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Assessment of Trace Elements and Fluoride Contamination in Kabul River: A Comparative Study Across Different Sites

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ABSTRACT

Purpose: This study assesses the concentrations of iron (Fe), fluoride (Fl), zinc (Zn), and copper (Cu) in water and sediment from three sites along the Kabul River: Attock, Nowshera, and Warsak Dam.

Methods: Water and sediment samples were collected over four months (April–July 2024) and analyzed using Atomic Absorption Spectrophotometry (AAS) for trace metals and Ion-Selective Electrode (ISE) for fluoride.

Results: Results show that Fe concentrations in water exceed WHO limits at all sites, with Nowshera having the highest Fe levels (125.28 mg/L), followed by Attock (100.58 mg/L) and Warsak Dam (90.64 mg/L). In sediment, Warsak Dam exhibits the highest Fe accumulation (192.18 mg/kg). Fl in water remains within safe limits, but sediment at Warsak Dam records the highest Fl levels (4.415 mg/kg). Zn concentrations in water remain below WHO thresholds, while sediment Zn accumulation is highest at Warsak Dam (6.891 mg/kg). Cu contamination is a major concern, with Warsak Dam's water showing the highest Cu level (3.06 mg/L), surpassing the WHO limit of 1.3 mg/L. In sediment, Cu exceeds the USEPA safe limit (0.2 mg/kg) at all sites, peaking in Nowshera (1.965 mg/kg).

Conclusions: These findings indicate significant Fe and Cu contamination in Nowshera and Warsak Dam, necessitating urgent water quality management interventions.

Key-words: fluoride toxicity; trace metals; water; sediment; Kabul River

INTRODUCTION

Rivers are crucial for sustaining ecological balance, preserving biodiversity, and supplying essential water resources for both human consumption and agricultural activities [1, 2]. However, increasing industrialization, urbanization, and agricultural runoff have led to the contamination of many river systems worldwide [3, 4]. The Kabul River, a major water body in Pakistan and Afghanistan is facing significant environmental threats due to the discharge of pollutants, including trace elements and fluoride [5]. The presence of heavy metals and fluoride in river water leads to significant contamination, posing severe threats to aquatic ecosystems, water quality, and human well-being [1]. These pollutants can accumulate in aquatic organisms, disrupt ecological balance, and deteriorate water resources, ultimately affecting both biodiversity and public health [6, 7]. Trace elements such as iron (Fe), zinc (Zn), and copper (Cu) are naturally present in aquatic ecosystems, but their elevated concentrations due to anthropogenic activities can lead to toxic effects [8]. Similarly, fluoride (F^-), while essential in small amounts, can cause adverse health effects when present in excessive concentrations [9]. Excess fluoride in drinking water is associated with skeletal and dental fluorosis [10], while heavy metals like iron, copper, and zinc can disrupt aquatic ecosystems and affect water usability [1, 11]. Understanding the distribution and concentration of these elements in river water is essential for assessing the extent of contamination and its potential impacts. The Kabul River, which serves as a critical water source for irrigation, domestic consumption, and industrial use, has been subjected to increased pollution due to untreated industrial effluents, municipal sewage, and agricultural runoff. Various studies have reported heavy metal pollution in major rivers worldwide, but comprehensive assessments of trace elements and fluoride contamination in the Kabul River remain limited. Therefore, this study aims to bridge this knowledge gap by evaluating the levels of Fe, Zn, Cu, and F^- in different sites along the river.

MATERIAL AND METHODS

Study area and sampling sites

The study was conducted along the Kabul River (Figure 1), a vital transboundary water body that flows through Afghanistan and Pakistan. It serves as a crucial resource for domestic, agricultural, and industrial activities; however, rapid urbanization and industrial expansion have significantly degraded its water quality. Three key sites were selected for this study: Attock district (Site 1), Nowshera (Site 2) and Warsak Dam (Site 3) each representing different environmental conditions and pollution sources. Attock district, where the Kabul River merges with the Indus River, faces contamination from upstream sources. Industrial activities, brick kilns, and petroleum industries in the region add to pollution, exacerbated by the region's arid climate and high summer temperatures exceeding 45°C. Across all sites, industrial discharge, domestic wastewater, and excessive agricultural practices have led to increased levels of contamination in the river. Nowshera, a rapidly urbanizing and industrial hub, experiences high pollution from textile, chemical, and metal industries. Untreated industrial effluents, along with municipal sewage and agricultural runoff, contribute to heavy metal contamination. The area has a humid subtropical climate with moderate rainfall, and seasonal flooding further disperses pollutants. Warsak Dam, located near Peshawar, is a major hydroelectric project. While it supports irrigation and energy production, it is increasingly affected by urban runoff, untreated sewage, and agricultural inputs. The semi-arid climate of the region, with summer temperatures reaching 40°C and mild winters, influences the accumulation of pollutants in the water and sediments.

Sampling

In this study, water and sediment samples were collected over a four-month period, from April to July 2024, at three distinct sites. April to July was chosen as the sampling period because these months are critical for pollution levels due to specific weather patterns and agricultural activities. Sampling was conducted only on non-rainy days to maintain consistency. A total of 30 water samples and 30 sediment samples were gathered from each site, resulting in 90 water samples and 90 sediment samples overall. A 1-liter water sample was carefully collected in a pre-sterilized glass bottle and appropriately labeled. The water sample was then promptly transported to the laboratory for further analysis. Sediment samples were collected using a plastic spade by carefully scooping material from the upper 3–5 cm layer [1]. These samples represented recent deposits and were obtained from areas with low flow rates, maintaining a water depth of around 50 cm. The collected sediment samples were then transported to the laboratory for further analysis.

Sample preparation and analysis

Water samples were filtered through Whatman No. 42 filter paper to remove suspended particles. The filtered samples were then stored in acid-washed polyethylene bottles at 4°C until analysis. Sediment samples were air-dried at room temperature, ground using a mortar and pestle, and sieved through a 2-mm mesh to obtain a fine, homogenous powder. The processed sediment was stored in airtight containers under cool, dark conditions to minimize contamination and loss of volatile components. Acid-digested water samples were analyzed using Atomic Absorption Spectrophotometer (AAS: Shimadzu AA-7000). A calibration curve was prepared using standard solutions of Fe, Zn, and Cu. The absorbance values of the samples were compared against the calibration standards to determine metal concentrations [4]. Sediment samples were digested using an acid mixture (HNO_3, $HClO_4$, and HF) in a microwave digestion system. The digested solution was filtered and analyzed for Fe, Zn, and Cu concentrations using AAS. Fl levels in water samples were measured using an Ion-Selective Electrode (ISE). The electrode was calibrated with fluoride standard solutions, and sample readings were taken under controlled conditions. Fluoride was extracted from sediment using an alkaline fusion technique, followed by measurement with an Ion-Selective Electrode (ISE). To ensure accuracy and reliability, quality assurance (QA) and quality control (QC) procedures included instrument calibration using certified standard solutions, procedural blanks to detect contamination, and the analysis of standard reference materials for method validation. All measurements were performed in triplicate, and replicate analyses ensured precision. Spike recovery tests were conducted to assess digestion and extraction efficiency, with acceptable recovery rates (85–115%). Instrument performance was monitored through quality control standards and calibration checks. Data validation involved statistical analysis and comparison with established guidelines to confirm result consistency.

Data analysis

A one-way ANOVA with multiple comparison tests was used to compare heavy metal concentrations across different sampling regions in the study. All statistical analyses were performed using GraphPad Prism 10.

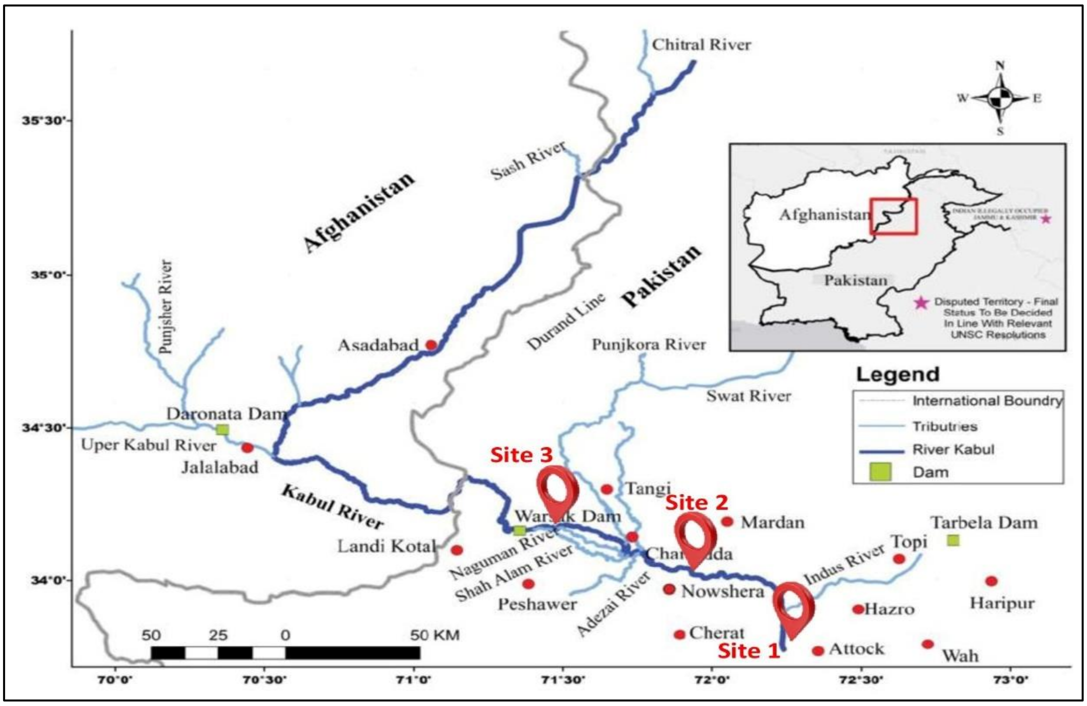

Figure 1. Map of River Kabul, red location mark icon shows sampling area on River Kabul.

RESULTS

Figure 2 compares the concentrations of Fe, Fl, Zn, Cu in water from Attock, Nowshera, and Warsak Dam sites. Fe shows the highest concentration, with significant differences ($p < 0.0001$) between all locations, where Nowshera has the highest levels. Fl shows no significant variation, while Zn exhibits slight differences ($p < 0.05$). Cu varies significantly ($p < 0.0001$) between Attock and Nowshera site but not with Warsak Dam. Overall, Fe shows the most significant variation, while other metals remain relatively stable.

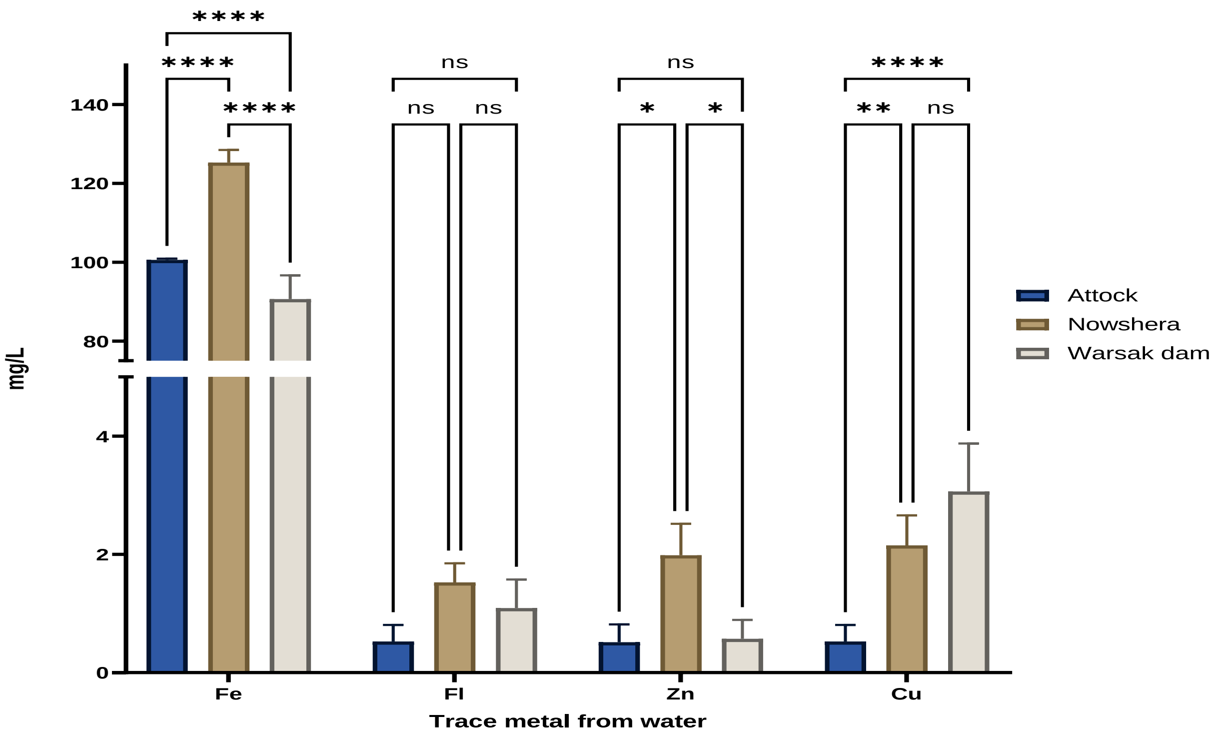

Figure 2. Concentrations of Fe, Fl, Zn, and Cu in water samples from Attock, Nowshera, and Warsak Dam sites. Statistical significance is indicated as **** ($p < 0.0001$, highly significant), ** ($p < 0.01$, significant), * ($p < 0.05$, least significant), and "ns" ($p > 0.05$, not significant), highlighting variations in metal concentrations across the different sites.

In case of sediment (Figure 3), like water, Fe shows the highest levels, with significant differences ($p < 0.0001$) across all locations. However, in this case Warsak Dam having the highest concentration. Fl and Cu exhibit no significant variation, while Zn shows notably higher ($p < 0.01$, $p < 0.05$) in Warsak Dam compared to the other sites.

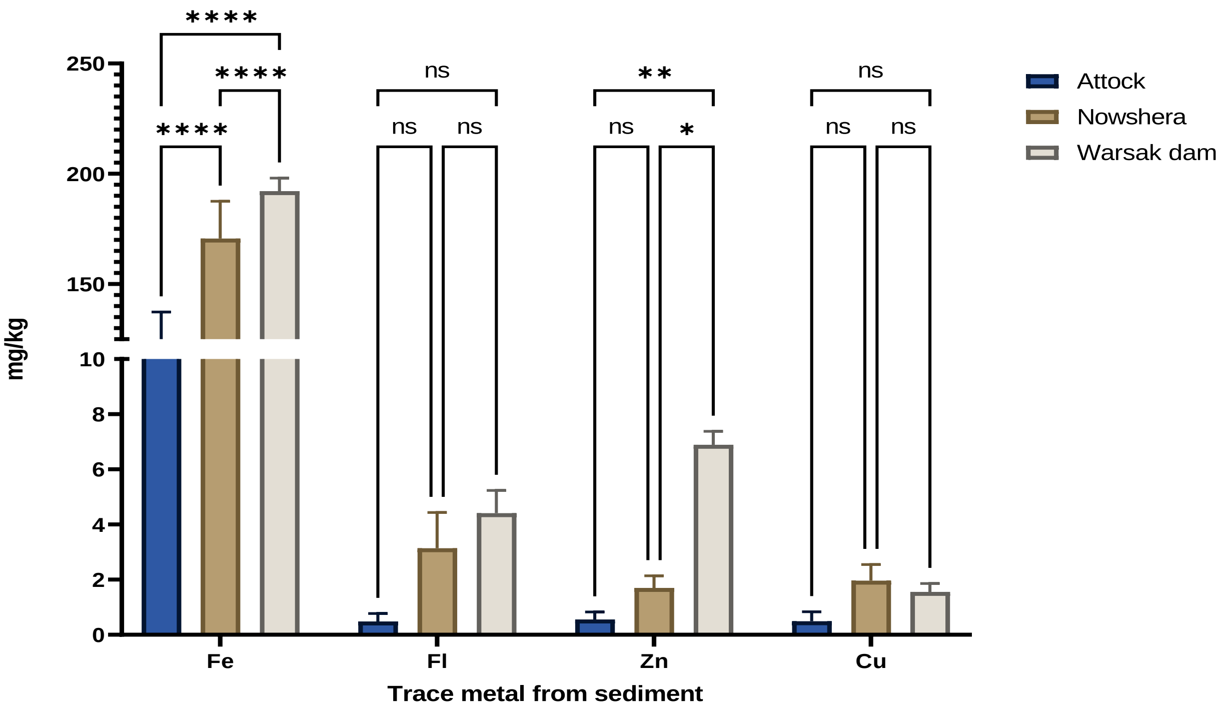

Figure 3. Concentrations of Fe, Fl, Zn, and Cu in sediment samples from Attock, Nowshera, and Warsak Dam sites. Statistical significance is indicated as **** ($p < 0.0001$, highly significant), ** ($p < 0.01$, significant), * ($p < 0.05$, least significant), and "ns" ($p > 0.05$, not significant), highlighting variations in metal concentrations across different sites.

Table 1 presents a comparison of trace metals and fluoride concentrations in the Kabul River with WHO and USEPA standards. The results indicate significant variations in contamination levels in both water and sediment samples. Fe levels in water exceed WHO limits in all three locations, with Nowshera having the highest Fe concentration (125.28 mg/L), followed by Attock (100.58 mg/L) and Warsak Dam (90.64 mg/L). However, Warsak Dam shows the highest Fe accumulation in sediment (192.18 mg/kg), surpassing Nowshera (170.67 mg/kg) and Attock (116.78 mg/kg), indicating long-term deposition. Fl concentrations in water are within safe limits, but Warsak Dam has the highest sediment accumulation (4.41 mg/kg), compared to Nowshera (3.14 mg/kg) and Attock (0.48 mg/kg). Zn levels in water are also below WHO limits in all locations, but Warsak Dam shows the highest Zn accumulation in sediment (6.89 mg/kg), suggesting ongoing contamination. A major concern is Cu contamination, particularly in Warsak Dam water (3.06 mg/L) and Nowshera water (2.153 mg/L), both exceeding WHO safety limit (1.3 mg/L). Attock has the lowest Cu levels in water (0.52 mg/L), remaining within safe limits. In sediment, Cu concentrations exceed USEPA safe limit (0.2 mg/kg) in all locations, with Nowshera (1.96 mg/kg) being the highest, followed by Warsak Dam (1.55 mg/kg) and Attock (0.49 mg/kg).

Overall, Warsak Dam shows the most severe Fe and Cu contamination in sediment and the highest Cu water contamination. Nowshera has the highest Fe and Cu levels in water, while Attock, though still exceeding safe limits, has relatively lower contamination levels compared to the other sites. These findings indicate a need for urgent water quality management, especially for Fe and Cu contamination in Nowshera and Warsak Dam.

Table 1. Comparison of trace elements and fluoride concentrations in water and sediment from Attock, Nowshera, and Warsak Dam sites with WHO and USEPA.

Parameter	**Attock (Water/Sediment)**	**Nowshera (Water/Sediment)**	**Warsak Dam (Water/Sediment)**	**WHO [12] Limit (Water)**	**USEPA [13] Limit (Sediment)**
Fe (mg/L, mg/kg)	100.58 / 116.78	125.28 / 170.67	90.64 / 192.18	0.3–1	30
Fl (mg/L, mg/kg)	0.527 / 0.485	1.526 / 3.140	1.09 / 4.415	NA	NA
Zn (mg/L, mg/kg)	0.514 / 0.556	1.985 / 1.699	0.57 / 6.891	5	110
Cu (mg/L, mgk/g)	0.526 / 0.490	2.153 / 1.965	3.06 / 1.558	1.3	0.2

DISCUSSION

Pollution by Fl and trace elements like Fe, Zn, and Cu in river water and sediments can have significant adverse effects on both the environment and human health. High levels of Fe in water can disrupt aquatic ecosystems by clogging filtration systems and depleting oxygen [14], while excess of Fl can cause toxicity in fish and soil, affecting plant growth [15]. Zn contamination harms aquatic life by disrupting reproduction and growth [16, 17], and Cu is particularly toxic to fish and invertebrates, leading to bioaccumulation in the food chain [18]. For humans, long-term exposure to these metals through contaminated water can result in gastrointestinal issues, organ damage, skeletal fluorosis, and other health problems [19, 20]. Additionally, trace elements in sediments can accumulate over time, causing long-lasting environmental changes [21]. Therefore, this study focuses on assessing the concentration of Fl, Zn, Cu, Fe at various sites along the Kabul River to determine the extent of pollution. By analyzing these contaminants, the research aims to provide crucial data that can aid policymakers, environmental agencies, and researchers in formulating effective pollution control strategies.

According to the results, Fe has the highest concentration among the studied metals, with significant variations across all locations, particularly peaking in Nowshera. Fl remains stable without significant differences, while Zn shows slight variations. Cu varies significantly between Attock and Nowshera but not with Warsak Dam. Overall, Fe demonstrates the most substantial variation, whereas the other metals exhibit relatively stable concentrations across the sites. Contamination in the river water and sediment poses a significant risk to aquatic life, as heavy metals can accumulate in fish and other organisms, leading to toxic effects [1]. Over time, these harmful contaminants gradually accumulate in aquatic organisms, including fish and shellfish, which serve as a primary food source for many populations. As these pollutants move up the food chain, they undergo biomagnification, leading to even higher concentrations in predatory species [1]. Consequently, humans who consume contaminated seafood may be exposed to toxic levels of heavy metals and fluoride, which can have detrimental effects on various physiological systems, including the nervous, renal, and skeletal systems. [22]. In the current study Fe levels in water exceed the WHO limits in all three locations, with Nowshera showing the highest concentration. Despite this, Warsak Dam has the highest accumulation of Fe in its sediment, while the water contains a high concentration of Fe, the dam's hydrological conditions (such as lower water flow) favor long-term deposition. Fl concentrations in water are within safe limits, but Warsak Dam shows the highest sediment accumulation of Fl, indicating that while the water is safe, Fl tends to bind to sediment over time, particularly in the dam. Zn levels in water are also within safe limits, but sediment in Warsak Dam shows the highest accumulation of Zn, pointing to ongoing contamination despite safe water levels. A significant concern is Cu contamination, especially in the water of Warsak Dam and Nowshera, where Cu concentrations exceed the WHO's safety limits. This suggests potential industrial pollution, corrosion of Cu pipes, or the use of copper-based pesticides in agriculture. Additionally, all three locations show elevated Cu concentrations in sediment, surpassing the safe limits set by the US Environmental Protection Agency (USEPA), with Nowshera having the highest sediment concentration. These findings indicate that Warsak Dam and Nowshera are experiencing significant contamination, particularly with Fe and Cu, which may pose long-term environmental and health risks. The data highlight the need for urgent water quality management to address contamination issues, especially regarding Fe and Cu in Nowshera and Warsak Dam. A study conducted by Nawab et al. [23] revealed that sediment in the Kabul River shows high concentrations of potentially toxic elements (PTEs) such as mercury (Hg), nickel (Ni), and lead (Pb), with values exceeding global river guideline standards. These metals exhibit severe contamination levels, particularly Hg and Ni, which demonstrate significant enrichment. Another study conducted Haq et al. [24] at river Ghizer River Basin (GRB), and report that the highest concentrations of potentially harmful elements (PHEs) were found in the Ishkomen River segment, including Cr, Cu, Ar, Co, and Ni. Downstream, manganese, Cd, Pb, and Zn concentrations were elevated. While most PHE concentrations were within WHO drinking water guidelines, Ni exceeded the threshold. The risk assessment revealed that manganese posed the highest non-cancer risk, with arsenic showing a moderate hazard. A study conducted Khan et al. [25], investigate contamination of Mn, Co, Cu, Zn, Cr, Ni, Cd, Hg and Pb for the first time along the entire Indus Drainage System of Pakistan and report that concentrations ranging from 5.05 to 101.59 µg/L. River Chenab showed the highest contamination, followed by River Indus.

CONCLUSIONS

In conclusion, the analysis of Fe, Fl, Zn and Cu in water and sediment from Attock, Nowshera, and Warsak Dam revealed significant contamination, with varying levels across the locations. Fe was the most prevalent metal in both water and sediment, exceeding WHO limits in all locations, while Warsak Dam has the highest Fe accumulation in sediment. Cu contamination was a major concern, particularly in the water at Warsak Dam and Nowshera, where concentrations surpass safe limits, with sediment levels also exceeding USEPA thresholds. Fl and Zn concentrations remain within safe limits in water, but sediment contamination, particularly for Fl in Warsak Dam and Zn in both Warsak Dam and Nowshera, was concerning. The findings highlight the need for urgent water quality management, especially focusing on reducing Fe and Cu contamination in Nowshera and Warsak Dam sites. Recommended actions include strengthening industrial regulation, improving wastewater treatment, monitoring agricultural runoff, and enhancing sediment management in these regions to mitigate ongoing contamination.

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CONFLICT OF INTERESTS

None

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