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Pollution assessment and apportionment of toxic elements within urban riverine: Economic implications for rehabilitation

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ABSTRACT

To combat rampant pollution, it is vital to implement approaches that quantify the contributions of various sources to the overall pollution levels, which could enhance comprehension of environmental impacts and formulate effective pollution control strategies. The study implemented an effective strategy to identify pollution sources, assess sediment quality and evaluate potential ecological risks. The sediment and water samples were collected from nine sampling points and subsequently analysed for total concentrations, yielding the following ranges: iron (Fe) 8200–32,167 mg/kg, lead (Pb) 13.9–130 mg/kg, uranium (U) 3.91–6.92 mg/kg, thorium (Th) 2.93–5.50 mg/kg, arsenic (As) 0.66–9.93 mg/kg, cadmium (Cd) <0.01–0.3 mg/kg, and mercury (Hg) <0.01–160 µg/kg. The quantities of toxic elements in water were determined as U (0.08–1.35 µg/L), As (97.2–114 µg/L), Th (0.01–0.48 µg/L), Hg (0.01–0.39 µg/L), and Fe (0.09–1.37 mg/L) and Cd (0.01–0.27 µg/L). The ecological risk index demonstrated low and moderate potential index risk, with the pollution index revealing very high and moderate contamination factors for Pb and U, respectively. A combination of Principal Component Analysis and Positive Matrix Factorization employed for potential source identification revealed atmospheric disposition, gold mining activities, domestic and urban activities waste, agricultural practices, and unidentifiable sources with contributions of 23.9 %, 19.0 %, 18.7 %, 8.1 % and 8.0 %, respectively. The economic advantages of river pollution rehabilitation mandate a balance between ecological integrity and socio-economic constraints to ensure an integrated approach to water management. To reduce long-term health effects, policies should address exposure thresholds and river pollution prevention strategies.

1. Introduction

Riverine environments are critical ecosystems that support biodiversity and provide essential services such as water supply, irrigation, and recreation. Pollutants, such as toxic elements, organic toxins, and other chemicals of emerging concern, are increasingly threatening these freshwater ecosystems. Toxic chemical pollution in river systems is an explicit environmental issue that presents substantial threats to aquatic ecosystems, human health, and overall sustainability that are exacerbated by bioaccumulation and long-term exposure (Hossain et al., 2025). The source, geological setting, and hydrological conditions significantly influence the distribution of these elements. Numerous studies have highlighted that the prevalence of a broader range of hazardous chemicals, including toxic elements, in river sediments and water is often linked to both natural and anthropogenic activities (Hossain et al., 2025; He et al., 2021; Letsoalo et al., 2018). Toxic elements leaching from landfills, abandoned industrial sites, mine tailings and municipal sewage discharges, and agricultural and urban runoff pose substantial ecological and health threats because of their persistence and bioaccumulation potential (Haghighizadeh et al., 2024). Latent capacity to pollute water exists in urban areas in many ways, as the waterways may transport oil and gasoline fumes, tire wear particles, toxic elements, and other pollutants from various sources into freshwater ecosystems (Monney, 2013; Mayer et al., 2024; Jayaneththi et al., 2024). Despite the anthropogenic activities being the primary source, it is also important to consider the natural background levels of these

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elements infiltrating from geological weathering, erosion of rocks, and atmospheric deposition to distinguish between anthropogenic and natural sources. Aquatic systems may distribute toxic elements among suspended particulate matter, with their concentrations often higher in sediments than in the water column (Liu et al., 2024).

Sediments and aquatic environments serve as reservoirs for these elements, which could accumulate over time and present long-term concerns, consequently becoming a major concern for aquatic ecosystems and water quality management (Chiaia et al., 2023; Machado et al., 2024). Mechanical disruptions and bioturbation can release toxic elements linked to bottom sediments into the water column resulting, in water pollution (Ray and Shaju, 2023; Mohajane and Manjoro, 2022). Bioaccumulation and biomagnification of toxic elements pose risks to the sediment-dwelling community, mostly affecting species that provide food for bottom-feeding fish and other aquatic inhabitants through the food chain (Gosar, 2022). Elevated levels of chromium in shellfish from the Buriganga, Turag, and Swat rivers highlighted the bioaccumulation of potentially harmful metals in aquatic species and the related health risks for humans in the food chain (Hossain et al., 2025). The source apportionment of toxic elements in river systems is a key aspect of understanding the origins of pollution, mitigating environmental risks, and ensuring the health of aquatic ecosystems. The identification and quantification of contributions from multiple natural and anthropogenic sources of toxic elements in river streams is a multifaceted process. This process holds significance in formulating efficient strategies for remediation and control of environmental pollution, as well as in comprehending the environmental impact and health risks linked to toxic elements (Zhang and Zhang, 2021). The complexity and variability of identified sources have been highlighted by the use of various methodological approaches, including multivariate statistical analysis, inversion modelling, and chemical speciation to apportion the sources of toxic elements in river systems (Basir et al., 2024; Chrapkiewicz et al.). These methods enable the determination of the proportional contributions from various sources and the comprehension of the spatial distribution of toxic elements across river systems. Using a variety of models and techniques, such as chemical mass balance models, Principal Component Analysis (PCA), and Positive Matrix Factorization (PMF), multivariate analysis has been widely used in pollution source apportionment. These models examine the chemical composition of environmental samples to ascertain pollution sources and their respective contributions (Kumar and Singh, 2018; Kumari and Tripathi, 2014). The PCA statistical technique can reduce data dimensionality by transforming associated variables into a set of orthogonal principal components to identify latent factors (e.g., pollution sources) that explain variations in measured parameters such as toxic elements and other pollutants. By analysing concentration levels of these pollutants, PCA can apportion the contributions of different sources and provide spatial and temporal distribution of pollutants (Zhang and Zhang, 2021). The variability in source contributions across different rivers, streams, and environmental conditions necessitates the use of comprehensive, integrated approaches for effective source identification and risk assessment. Beyond qualitative identification, the versatility of PCA allows for the integration of other models and data types, like isotopic ratios, network topologies, and PMF models, to enhance the accuracy and comprehensiveness of source apportionment as well as unravel complex pollution sources that may arise between natural and anthropogenic factors (Sun et al., 2020; Jiang et al., 2019). It is a widely used receptor model that operates on the principle of mass balance, apportioning the contribution of different sources to observed pollutant concentrations. The model assumes that the concentration of pollutants at a receptor site is a linear combination of source contributions, weighted by their respective source profiles. The modelling's uncertainty estimation enables improved handling of missing values and below-detection (Kim et al., 2024). The PMF model is particularly advantageous because it does not require previous understanding of source profiles, making it a flexible tool for identifying unknown or mixed sources (Liu et al., 2025).

Recognising intricate interactions between natural processes and human activities is essential for assessing ecological risks because it elucidates contamination levels and the potential effects of hazardous components. The evaluation of contamination level and ecological risk is an indispensable feature in this study, accompanied by source apportionment owing to the increasing prevalence of toxic elements in the aquatic environment. Conversely, rehabilitating river pollution has significant economic implications, and its feasibility depends on a comprehensive cost-benefit analysis that considers both market and non-market factors to demonstrate potential positive economic outcomes that can enhance ecosystem services and improve environmental quality. The rehabilitation initiatives are capable of producing considerable financial advantages yet typically encounter limitations such as elevated initial costs, opportunity costs, and potential public opposition due to conflicting interests. This study aimed to assess the potential ecological risk index (PERI) and contamination factor (CF) of selected toxic elements, as well as to identify their potential sources using PCA and PMF models for the strategic management of the heavily polluted Jukskei River. The quantitative amounts of toxic elements such as cadmium (Cd), lead (Pb), mercury (Hg), arsenic (As), iron (Fe), uranium (U), and thorium (Th) in the river water and sediment were determined using inductively coupled plasma-mass spectrometry (ICP-MS) and optical emission spectroscopy (ICP-OES). The levels of these elements were used to determine potential ecological risk assessments (PERI), pollution assessments, and source apportionment investigations. The PERI and CF pollution indices were adopted to reveal the extent and severity of ecological risks and the degree of toxic element contamination. Many studies have been conducted to evaluate the impact of toxic elements on the river health; however, the economic benefits of restoration strategies, such as sediment remediation, pollutant source identification and elimination and ecological rehabilitation, have been disregarded (Hoorzook et al., 2021; Webster and Iqani, 2024; Moeketsi et al., 2022). In contrast to cost of inaction, this research suggests and support the development of cost-effective environmental rehabilitation of the river system strategies. This study object to link environmental science and policy formulation by suggesting for possible strategies for cost of implications for river rehabilitation, identifying pollution sources and guiding economically feasible restoration approaches that improve the river health.

2. Methodology

2.1. Study area

The Jukskei River originates in Ellis Park, Johannesburg, where its primary spring was discovered on the former Doornfontein farm. The spring could produce 18,000 litres per hour; however, it has since vanished because of subsequent urban development. Currently, the original surface appearance of the Jukskei River with a geographical coordinate of 25°52′34″S 27°55′38″E (Fig. 1) is observed in Bertram, where it emerges from a storm drain and passes through industrial, formal and informal residential areas. To ensure a comprehensive and representative assessment of the city's geochemical landscape, the nine sediment and water samples were carefully arranged geographically using a combination of geographic zoning, land use diversity and hydrological significance. There are significant pollution concerns regarding the Jukskei River in Johannesburg, South Africa, which are predominantly attributable to human activities. The river is significantly polluted with a variety of pollutants, such as toxic elements, pesticides, industrial chemicals, and faecal matter, which pose significant risks to the communities that depend on its water (Mukwevho et al., 2024). Industrial activities and urban runoff contribute to the river's pollution, with high concentrations of inorganic chemicals like sulphates, nitrates, and phosphates. These pollutants originate from industrial effluents and urban waste, reflecting the impact of urbanisation on water quality. The pollution is exacerbated by failing infrastructure and inadequate waste

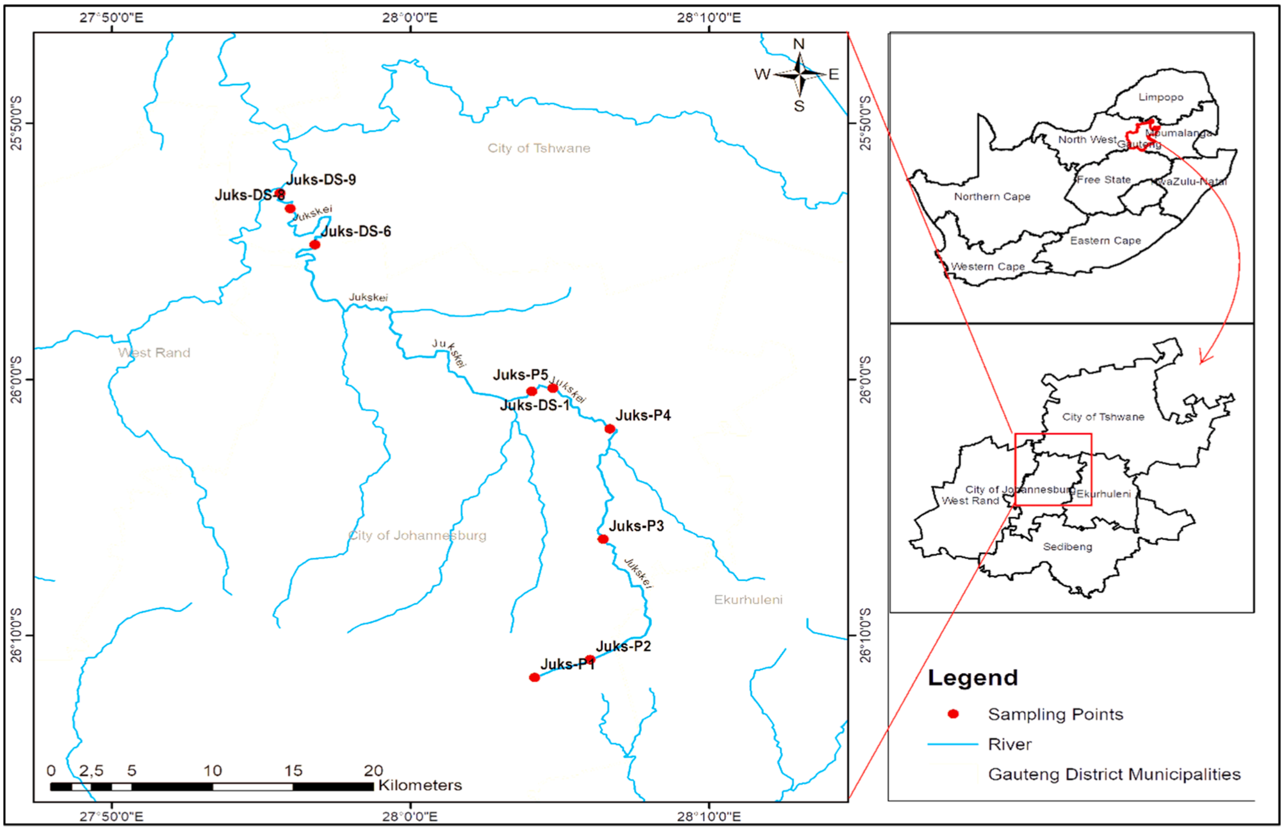


Fig. 1. Sampling points for Jukskei River.

management, reflecting broader systemic issues in governance and urban planning (Hoorzook et al., 2021). For instance, high levels of *Escherichia coli* and other pathogenic bacteria have been detected, exceeding South African water quality guidelines, making the water unsafe for domestic and recreational use. Moreover, toxic elements such as sodium (Na), zinc (Zn), nickel (Ni) and lithium (Li), among others, were notable for surpassing safe levels for domestic and agricultural use (Hoorzook et al., 2021). The organic contaminants, such as organochlorine pesticides and brominated flame retardants, have been reported in the river's water and sediments, with concentrations exceeding recommended safety levels, posing risks to aquatic life and human health (Water, 2008). The continual degrading water quality of the Jukskei River prompted the need for a source apportionment ecological risk assessment of toxic elements to integrate the targeted interventions that are essential to manage and mitigate the impacts of river pollution. The dry season may exacerbate pollution levels due to reduced water flow, less dilution, and increased human activity, enabling more accurate identification of pollution sources. A sampling campaign of the Jukskei River was conducted during the dry season (September 2024), and points were accessed based on convenience sampling as indicated in Fig. 1.

2.2. Sample preparation and analysis

Samples collected from the Jukskei River were treated in the Analytical Chemistry Facility accredited for International Organisation for Standardisation (ISO) 17025, which is a critical standard for testing and calibration laboratories, emphasising competence and reliable results (L. (Chief A. for G. F. and I. 17025 C. L. Huber 2009; Mukwevho et al., 2024). A total of nine sediment and nine water samples were collected from the Jukskei River, labelled as Juks-P1, Juks-P2, Juks-P3, Juks-P4, Juks-P5, Juk-DS-1, Juk-DS-6, Juk-DS-8, and Juk-DS-9. Multi--element standard solutions based on six calibration points were used to determine linearity. The blank samples were used to monitor the carry-over effects whereas the quality control (QC) standard was used to verify accuracy of the method for water analysis. The certified reference materials (CRMs), such as Oreas 751, Oreas 317 and Amis 56, were used for quality assurance (QA/QC). Analytical figures of merit and quality control measures were conducted within the acceptable scope of accreditation. Briefly, water samples were diluted with HNO_3 followed by the addition of an internal standard for analysis using ICP-MS. Sediments were subjected to open flame digestion with appropriate amounts of HNO_3, HF and $HClO_4$, followed by required dilutions prior to analysis using ICP-MS. Pearson coefficient correlation and statistical significance (P-values) determined using Origin Pro Graphing and Analysis software were applied to evaluate the magnitude of the correlation and the significance of the relationship between toxic elements. The degree of correlation was evaluated within the ranges of 1.0–7.0, 0.69–0.4, and 0.39–0.1, suggesting relative correlation is classified as extremely high to strong, moderate, and low to negligible, respectively. The P-value was employed to assess the strength of evidence against the null hypothesis in establishing the significance threshold.

2.3. Contamination factor and ecological risk assessment

The CF (Eqn (1)) is the ratio of the detected amount of toxic metals in the water body's sediment to the metal's pre-industrial reference value (Rahman et al., 2022). The C_i is the amount of toxic elements measured in sediment, and C_r denotes the pre-industrial reference level. The standard pre-industrial reference levels for selected toxic elements were described several researchers (Effects, 2001; Masok et al., 2018; Sojka and Jaskuła, 2022; Cohen and Rutherford, 2011). The PERI assessment of toxic elements pollution in river sediments were evaluated by determining the contamination factor (Eqn (1)), single factor ecological risk index (RI), (E_r^i) and comprehensive ecological RI of toxic elements presented in Eqn (2) and Eqn (3), respectively. The E_r^i and C_f^i values classified in Table 1 were used to evaluate ecological risk in the river system.

$$C_f^i = C_s^i / C_n^i \quad (1)$$

$$E_r^i = T_r^i \text{ x } C^i \quad (2)$$

$$RI = \sum_{(i=i)}^{n} E_r^i \quad (3)$$

C_s^i is the sediment's measured i concentration, the contamination coefficient of element i is denoted by C_f^i, C_n^i is reference concentration of the element of interest, E_r^i is the PERI of I and T_r^i is the toxicity response parameter of I, RI is the potential ecological risk index (Chen et al., 2020; Zhao et al., 2022).

2.4. Source apportionment of selected toxic element pollutants

2.4.1. Principal component analysis

Multivariate statistical analyses, such as PCA and PMF, were employed to apportion pollution sources and associations between concentration levels of toxic elements and sampling points. The XLSTAT Basic software (Addinsoft, Paris, France) was employed to determine factor analysis to achieve dimensionality reduction of the quantity of interconnected variables in a complicated data set (Jollife and Cadima, 2016). The information in the original data was simplified by using variables which are linear combinations of the original variables. Absolute factor loadings over 0.75, between 0.50–0.75, and 0.30–0.50 were categorised as strong, moderate, and light loadings, respectively (Chen et al., 2022).

2.4.2. Positive matrix factorization model

The PMF model was invented by the United States Environmental Protection Agency as a general apportionment modelling tool to distinguish different sources of toxic elements based on its non-negative constraint on the factor score that drives deeper physical meaning (Gugamsetty et al., 2012; Ma et al., 2023). The efficient factorisation capabilities of PMF separated the sample's concentration matrix into factor distribution matrix and factor contribution matrix using the least iterative square approach as presented in Eqn (4) (Current Research in Environmental Sustainability Positive matrix factorization-based receptor modelling of particulate matter in northwest India 2023; Comero et al., 2009). The gik is the contribution of the k^{th} factor to the i^{th} sample, fkj is the concentration of the j^{th} sediment parameter in the k^{th} factor, eij is the residual matrix for each parameter, xij is the sample concentration matrix of n samples and j sediment quality parameters

$$xij = p\Sigma k{=}1 \text{ gik x fkj} + eij \quad (4)$$

The residual error matrix, eij, was obtained by minimizing the object function Q as presented in Eqn (5) (Saha et al., 2022).

$$Q = (eij/\mu ij)^2 \quad (5)$$

The method detection limit (MDL) and standard deviations of the surrogate standards were used to compute μij, the uncertainty in the measurement of xij, in the Eqn (4). The Eqn (6) and Eqn (7) were used to determine the associated uncertainty when a sediment toxic element parameter's concentration is less or equals to method detection limit and c denoted the level of the sediment toxic element parameter whereas σ is the relative standard deviation

$$Unc = 5/6\text{x MDL} \quad (6)$$

$$Unc = ((\sigma + c)2 + 0.5\text{Xmdl})2)^{1/2} \quad (7)$$

Table 1
The connection between pollution levels, potential toxicity index scope, and Potential ecological risk index's range (Zhao et al., 2022).

Potential ecological risk index's range (E_f^i)	The degree of ecological risk associated with single-factor pollution	Potential toxicity index scope (RI)	Total ecological risk
E_f^i <40	low	RI <150	low-level
40≤ E_f^i<80	moderate	150 ≤RI <300	moderate
80≤ E_f^i<160	higher	300≤RI <600	severe
160≤ E_f^i<320	high	600≤RI	Serious
E_f^i≤320	serious		

3. Results and discussion

3.1. Determination of selected toxic elements in the jukskei river

Prior to analysis of water and sediment samples, analytical figures of merit were assessed to ensure validity of the methods. For instance, the calibration curves' correlation coefficients (R^2 values), obtained from six points ranging between 0.995 and 1.005, were acceptable within the standard guideline for method validation (Letsoalo et al., 2021). The obtained percentage relative standard deviation of triplicate sample analysis of less than 10 % and respective recovery rates for QC standard and CRMSs (Table 2) ranging between 95.6–101 % and 96.8–105 % demonstrated reliability of the analytical methods determination of toxic elements in water and sediments samples.

3.1.1. Total quantities of toxic elements in the river water

The amount of toxic elements in water samples as presented in Table 3, were decreasing in the order of Fe > As > Th > *U* > Hg > Hg > Cd > Pb. The alarming As concentration in the range of 97.2 to 114 μg/L were higher than the World Health Organization (WHO) and South African water quality standard guideline of 10 μg/L in the freshwater. A prior study conducted by Mukwevho et al. (Mukwevho et al., 2024) reported the highest As concentration of 21.9 μg/L in the Jukskei River. The accumulating levels of As demonstrate degrading water quality of the river with potential threat to the human health and ecological risks (Teffo et al., 2023). Exposure to water containing high amounts of As can lead to major health issues, including the slow onset of diabetes, malignancies of the bladder, liver, lungs, and skin, as well as respiratory and cardiovascular disorders (Jegen and Jannetto, 2023). Several studies reported variable concentration ranges of As in the river water streams as presented in Table 4, which are lower than As concentrations reported in this study. The Pb were undetected in all sampling sites whereas Cd, Hg, Th, U and Fe were detected in the concentration ranges which are below maximum permissible levels as initiated by WHO and South African water quality standard guidelines (Raji et al., 2021; Frisbie, 2023). Despite low levels of these toxic elements in the water, their presence is of significant environmental concern particularly in areas affected by mining activities. Detected toxic elements have capability to bioaccumulate to significant levels aggravated by intensive anthropogenic activities and environmental conditions which may lead to potential ecotoxicological risks and health impacts. Various chemical processes occurring within river streams such as reduction-oxidation,

Table 2
Recovery rates for quality assurance of methods of analysis.

CRMs	Elements	Certified value	Measured value	% Recovery rate
Oreas 751 (mg/kg)	As	10.3 ± 1.3	10.2 ± 0.17	99.0
	Cd	1.14±0.12	1.16±0.02	102
	Pb	19.2 ± 0.86	18.2 ± 0.66	94.8
	Th	6.07±0.36	6.05±0.04	94.7
	U	6.81±0.49	6.85±0.16	98.1
Oreas 317 (mg/kg)	Hg	6.01±0.67	6.34±0.06	104
Amis 56 (mg/kg)	Fe	70,200± 300	70,814±421	101

Table 3
Toxic element concentrations in river water.

Sample ID	As (μg/L)	Cd (μg/L)	Hg (μg/L)	Pb (μg/L)	Th (μg/L)	U (μg/L)	Fe (mg/L)
Juks- P1	114 ±3.85	<0.01	0.39 ±0.07	<0.01	0.48 ±0.00	1.35 ±0.04	0.56 ±0.00
Juks- P2	104 ±0.66	0.02 ±0.00	<0.01	<0.01	0.05 ±0.01	0.38 ±0.02	0.14 ±0.02
Juks- P3	111 ±4.25	<0.01	<0.01	<0.01	<0.01	0.08 ±0.00	0.09 ±0.02
Juks- P4	108 ±1.79	0.07 ±0.00	<0.01	<0.01	0.14 ±0.01	0.79 ±0.06	0.38 ±0.01
Juks- P5	106 ±3.32	0.27 ±0.00	<0.01	<0.01	<0.01	0.69 ±0.02	0.6 ± 0.01
Juk-DS-1	102 ±2.28	<0.01	0.31 ±0.01	<0.01	0.03 ±0.001	0.59 ±0.06	0.79 ±0.00
Juk-DS-6	97.2 ± 3.72	0.03 ±0.00	<0.01	<0.01	0.17 ±0.001	0.99 ±0.08	0.27 ±0.04
Juk-DS-8	104 ±3.19	<0.01	0.23 ±0.08	<0.01	0.07 ±0.001	0.54 ±0.00	0.23 ±0.03
Juk-DS-9	104 ±2.14	<0.01	0.16 ±0.01	<0.01	<0.01	0.39 ±0.02	1.37 ±0.17

Table 4
Arsenic concentrations in river water around the world.

Study area	Location	As (μg/L)	References
Gomati River Basin	India	1.4–9.6	(Frisbie, 2023)
Boroo river	Mongolia	6.05–6.25	(Zhao et al., 2023)
Mantaro river	Peru	0.70–21.10	(Kloos, 2019)
Lancang River Basin	China	0.93–20.84	(Zhao et al., 2023)
Shiquan Reservoir (inflow)	China	90.0	(Kloos, 2019)
Moira Lake	Canada	22.0–47.0	(Turcotte et al., 2025)
Mono Lake	USA	10,000–20,000	(Hollibaugh et al., 2005)
Madison River	USA	19–67	(Nimick et al., 1998)
Danube River	Romania	0.5–5.88	(Turcotte et al., 2025)
Jukskei River	South Africa	97.2–114	This study

pH, adsorption and desorption may prompt release of these toxic elements from sediments, thus increasing their prevalence in the river water (Letsoalo et al., 2018).

3.1.2. *Quantification of toxic elements in the sediments*

The amounts of toxic elements presented in Table 5 show that the average Pb exceeded the corresponding background concentration of 10 mg/kg in all sampling points, with the highest amount of 130 mg/kg in the upstream, influenced by extensive domestic and industrial activities. The lowest Pb level of 14.2 mg/kg was notable in the downstream area predominated by agricultural activities. The Food and Agriculture Organization (FAO) recommends Pb level of 5 mg/kg in sediment, and the detected amount in this study exceeded the threshold, thus highlighting significant Pb pollution which threatens aquatic and human health (Hossain et al., 2025). Previous studies in the Jukskei River conducted by Mukwevho et al. (Mukwevho et al., 2024) reported Pb levels ranging from 12.6–38.8 mg/kg whereas Wittmann and Forstnert (Wittmann and Forstnert, 1976) detected 556 mg/kg which underscores the history of Pb pollution in the river. The highest Pb level in the Jukskei River is higher than the concentrations reported in the yellow river, China (Liu et al., 2009) and Georges River, Australia (Hacking et al., 2021). The Fe concentrations determined in the range of 8200–32,167 mg/kg are possibly introduced by various sources including weathering and anthropogenic activities like mining, agriculture, and industrial discharges (Isah et al., 2020).The significant concentration of Fe might have impact in the distribution of toxic elements as reported in previous studies (Thalassinos et al., 2023). The Juks-P1 and Juks-P2 show Fe concentrations that are comparable with lowest and severe effect levels of sediment standard guidelines established by the Canadian Council of Ministers of Environment and Ontario Ministry of Environment and Energy organisations (Sediment et al., 2001; August, 1993 1993). The effects of Fe pollution are multifaceted, influencing water quality, sediment composition, and biological communities. The sediment dwelling community exposed to severe effect levels of Fe may be detrimental to the majority of aquatic organisms (Sediment et al., 2001; Thalassinos et al., 2023). As values in the sediment vary from <0.01 mg/kg to 9.93 mg/kg, above the concentration found in the river water. Sediment functions as a repository and archive for toxic metals and metalloids within the river system (Jacob-Tatapu et al., 2021). The solubility and mobility of arsenic in the environment are profoundly affected by geochemical circumstances, especially redox potential (Eh), pH, and the presence of additional ions. These factors influence the translocation of arsenic from sediment to surface water (Meng et al., 2017).

Table 5
Concentration of toxic elements in the river sediments.

Sample ID	As (mg/kg)	Cd (mg/kg)	Hg (μg/kg)	Pb (mg/kg)	Th (mg/kg)	U (mg/kg)	Fe (mg/kg)
Juks-P1	9.93 ±0.05	0.3 ± 0.06	160 ±00	130 ±5.06	4.34 ±0.21	4.81 ±0.33	32,167 ±473
Juks-P2	7.53 ±0.06	0.13 ±0.08	0.04 ±00	38.2 ± 2.82	3.60 ±0.60	4.66 ±0.14	21,133 ±416
Juks-P3	2.27 ±0.26	0.16 ±0.03	0.04 ±00	21.5 ± 0.77	4.06 ±0.33	5.15 ±0.12	14,667 ±723
Juks-P4	0.92 ±0.30	0.14 ±0.03	<0.01	15.7 ± 0.63	3.86 ±0.18	4.01 ±0.15	10,267 ±57
Juks-P5	0.66 ±0.00	0.13 ±0.08	<0.01	19.1 ± 0.72	4.39 ±0.00	6.22 ±0.05	10,633 ±153
Juk-DS-1	3.29 ±0.36	0.13 ±0	<0.01	17.0 ± 0.11	5.50 ±0.16	6.92 ±0.13	14,150 ±353
Juk-DS-6	1.19 ±0.02	0.15 ±0.03	0.04 ±00	14.1 ± 0.00	2.93 ±0.00	4.04 ±0.04	12,333 ±152
Juk-DS-8	0.72 ±0.02	0.19 ±0.03	0.04 ±00	17.7 ± 1.38	3.19 ±0.00	4.28 ±0.03	13,000 ±173
Juk-DS-9	<0.01	<0.01	0.07 ±00	13.9 ± 1.48	3.46 ±0.78	3.91 ±0.28	8200 ±200

The Hg, Cd and As concentrations detected on the sampling points, with the ranges of 0.04–60 μg/kg, 0.04–0.3 mg/kg and 0.66–3.29 mg/kg showed no effect level on sediment quality. However, the As detected particularly on Juks-P1 and Juks-P2, with concentrations of 7.53–9.93 mg/kg exceeding the background value, exhibited lowest effect levels which has minimal effect on the majority of the sediment-dwelling organism. The Hg, Cd and As pollution of river sediments pose significant environmental and health risks requiring a comprehensive understanding of their sources, distribution, and impacts. Sediments can act as reservoirs which could release these pollutants into the water column under certain conditions, such as flooding or human activities resulting with complexity and variability of metal pollution. The Hg predominantly originates from industrial activities, including coal burning and mining, as well as from urbanisation and agricultural activities (Xie et al., 2023) whereas Cd and As mainly sources originate from industrial and agricultural activities, with significant contributions from urban runoff and sewage discharge (Disease and Healthy). Moreover, As often associated with agricultural runoff particularly from areas with intensive farming practices (Xie et al., 2023). Numerous studies have assessed the levels and sources of Hg, Cd and As in different river systems. In the Tigris River, Iraq, Cd and As levels exceeded natural background concentrations in areas influenced by the petroleum industry (Aromatic, 2023). For instance, gold mining activities in Northwest China have been identified as a major source of Hg and Cd contamination in river sediments (Luo et al., 2024). Similarly, urban rivers in Bangladesh, such as the Shitalakshya River, have been found to have elevated levels of Hg and Cd due to industrial effluents (Ahmed et al., 2024).

The Th and U concentrations determined in the range of 3.03–5.50

mg/kg and 3.76–6.92 mg/kg were below and higher than the background concentration values, respectively. The concentrations of Th and U in river sediments have been studied extensively due to their implications for environmental and human health. Studies from different regions have reported varying concentrations in river sediments of which regional variations are significant due to differences in geological settings, anthropogenic and environmental factors. The previous study by Mukwevho et al. (2025) reported respective Th and U in river sediments ranging between 3.14–5.9 mg/kg and 0.93–2.86 mg/kg. The Th and U findings are comparable with other reported studies which highlight the importance of continuous monitoring of radioactive pollution to mitigate the impact on the overall aquatic ecosystem and human health in the river. For instance, In the Ditrău Alkaline Massif, Romania, the concentrations of U and Th in river sediments were found higher than the Upper Continental Crust values, attributed to the presence of Th-and-U bearing minerals while river sediments from the Cananéia-Iguape system in Brazil showed the averaged U and Th concentrations of 2.9 mg/kg and 6.6 mg/kg, respectively (Coțac et al., 2024; Flávio et al., 2019). The geological characteristics of the river basins influenced the activity concentrations of U and Th in sediments in the study reported by Omogunloye et al. (2025). Generally, mining activities and industrial processes influence Th and U concentrations in the river sediments.

3.1.3. Pearson correlation coefficient assessment of toxic elements in sediments

The use of Pearson correlation coefficient and descriptive statistics methods was important to determine the relationships between toxic elements pollution and various parameters in the river system. These statistical tools are instrumental in identifying pollution sources and analysing the spatial distribution of toxic elements. The Pearson correlation coefficient assessed the strength and direction of linear correlations between toxic elements and the coefficient matrix is presented Fig. 2. The extreme to high degree of correlation of 0.856, 0.882, 0.880 and 0.746 was notable for As–Pb, Pb–Hg, Th–U and Cd–Pb respectively with significant correlation indicated by P-value ranging from 0.002 to 0.003, except Cd-Pb ($P = 0.021$) respectively, which demonstrated insignificant correlation. The significant correlation between As–Pb, Pb–Hg and Th–U suggests comparable spatial distribution, with their presence in the Jukskei River attributable to vehicular emissions, urban runoff, wastewater, and industrial effluent, while Th-U is linked to the mine dumps. The moderated correlation of As-Cd ($r = 0.633$) and As–Hg ($r = 0.648$) are statistically negligible yet suggesting potential common source or similar distribution mechanism for these toxic elements.

Table 6 presents descriptive statistics that provide an extensive overview of pollution in river sediments, characterised by the attributes of the heavy metal's dataset, including measures of central tendency and variability. The average quantities of Pb, U and Fe exceeded baseline values, indicating significant pollution enrichment in the river sediment, which poses a substantial hazard to public health and the aquatic ecosystem. The findings in this study were comparable to those of other documented studies. In River Isiukhu, Kenya, notable positive correlations were identified between Zn and Cu concentrations in sediments and benthic macro-invertebrates, with correlation coefficients of $r = 0.655$ and $r = 0.641$, respectively, suggesting a common source or similar behaviour in the environment (Oremo et al., 2019). In the River Nile, Egypt, Zn, Cu, and Pb exhibited positive correlations with physico-chemical parameters, indicating that these metals may be affected by analogous environmental factors or sources (Rashed et al., 2018).

The Olt River in Romania revealed significant positive correlations among several metals, including Pb, Ni, Cu, Cr, and Zn, which were associated with river discharge and anthropogenic activities (Iordache et al., 2022). On the contrary, in the Buriganga River, descriptive statistics indicated that the mean concentrations of several heavy metals exceeded Canadian sediment quality limits, suggesting possible hazards to aquatic organisms and human health (Abdus-Salam et al., 2017). In the Savar industrial region, descriptive statistics indicated that the mean amounts of many heavy metals exceeded WHO and local standards, underscoring the severity of pollution (Ioniță et al., 2024). Although the Pearson correlation coefficient and descriptive statistics have significance for elucidating toxic elements pollution distribution but could not encompass the intricacies of environmental interactions. Multivariate analyses using PCA and PMF approaches were employed in this study to explain the complex relationships among different factors and identify the fundamental sources of pollution.

3.2. Contamination factor and pollution and ecological assessment

The CF is a key metric used to assess the degree of toxic element pollution in sediments, indicating the level of contamination relative to a baseline or background concentration. Evaluating the CF of toxic

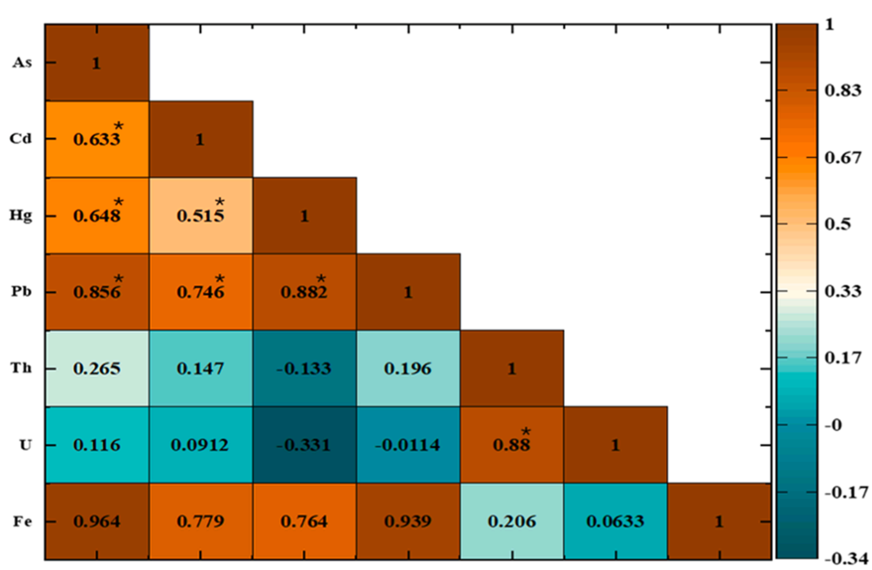


Fig. 2. Correlation matrix of levels of toxic elements in the sediments.
*denotes significant correlation ($p < 0.05$)

Table 6
Descriptive statistics of toxic elements based on Pearson correlation coefficient.

Variables	Dataset						Baseline values (mg/kg) (Sojka and Jaskuła, 2022; Cohen and Rutherford, 2011)
	N	Mean	SD	Sum	Min	Max	
As	9	0.411	0.483	3.7	0	1.38	7.2
Cd	9	0.148	0.0774	1.33	0	0.3	0.5
Hg	9	0.0456	0.04799	0.41	0	0.16	0.02
Pb	9	31.9	37.5	287	13.9	130	10
Th	9	3.92	0.770	35.3	2.93	5.5	7.2
U	9	4.89	1.05	44.0	3.91	6.92	2.67
Fe	9	15,170	7346	136,550	8200	32,167	10 000

elements in Jukskei River sediments is crucial for understanding the extent of pollution and its potential ecological impacts. The boxplot analysis (Fig. 3 inset) statistical tool was used to visualise the distribution and variability of data which useful in assessing pollution levels of heavy metals in the river. As presented in Fig. 3, detected CF values of Cd, As, Pb, Th, and U were ranging from 0.26–0.38, 0.09–1.38, 1.39–13.0, 0.41–0.76, and 1.46–2.59, respectively. The analysis indicated that 11.1 % and 77.8 % of the sampling points exhibited extremely high (> 6), considerable (3 < Cf < 6), and low (CF < 1) contamination levels for Pb while Hg and Cd exhibited negligible CF. This indicates that these elements are affected by both natural sources and human activity, including agricultural runoff and industrial discharges (Safety, 2025). The Pb contamination represented a public health risk because it is employed in various domestic and commercial applications, including the manufacture of paints, corrosion-resistant pipes, automotive batteries, pigments, cable sheathing, weights for lifting and diving, lead crystal glass, radiation shielding, and certain solders (Raj and Das, 2023; Lynch et al., 2018). The analysis revealed that all samplings are classed as moderate (1 ≤ CF < 3), with 22 % and 78 % of the sampling points designated as moderate and low contamination for U, respectively. The CF revealed substantial sediment contamination across upstream to downstream, with Th and U comprising a larger proportion, possibly due to mining activities. The mining impact continues to be apparent in the river stream, as evidenced by prior studies on U pollution in the downstream (Abdelkarim et al., 2022; Grangeon et al., 2023; Raji et al., 2021). The Juks-P1 and Juks-P2 demonstrated moderate CF, whilst other sites exhibited low contamination for As. The moderate CF in the upstream suggests that pollution is likely most severe within the point of pollution source, indicating that the upstream may be the principal source of chemical pollutants. These findings align with prior studies that linked toxic elements pollution to the Modderfontein stream, which traverses near several businesses and serves as a tributary of the Jukskei River (Huizenga and Harmse, 2005; Yüksel and Ustaoğlu, 2025; Zhao et al., 2024).

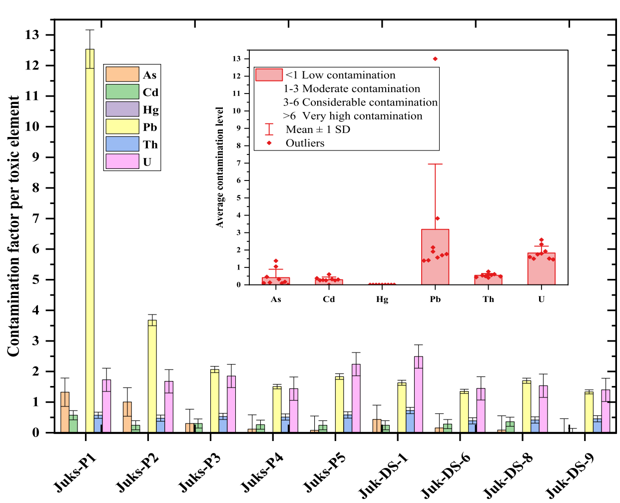


Fig. 3. Contamination factor and boxplot (inset) assessment of toxic elements in sediments.

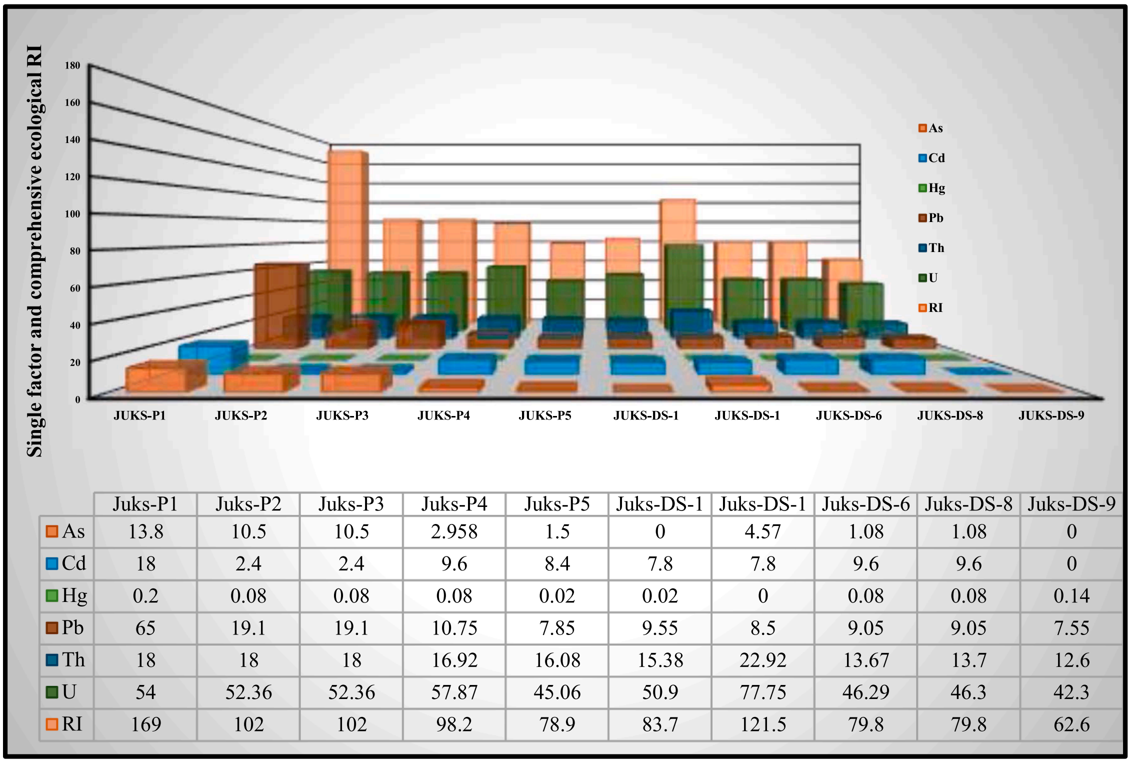
The boxplot analysis (Fig. 3 inset) provided notable information regarding pollution distribution and severity, consequently elucidating the pollution status of the river. The average high CF for lead and moderate CF for U, Th, As and Cd across the upstream, midstream, and downstream regions of the river were illustrated using a boxplot analysis. These findings complement the descriptive statistical analysis of the Pearson correlation coefficient in identifying the spatial distribution trends of these heavy metals in the Jukskei River. To fully understand the sources and impacts of pollution, it was imperative to augment pollution index for assessment CF and boxplot analysis with potential ecological risks, PCA and PMF statistical methods for a comprehensive approach that can inform effective management strategies that protect river ecosystems and public health.

3.2.2. *Assessing the potential ecological risk*

Monitoring the ecological risk of toxic elements in river sediments is vital for identifying their impact on aquatic ecosystems and human health and the PERI was used to predict risk to the river ecosystem (Kars and Dengiz, 2020). Fig. 4 presents the findings from the ecological risk assessment of toxic elements exposure. The potential ecological risk index for toxic elements in the Jukskei River is ranked as follows: Pb > *U* > Th > As > Cd > Hg, in descending order. The sampling site Juks-P1 demonstrates a moderate combined risk index whereas Juks-P2 to Juks-DS-9 exhibited minimal ecological risk. All sampling points exhibited moderate risk for U, while Pb showed moderate risk only at the Juks-P1 sampling point. Pb permeates surface rivers through agricultural practices and urban automobile workshops, accumulating in bottom sediments (Ye et al., 2022; Aguilera et al., 2022). The ecological risk factor for Pb is comparable with that reported in Buriganga River, Dhaka City Bangladesh (Islam et al., 2018), Barong River (Aguilera et al., 2022) as well as lagoon lakes Akgöl and Simenit Rivers in Türkiye (Yüksel and Ustaoğlu, 2025). Prior research demonstrated that toxic elements accumulate within river ecosystems, posing possible risks to the marine environment, a finding that parallels the findings of U in the present study (Pérez-López et al., 2016; Liu et al., 2003). Moreover, toxic elements examined in this work lack biological importance in the sediments; yet, can pose a major health concern to organisms and humans due to their toxicity, persistence, and bioaccumulation potential (Teffo et al., 2023; August, 1993 1993).

3.3. *Source apportionment with principal component analysis*

PCA was employed to apportion the contribution of different sources to the overall pollution of toxic elements in this study by analysing factor loadings. The factor loadings identified 6 principal components that described the variability in the data. The literature indicates that if the initial principal components have variance of over 70 % this suggest that these principal components capture the critical relations in the data set (Bartholomew, 2010; Jollife and Cadima, 2016; Zhang and Castelló, 2017). In the present study the variance for the first three components is 94.65 % which indicate that the first three components are statistically



	Juks-P1	Juks-P2	Juks-P3	Juks-P4	Juks-P5	Juks-DS-1	Juks-DS-1	Juks-DS-6	Juks-DS-8	Juks-DS-9
As	13.8	10.5	10.5	2.958	1.5	0	4.57	1.08	1.08	0
Cd	18	2.4	2.4	9.6	8.4	7.8	7.8	9.6	9.6	0
Hg	0.2	0.08	0.08	0.08	0.02	0.02	0	0.08	0.08	0.14
Pb	65	19.1	19.1	10.75	7.85	9.55	8.5	9.05	9.05	7.55
Th	18	18	18	16.92	16.08	15.38	22.92	13.67	13.7	12.6
U	54	52.36	52.36	57.87	45.06	50.9	77.75	46.29	46.3	42.3
RI	169	102	102	98.2	78.9	83.7	121.5	79.8	79.8	62.6

Fig. 4. Statistical ecological risk assessment of toxic elements in the sediments.

significance and can be used for data interpretation. The PCA results reported in Table 7 and Fig. 5 demonstrate that Factor 1 accounts for 49.069 % of the variance, with an eigenvalue of 2.9, signifying high anthropogenic loading for Pb, As, and Cd, with moderate loading for Hg and Th. The source of these elements might have comparable distribution source based on the Factor 1 characteristics. The distinct features of the study area suggest that contribution of these elements may be linked to pollution from domestic and urban activities wastes, corroborated by prior research that documented As, Cd and Pb contamination linked to urban runoff due use of pesticides, fertilisers, waste from household waste like paints and toys (Seloa and Ngole-Jeme, 2022; Emuze and Hauptfleisch, 2014; Ndhlovu et al., 2024; Massadeh and Snook, 2002). However, Cd concentration was below background values in all sampling points. The Factor 2 exhibited high loading for Th and U, suggesting an anthropogenic origin, given that these elements are primarily associated with mining activities in the studied area (Winde and Sandham, 2004; Matshusa and Makgae, 2017). The gold dumps in the study area present a significant issue, as the measured U concentration from the mine waste dumps was reported to exceed that found in tailings from dedicated for U mining (Id et al., 2019).

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Table 7
Loadings profiles derived from the Principal Component Analysis of toxic elements.

Variables	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
As	0.884	−0.087	−0.353	−0.281	−0.083
Cd	0.740	−0.012	0.668	−0.017	−0.078
Hg	0.544	−0.748	−0.182	0.331	−0.035
Pb	0.934	−0.318	−0.005	−0.032	0.128
Th	0.537	0.820	−0.033	0.088	0.165
U	0.399	0.876	−0.152	0.161	−0.147
Eigenvalue	2.944	2.108	0.627	0.223	0.079
Variability (%)	49.069	35.127	10.457	3.724	1.324
Cumulative %	49.069	84.196	94.653	98.376	99.700

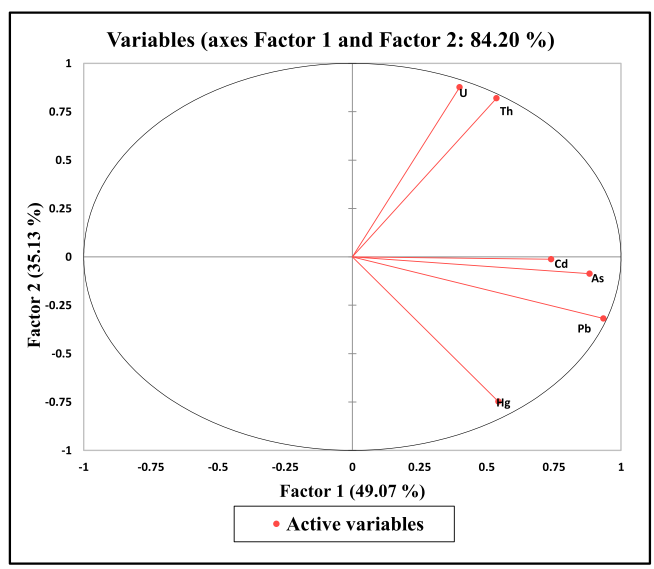

Fig. 5. Principal Component Analysis biplot showing the distribution of toxic elements in sediment samples collected from Jukskei River.

effects and identifying significant features within complicated datasets . (Ogwu et al., 2025) The pattern identified by PCA resembles the Pearson correlation analysis, whereas PMF was employed to further investigate quantitative source allocation, revealing certain features of PCA, including the possibility of mixed or different sources (Chen et al., 2022).

3.4. Source apportionment using positive matrix factorization

The PMF model employed as a complementary tool for confirming the source and contribution of toxic elements revealed by PCA and other statistical analysis. While PMF offers more accurate quantitative contributions from each source, PCA aids in identifying the main sources of pollution, enabling a more thorough understanding of the sources of pollution (Doumbia et al., 2023). The PMF receptor model employed factor analysis after determining the concentration levels and uncertainty data of selected toxic elements. As presented in Fig. 6, PMF model set to three factor solution was identified based on minimum and stable Q-value with most residuals between +3 to −3 range indicating a good fit to the data. Fig. 6(a)–(c) shows the contribution of the three factor components and fingerprints extracted from the PMF Model to the load of each toxic elements which confirmed that the accurate quantification of the respective contributions of individual pollutant sources to toxic elements contamination. Factor 1 exhibits significant contributions of As, Th and U with respective rates of 61 %, 13 % and 19.5 % which could be attributed to the usage in pesticides and fertilisers. It has been reported levels of U and Th are naturally present in phosphate fertilisers, which are made from phosphate rock (Islam et al., 2023). When fertiliser is being made, these elements are usually present in the rock as impurities which can accumulate to toxic levels and pose significant risks when the fertiliser is continuously applied. Even though the concentration of Th and U is often low in the phosphate fertilisers it can however build up in the river sediments over time and could reach undesired quantities. The concentration of U in all sampling points is high than background concentration which indicate that the source maybe anthropogenic. Other studies have raised concerned about the risks of elevated levels of radioactivity in the sediments because of phosphorus-based fertilisers (Mwalongo et al., 2024; Porntepkasemsan et al., 2018).

The Jukskei River traverse the area where farming and landscaping are practiced with possible application of As herbicides and pesticides. As concentration in the upstream is little bit higher than the background concentration which indicate that the source maybe anthropogenic whereas in the downstream the concentration is lower than the background concentration. Factor1 can therefore be associated with agricultural practices. Significant contribution to factor 2 is Cd with 27 %. The concentration of Cd in this study was significantly lower than background value. Due to the Cd significant contribution to Factor 2, This suggests that this Factor 2 may be related to natural processes. Significant contribution to factor 3 is Pb with 37.2 % followed by U with 31.5 % and Cd 28 %. Pb has proven to be a major problem in the environment because it is used many household's products and industrial activities. Pb is utilised in products like some cosmetics and spices, and the sources of Pb pollution are mining, the production of lead-acid batteries, garbage incineration, and industrial activities like smelting (Kloos, 2019; Raj and Das, 2023). Pb has been shown to have significantly accumulated in a number of rivers that receive runoff and groundwater from the Witwatersrand Basin (Atangana and Oberholster, 2021; Oyourou et al., 2019). The concentrations of Pb found in this study was higher that background concentration which means that the source of Pb may be anthropogenic. The are several old gold mine dumps that are scattered in the study area. Toxic elements such as Pb and Cu contaminated dust, ascend to the atmosphere during windy seasons but then deposit on the environmental surface, thus becoming the pollution source (Ebenebe et al., 2018). It can be concluded that Factor 3 represent atmospheric deposition. Previous studies found that U pollution in rivers and plants is impacted by atmospheric disposition (Pourcelot et al., 2015; Raji et al., 2021).

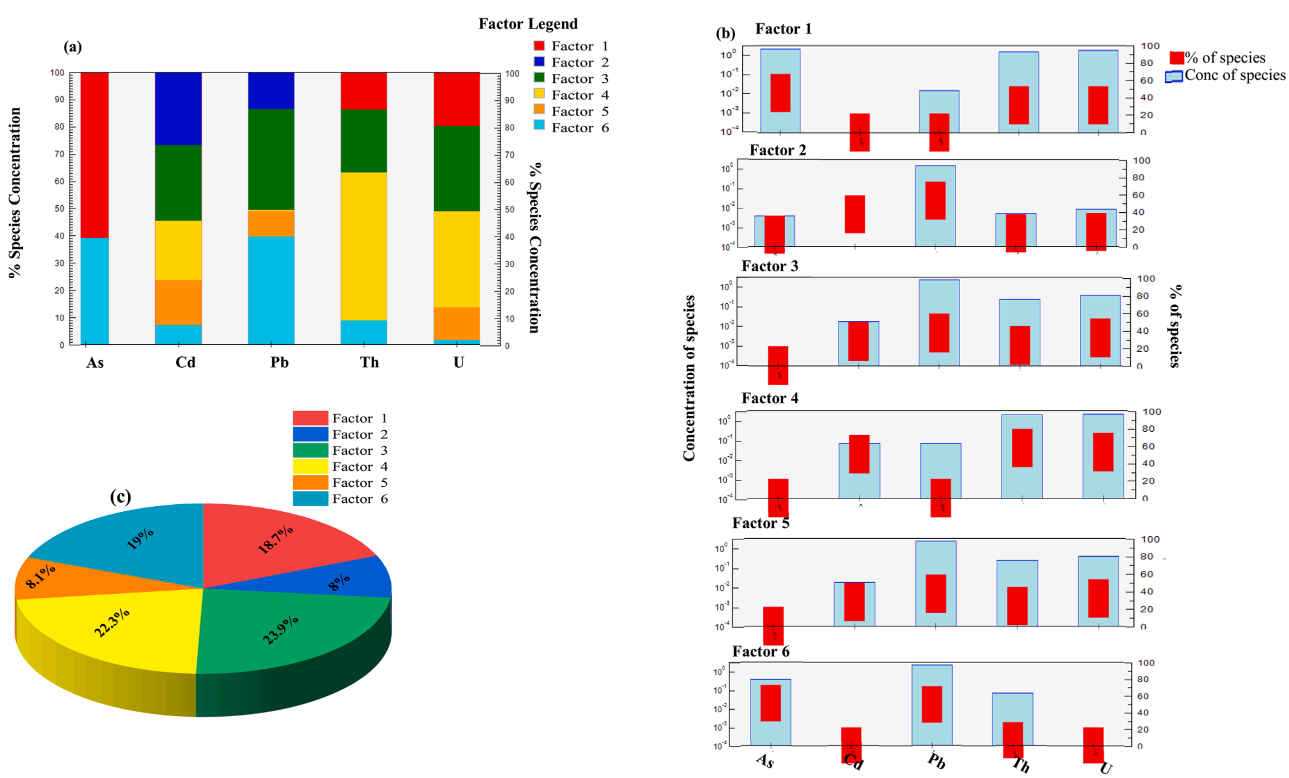

Fig. 6. Positive Matrix Factorization illustrating (a) factor contributions, (b) factor loading plots, and (c) source contributions derived from the model using elemental concentration data.

U and Th contribution rate to Factor 4 was 55 % and 35.1 % respectively, linked with mining activities as confirmed with statistical correlation ($r = 0.880$; $P = 0.002$) and PCA showing similar distribution channels. The impact of mine sites in the proximity of the study area demonstrated high runoff containing Th and U into the water bodies is significant. U is recorded to be significantly high in the study areas and it is higher than the background values which means this factor is associated with anthropogenic activities and the possible source was the legacy of gold mining and seepage of acid mine drainage from abandoned gold shafts. Factor 5 was associated with the accumulation of Cd, Pb and U with contributions 16 %, 9 % and 12.5 % respectively. As mentioned above, the concentration of Cd in the study area was lower than background concentration. The CF for Cd indicated no contamination which means that Factor 5 can described as unidentifiable sources.

Factor 6 is associated with the accumulation of As, Cd, Pb and U with contributions 39 %, 7.5 %, 40 % and 9 %. Insecticides containing Pb and As have contaminated soil, water, and air, endangering the human health and the environment (Ahmed et al., 2021). Because of their toxicity and persistence, they continue to pose a serious environmental risk even though their usage as pesticides is currently limited or prohibited in many nations (DAFF 2017). Factor 6 is linked to domestic and urban activities that significantly contribute to the presence of As and Pb, which can be ascribed to the use of pesticides and other household waste, such as children's toys and the disposal of lead-acid batteries (Kars and Dengiz, 2020). As indicated above there is significant correlation between As-Pb which signify strong probability of similar distribution and similar pollution source. The amount of As in the upstream of the river exceeds the background level, coinciding with a densely populated area that has reported a high incidence of rodent infestation (Ye et al., 2022; Aguilera et al., 2022). This has led to the acquisition of unlicensed pesticides and inadequate refuse disposal, which are contributing to the contamination of river sediment (Ye et al., 2022). Briefly, the river sediment contamination by toxic elements in the study area was mainly impacted by agricultural practices, natural processes, atmospheric disposition, gold mining activities, unidentifiable sources and domestic and urban activities wastes. PMF revealed in Fig. 6(c) that atmospheric disposition has contributed significantly to sediment contamination accounting for 23.9 % followed by gold mining activities at 22.3 %. Domestic and urban activities waste, agricultural practices, unidentifiable sources and natural processes contributed 19.0 %, 18.7 %, 8.1 % and 8 %. The results of the source apportionment indicate that anthropogenic activities are negatively impacting the river system. Two component factors from the PCA are in agreement with Factor 4 and Factor 6 of PMF analysis.

4. Rehabilitation approaches and economic implications

Restoration strategies for river pollution encompass various approaches, ranging from eco-engineered systems to community involvement and regulatory measures. These strategies aim to maintain the ecological balance of river ecosystems and protect human health, which are often disrupted by industrial activities, accidental pollution, and other anthropogenic factors. This study recommends implementation of a combination of natural and engineered remediation technologies and public engagement as effective management practices to address the multifaceted nature of river pollution, considering the diverse array of pollutants. Constructed wetlands, floating islands, and biofilters are examples of eco-engineered systems that use natural processes to treat polluted river water. These systems can be implemented on-site and are effective in removing various pollutants through biological and physical processes (Shaikh et al.). Hybrid integrated treatment systems combine multiple bioremediation technologies to enhance pollutant removal efficiency, offering a comprehensive solution for river pollution. Reservoirs can be employed to store pollutants temporarily or to dilute them by releasing clean water into the river. This is particularly useful in managing accidental pollution events and can be tailored to different flow levels (Mukwevho et al., 2025). Community involvement is crucial in preventing and mitigating river pollution. Educating upstream communities about the impact of their actions on downstream areas can foster better water management practices (Mukwevho et al., 2025). Regulatory measures, including periodic water quality monitoring and enforcement of pollution control laws, are essential for maintaining river health. Companies can be incentivised to comply with regulations through corporate social responsibility programs (Liu et al., 2024).

These strategies offer promising solutions, challenges remain in their implementation considering financial constraints. Despite this study identifying the extent and sources of pollution, it is a critical next step to assess the economic implications of river degradation and the potential benefits of restoration. The economic implications of river pollution rehabilitation are influenced by socio-political and commercial demands and the costs associated with restoration efforts. Regional economic factors frequently determine the success of rehabilitation efforts, with financial incentives occasionally obscuring ecological objectives during the planning and execution of initiatives. The costs of river pollution rehabilitation, which may include direct financial expenditures, economic burdens, and long-term ecological impacts, can be extensive and multidimensional. For instance, economic burden of river pollution can magnify as poor water quality requires costly treatment methods, thus straining local economies. The socio-economic factors driving rehabilitation efforts can impede funding and execution, as popular opinion and political interests could supersede ecological considerations, undermining long-term ecological benefits. To effectively manage river initiatives for restoration and execute informed decisions, it is imperative to understand these expenses.

The future studies should account for economic valuation of river rehabilitation, which could quantify the financial and social costs of pollution and the economic benefits of remediation efforts (Shirmohammadi et al., 2020; Turner et al., 2007). Impact of economic growth in downstream regions is one of the major economic effects of river pollution (Russ et al., 2022). The World Bank reported that declining water quality can impede economic growth and worsen poverty in many nations (Desbureaux et al., 2019), and studies indicate that highly polluted rivers can result in a drop in economic growth (Phys Org 2019; Yang et al., 2024). Investing in river and polluted land restoration is not only an environmental necessity but also an economic opportunity, it has environmental benefits and economic opportunities like tourism and job creation. Even though these strategies show promising outcome, balancing industrial growth and environmental protection remain a challenge that necessitate continuous research and adaptive management for effective long-term solutions.

5. Conclusion

The upstream of the river has exhibited the high CF for Pb and moderate contamination for As. Both the upstream and downstream exhibit moderate contamination factor for U. The downstream revealed low ecological risk while the upstream showed moderate ecological risk. The presence of toxic elements in sediments can lead to bioaccumulation in aquatic organisms, posing risks to the food chain and human health. Additionally, understanding the sources of contamination, whether anthropogenic or natural, is essential for developing effective management and remediation strategies. The regional variability within the river system may have been limited provide comprehensive diagnostic pollution assessment due to the possible accessibility of nine sampling points for sediment and water samples collections. The sampling plan may have neglected seasonal variations and disparities in land usage, thereby compromising the precision of source identification. The absence of comprehensive land-use or hydrological data restricts the capacity to associate geochemical trends with sources. Nonetheless, the co-application of PCA and PMF was used to identify source of sediment contamination. Both methods of source apportionment indicated that

Th-U are the results of mining activities and As-Pb pollution are as the consequences of domestic and urban activities waste. According to PMF, gold mining operations accounted for 22.3 % to the sediment pollution, whereas atmospheric disposition accounted for 23.9 %. Waste from urban and domestic activities, farming methods, unknown sources, and natural processes made up 19.0 %, 18.7 %, 8.1 %, and 8 %, respectively. The combination of source identification models can strengthen strategic actions for river pollution since they reveal significant distribution of pollutions sources. This emphasises the need for policy makers to implement impactful waste management policies that enforce water pollution prevention. A coordinated effort must be undertaken to regulate mine dumps and avert intentional waste disposal into water systems. Economic potential will materialise provided the river and contaminated sediments are rehabilitated. Remediation strategies must be implemented, and policy formulation must align urban river restoration strategies with vulnerable communities.

CRediT authorship contribution statement

Nehemiah Mukwevho: Writing – original draft, Methodology, Investigation. **Mothepane H Mabowa:** Writing – original draft. **Thandukwazi Bungani:** Writing – original draft. **Mothwethwi P Toona:** Writing – review & editing, Resources. **Napo Ntsasa:** Validation, Resources. **Andile Mkhohlakali:** Investigation, Formal analysis. **Thembakazi Ncedo:** Writing – original draft, Investigation, Conceptualization. **Luke Chimuka:** Supervision, Conceptualization. **James Tshilongo:** Writing – review & editing, Supervision, Funding acquisition. **Heidi Richards:** Writing – review & editing, Resources. **Mokgehle R Letsoalo:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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