Curr. Opin. Environ. Sustain.* **2019**, *36*, 126–140. [[CrossRef](#)]
74. Rajasekar, A.; Wilkinson, S.; Moy, C.K. MICP as a potential sustainable technique to treat or entrap contaminants in the natural environment: A review. *Environ. Sci. Ecotechnol.* **2021**, *6*, 100096. [[CrossRef](#)] [[PubMed](#)]

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