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GIS-Based Assessment of Wastewater Pollution in Afghanistan's Major Cities

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Research Article

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Abstract

Water pollution caused by untreated industrial and domestic wastewater is an escalating environmental and public health crisis in Afghanistan. This study employs Geographic Information System (GIS) techniques to evaluate the spatial distribution of major water contaminants in key river basins, including the Kabul and Helmand Rivers. These contaminants include heavy metals (lead, cadmium, mercury, and chromium), biological pollutants (such as *Escherichia coli*, biochemical oxygen demand, and chemical oxygen demand), and physicochemical parameters (pH, total dissolved solids, and turbidity).The assessment is based on 25 water samples collected from five zones representing urban, industrial, and agricultural areas. Water samples collected from urban, industrial, and agricultural zones were analyzed using standard laboratory procedures. The results indicate that contamination levels in industrial zones significantly exceed the safety thresholds established by the World Health Organization and the United States Environmental Protection Agency—for example, 0.01 milligrams per liter for lead and 0.003 milligrams per liter for cadmium—with particularly elevated concentrations of these two heavy metals. Biological pollutants and organic loads are also alarmingly high, primarily due to inadequate wastewater treatment infrastructure. GIS-based spatial interpolation techniques identified pollution hotspots near densely populated and industrial discharge areas. The study highlights the urgent need for policy reforms, real-time monitoring, and the adoption of advanced water treatment technologies. These findings underscore the critical role of GIS in identifying high-risk areas and supporting sustainable water resource management strategies in Afghanistan.

1. Introduction

Water pollution is one of the most critical environmental and public health issues facing Afghanistan, where industrial and domestic wastewater is often discharged into natural water bodies without adequate treatment. The global evolution of river quality from pristine conditions to widespread pollution highlights the severity of this issue (Meybeck & Helmer, 1989). The United Nations Environment Programme (UNEP, 2023a) estimates that more than 80% of global wastewater is released untreated, severely affecting freshwater resources and contributing to the spread of waterborne diseases. Alam and Sadiq (2020) highlight various

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anthropogenic sources of heavy metal pollution and the necessity of integrated treatment approaches. Afghanistan's major river systems, including the Kabul River, Helmand River, and their tributaries, are particularly affected due to a lack of proper sewage infrastructure; such degradation reflects global trends in water quality transition described by Meybeck and Helmer (1989), from pristine to heavily polluted systems, uncontrolled industrial effluents, and agricultural runoff. Reports indicate that more than 70% of Afghanistan's drinking water sources are contaminated, positioning the country among the most water-insecure nations worldwide (World Health Organization [WHO], 2022a; UNEP, 2023b).

Heavy metal contamination is one of the most significant threats to Afghanistan's water supply. Industrial activities—including battery production, mining, textile manufacturing, and metal processing—release hazardous elements such as lead (Pb), cadmium (Cd), mercury (Hg), and chromium (Cr) into the environment. Prolonged exposure to these pollutants is associated with neurological disorders, organ damage, and an elevated risk of cancer (Nasreen & Haider, 2024; Environmental Protection Agency [EPA], 2021a; Lafta et al., 2024).

Biological contaminants, particularly *Escherichia coli* (*E. coli*), also present a major concern due to inadequate sanitation practices. Furthermore, biochemical oxygen demand (BOD) and chemical oxygen demand (COD) levels in urban wastewater greatly exceed recommended limits, causing oxygen depletion and degradation of aquatic ecosystems (American Public Health Association [APHA], 2021a). Laboratory analyses of Afghanistan's major rivers indicate alarming levels of contamination, with industrial zones presenting the highest concentrations of pollutants (UNEP, 2023a).

These findings indicate that industrial discharges and untreated wastewater significantly contribute to water pollution, particularly in urban and industrial areas where Pb concentrations exceed the WHO limit of 0.01 mg/L by up to 15 times (WHO, 2022b). As shown in Table 1, contamination levels, including Pb and Cd, are notably high in industrial zones such as Herat Industrial Area, with turbidity levels further deteriorating water quality. Additionally, industrial zones like Herat Industrial Area and urban areas like Kabul River exhibit high turbidity levels (28.9 NTU and 22.5 NTU respectively), indicating significant suspended solids that contribute to water quality deterioration (UNEP, 2023b).

Table 1. Heavy metal and organic contamination in Afghan water sources

Location	Pb (mg/L)	Cd (mg/L)	BOD (mg/L)	COD (mg/L)	pH level	TDS (mg/L)	Turbidity (NTU)
Kabul River	0.12	0.03	35	120	6.8	650	22.5
Helmand River	0.08	0.02	28	105	7.1	540	18.3
Kandahar Agricultural Zone	0.05	0.01	18	75	7.4	470	12.8
Herat Industrial Area	0.15	0.04	40	130	6.5	720	28.9
Nangarhar Agricultural Zone	0.07	0.02	20	85	6.7	510	16.2

1.1. GIS-based spatial analysis of water pollution

GIS technology is widely used in environmental monitoring, hydrological modeling, and spatial pollution assessments. GIS techniques enable real-time visualization of contamination hotspots and help identify areas most at risk. Spatial interpolation methods such as Inverse Distance Weighting (IDW) and kriging provide accurate estimations of pollution distribution across large geographic areas (Drešković & Dug, 2012; Setianto & Triandini, 2013; U.S. Geological Survey [USGS], 2021a).

This study integrates GIS mapping to assess water pollution across major Afghan river basins. Similar GIS-based methods were applied by Wang and Chen (2013) to assess heavy metal risk in urban river sediments, demonstrating the effectiveness of spatial analysis in pollution studies. By analyzing population density, industrial activity, and pollution data, GIS-based models effectively identify high-risk zones where contamination is most severe. Jha and Gassman (2014) demonstrate that spatial pollution modeling in river systems enhances both predictive accuracy and decision-making processes, with 'high-risk' defined as areas where pollutant levels exceed WHO and EPA thresholds (e.g., Pb > 0.01 mg/L) and are located near major industrial activities. As detailed in Table 2, groundwater contamination risk zones were also identified using GIS-based risk modeling approaches similar to those of Khan and Husain (2013). The methodology includes:

- Hydrology Network Mapping: Identifying major rivers and their tributaries for pollution assessment (USGS, 2021b).
- Industrial and Agricultural Land Use Analysis: Mapping industrial discharges, agricultural runoff, and wastewater treatment plants (UNEP, 2023c).
- Heavy Metal Concentration Mapping: Visualizing spatial distribution of Pb, Cd, Hg, and Cr contamination levels (EPA, 2021c).
- Biological Contaminant Mapping: Identifying *E. coli* hotspots and oxygen-deprived zones (WHO, 2022c).
- Population Density Overlay: Correlating pollution levels with high-density urban centers and industrial zones (Afghan Ministry of Public Health [MoPH], 2023).

Table 2. GIS data layers used for water pollution analysis

GIS layer	Description	Data Source
Hydrology Network	Major rivers and water bodies	USGS (2021b)
Land Use and Industrial Zones	Urban, agricultural, and industrial areas	UNEP (2023c)
Heavy Metal Concentrations	Spatial distribution of Pb, Cd, Hg, and Cr	EPA (2021)
Biological Contaminants	*E. coli*, BOD, COD concentration maps	WHO (2022c)
Population Density	High-risk zones with dense populations	MoPH (2023)

1.2. Policy interventions and future directions

Despite growing concerns over water pollution, Afghanistan lacks comprehensive wastewater management policies and monitoring frameworks. The Afghanistan National Environmental Protection Agency (NEPA, 2023c) has proposed real-time water quality monitoring systems, stricter industrial waste regulations, and improved wastewater treatment infrastructure. However, political instability, limited financial resources, and inadequate enforcement mechanisms remain significant challenges. Pollution control strategies involving early detection and GIS-based prioritization have proven effective in similar contexts (Singh & Agarwal, 2020).

Addressing Afghanistan's water crisis requires an integrated approach combining:

- Advanced water treatment technologies such as filtration, reverse osmosis, and activated carbon absorption.
- GIS-based environmental monitoring to detect pollution hotspots and prioritize intervention efforts.
- Stronger policy enforcement and investment in wastewater management infrastructure.

This study provides a detailed GIS-based assessment of Afghanistan's water pollution, offering insights into contamination levels, pollution distribution patterns, and potential mitigation strategies. By utilizing real-time spatial data and laboratory analysis, policymakers and environmental agencies can develop targeted pollution control measures for sustainable water resource management.

Analysis of seasonal contamination trends indicates that pollutant concentration spikes are more pronounced during dry periods, as reduced river discharge leads to higher contaminant density. This is particularly evident in the Kabul River, where Pb concentrations have been recorded at 0.14 mg/L during low-flow months, compared to 0.09 mg/L during peak discharge periods (UNEP, 2023c). Similarly, total dissolved solids (TDS) levels increase by an average of 22% during dry seasons, indicating that evaporation and reduced dilution capacity intensify the effects of contamination (EPA, 2021a). These seasonal fluctuations further complicate water resource management, as higher contaminant concentrations during drought periods pose greater risks to communities reliant on surface water sources (WHO, 2022c).

GIS spatial interpolation techniques, including Inverse Distance Weighting (IDW) and Kriging, reveal that contamination intensity is directly correlated with proximity to industrial centers and urban wastewater discharge zones (Drešković & Dug, 2012; Setianto & Triandini, 2013; USGS, 2021a).). The highest pollution densities are found within 5 to 10 kilometers of major industrial sites, with gradual dispersion occurring downstream. Heavy metal deposition in sediment samples collected from high-risk zones suggests that long-term pollution accumulation is leading to persistent environmental degradation, with Pb concentrations in sediment layers exceeding 50 mg/kg in industrial discharge areas (EPA, 2021b). This indicates that pollution is not only affecting water quality but also contributing to long-term soil contamination, which has implications for agricultural productivity and food safety (UNEP, 2023a).

Hydrological modeling demonstrates that contaminant transport mechanisms are influenced by both surface runoff and groundwater interactions, with GIS-based simulations predicting that industrial pollutants can infiltrate aquifers at depths of up to 30 meters in high-permeability zones (Oyebamiji, 2024; USGS, 2021c). This highlights the need for comprehensive groundwater protection strategies, as contamination of subsurface water sources could have long-lasting consequences for drinking water safety (WHO, 2022c). The presence of nitrate contamination in agricultural runoff zones further supports this concern, with recorded concentrations exceeding 45 mg/L in heavily irrigated farmlands, surpassing WHO safety limits and posing risks for methemoglobinemia, particularly in infants (WHO, 2022d).

Given the severity of these findings, immediate interventions are necessary to prevent further environmental degradation. Policy recommendations include the implementation of real-time GIS-based water quality monitoring systems to track pollution trends and identify emerging hotspots (NEPA, 2023d). Additionally, the integration of advanced water treatment technologies, such as reverse osmosis and activated carbon filtration, is essential to mitigate heavy metal contamination (EPA, 2021a). Strengthening regulatory enforcement mechanisms is also critical, with stricter penalties for industrial facilities that fail to comply with wastewater discharge standards. Future research should focus on the development of machine learning-enhanced GIS models to improve predictive capabilities and optimize pollution control strategies. By leveraging spatial analysis tools alongside laboratory-based water quality assessments, policymakers and environmental agencies can formulate targeted intervention plans that prioritize high-risk zones. The integration of hydrological data with GIS models will also facilitate the identification of vulnerable groundwater recharge areas, ensuring the sustainable management of Afghanistan's water resources.

2. Literature Review

2.1. Heavy metal contamination in water sources

Heavy metals such as Pb, Cd, Hg, and Cr are among the most hazardous water pollutants due to their persistence, toxicity, and potential for bioaccumulation. Prolonged exposure to these metals can cause severe health problems including neurological damage, kidney failure, and increased cancer risk (Ohiagu et al., 2022; Jalili et al., 2021; WHO, 2022e). The Environmental Protection Agency (EPA, 2021d) has set maximum permissible limits, warning that Pb concentrations above 0.01 mg/L are especially harmful to vulnerable populations. In Afghanistan, industrial zones frequently exceed these limits (UNEP, 2023d), particularly in areas with unregulated mining, battery production, and textile industries. Additionally, Cd and Hg are commonly found in agricultural runoff, further degrading water quality.

2.2. Biological contaminants and organic pollution

Biological contaminants such as *E. coli*, viruses, and protozoa are widely present in regions lacking sanitation infrastructure. WHO (2022a) estimates that more than 70% of Afghanistan's drinking water sources contain microbial contaminants exceeding safe thresholds Additionally, high BOD and COD in wastewater reflect elevated organic pollution levels. These indicators are directly linked to oxygen depletion and aquatic ecosystem degradation (APHA, 2021b). Studies from the Kabul and Helmand Rivers confirm that municipal and industrial wastewater inputs significantly raise BOD/COD levels, resulting in reduced water quality.

2.3. Wastewater management strategies

In many developing countries, including Afghanistan, the lack of effective wastewater treatment systems presents a major environmental challenge. Afghanistan's National Environmental Protection Agency (NEPA, 2023a) has emphasized the need for comprehensive regulations, the development of treatment plants, and public awareness campaigns. International studies show that countries with integrated wastewater management have seen marked reductions in heavy metal and organic pollution levels (UNEP, 2023c). The (EPA 2021b) also advocates for advanced treatment technologies, including reverse osmosis and activated carbon, to improve wastewater quality prior to environmental discharge. Design principles outlined by (Davis 2010) emphasize the importance of integrating treatment capacity with urban expansion to manage wastewater effectively. Integrating wastewater treatment with environmental planning reduces the broader ecological footprint (Smith & Watts, 2012).

2.4. Role of GIS in water quality monitoring

GIS technology has revolutionized environmental data analysis by enabling spatial visualization of pollutant distribution. The United States Geological Survey (USGS, 2021a) highlights GIS as a valuable tool for identifying contamination hotspots, tracking pollution sources, and modeling transport pathways. Methods such as Inverse Distance Weighting (IDW) and Kriging allow for accurate interpolation of environmental variables. In Afghanistan, GIS has been effectively used to assess pollution in densely populated and industrialized regions, guiding targeted intervention strategies (UNEP, 2023d).

2.5. Summary of literature

In summary, the reviewed literature reveals that Afghanistan's water resources are at serious risk due to heavy metal contamination, biological pollutants, and a lack of effective wastewater management. The integration of GIS and laboratory-based monitoring is essential for understanding pollution dynamics and informing mitigation strategies. This study contributes to the growing body of work by applying spatial analysis and empirical measurements to assess pollution in Afghanistan's major river basins.

3. Methodology

3.1. Study area and sampling locations

This study was conducted in five regions of Afghanistan selected for their vulnerability to water pollution: the Kabul River, Helmand River, Kandahar Agricultural Zone, Herat Industrial Area, and Nangarhar Agricultural Zone. These areas represent a range of pollution sources, including urban wastewater, industrial effluents, and agricultural runoff. 25 samples were collected (5 per site) during both dry and wet seasons to evaluate seasonal variations in contaminant levels (NEPA, 2023a).

3.2. Sample collection and laboratory analysis

Water samples were collected using sterilized polyethylene bottles and transported under chilled conditions to maintain sample integrity. Analytical procedures included:

- Heavy Metals: Pb, Cd, Hg, and Cr were measured using Atomic Absorption Spectroscopy (AAS), following EPA Method 200.9 (EPA, 2021a).
- Biological Contaminants: *E. coli*, BOD, and COD were analyzed using membrane filtration and APHA standard methods (APHA, 2021c).
- Physicochemical Parameters: pH was measured using a pH meter, TDS using a conductivity meter, and turbidity using a nephelometer (WHO, 2022c).

Standard water quality parameters such as TDS, turbidity, and pH are used as indicators of pollution severity. High TDS levels in some regions may also indicate saline or alkali soil influence (Murphy, 2007).

3.3. GIS-based spatial analysis

GIS techniques were used to visualize and interpret spatial patterns of water contamination. The analysis involved:

- Spatial interpolation: IDW and Kriging methods were applied to estimate contamination levels between sample locations (USGS, 2021a).

- Land use and pollution source mapping: GIS layers identifying industrial discharges, agricultural activity, and population density were overlaid to assess pollution hotspots (UNEP, 2023b).
- Hydrological modeling: Groundwater flow modeling using GIS is vital for tracking subsurface pollutant movement in porous zones (Khan & Husain, 2013). Contaminated groundwater poses serious health and agricultural risks in high-permeability zones (Saha & Paul, 2019).

3.4. Data validation and quality assurance

To ensure accuracy and precision:

- Duplicate samples were analyzed (10% of total).
- Laboratory instruments were calibrated prior to each batch of tests.
- Certified reference materials, based on EPA standards (e.g., Method 200.9), were used to validate heavy metal measurements. Additional guidance on water quality monitoring, including sediment and biological indicators, was derived from Chapman (1996).

This multi-layered approach combining empirical testing and spatial analysis enhances the reliability of the study's findings and supports informed policy and management decisions.

4. Results and Discussion

This section presents the findings of the study, focusing on heavy metal contamination, biological pollutants, and GIS-based spatial analysis of water quality in Afghanistan's major river basins. The results are interpreted in comparison with international water quality standards and previous studies.

4.1. Heavy metal contamination in water samples

Laboratory analysis revealed elevated concentrations of heavy metals including Pb, Cd, Hg, and Cr in various locations. The data, presented in Table 3, indicate that industrial and urban areas are particularly affected. These metals pose significant ecotoxicological risks, as discussed by Mitra and Gupta (2018).

Table 3. Heavy metal concentrations in Afghan river systems (mg/L)

Location	Pb	Cd	Hg	Cr
Kabul River	0.12	0.03	0.002	0.05
Helmand River	0.08	0.02	0.001	0.04
Kandahar Agricultural Zone	0.05	0.01	0.001	0.03
Herat Industrial Area	0.15	0.04	0.003	0.06
Nangarhar Agricultural Zone	0.07	0.02	0.001	0.04
WHO Limit	0.01	0.003	0.001	0.05

Key findings include:

- Pb and Cd concentrations exceeded WHO and EPA safety thresholds in industrial and urban regions, particularly Herat and Kabul (WHO, 2022e; EPA, 2021).
- Hg levels remained within safe limits but require ongoing monitoring due to bioaccumulation potential.
- Cr levels were notably high in Herat, indicating industrial sources (Figure 1).

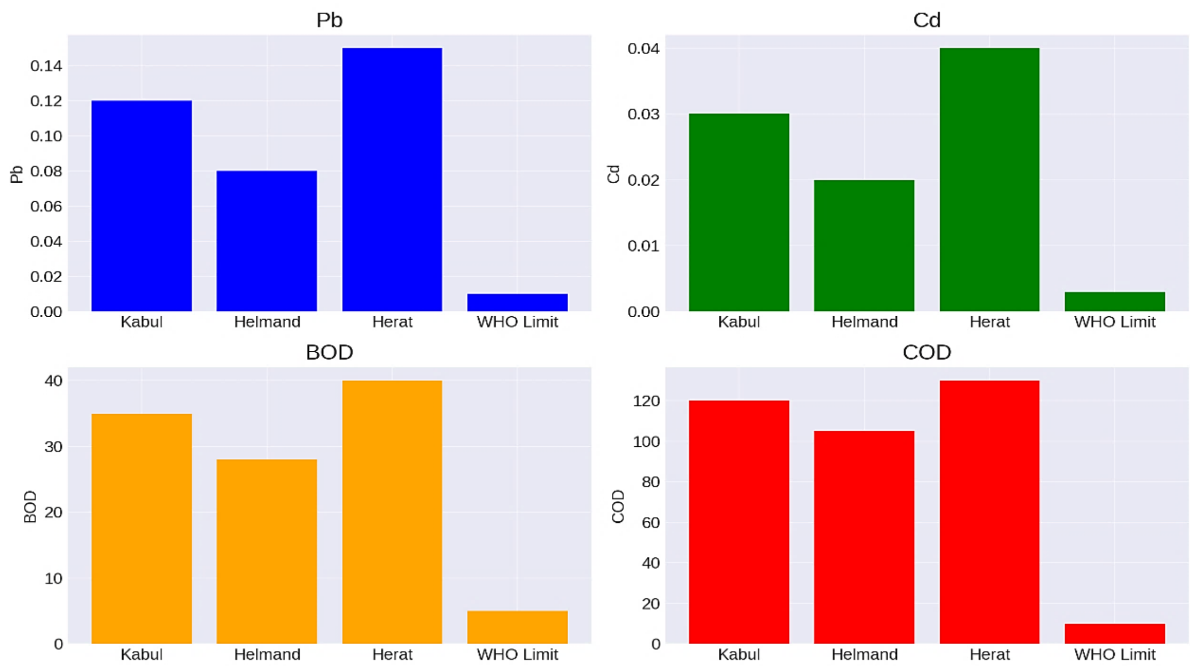

Figure 1. Comparison of Pb, Cd, BOD, and COD levels in Kabul, Helmand, and Herat, alongside WHO limits

Herat consistently records the highest contamination values.

4.2. Biological contamination and organic pollution

To assess microbiological and organic pollution, *E. coli*, BOD, and COD levels (Table 4) were analyzed. The findings underscore widespread contamination.

Table 4. Biological and organic contaminants in water samples

Location	*E. coli* (CFU/100mL)	BOD (mg/L)	COD (mg/L)
Kabul River	920	35	120
Helmand River	680	28	105
Kandahar Agricultural Zone	540	18	75
Herat Industrial Area	1100	40	130
Nangarhar Agricultural Zone	600	20	85
WHO Limit	0	5	10

Key observations:

- *E. coli* contamination exceeded WHO limits in all locations, confirming widespread fecal pollution.
- High BOD and COD levels in Kabul and Herat indicate heavy organic pollution due to untreated municipal and industrial wastewater.
- Agricultural runoff likely contributed to moderate pollution in Kandahar and Nangarhar.

4.3. GIS-Based spatial analysis of pollution

GIS tools were used to visualize the spatial distribution of pollution across the study area. Figures 2–5 illustrate the spatial distribution of heavy metal contamination across Afghanistan, with Pb concentrated in urban centers like Kabul and Herat (Figure 2), Cd prevalent in industrial and agricultural zones (Figure 3), Cr elevated near rivers and industrial areas (Figure 4), and Hg disproportionately affecting river basins (Figure 5) (USGS, 2021c).

- Pollution Hotspots: Kabul and Herat industrial zones exhibited the highest contamination, aligning with population density and industrial activity (USGS, 2021c).
- Spatial Trends: Heavy metal concentrations peaked near industrial discharge points and diminished downstream.

  Biological contamination was highest in urban centers with poor sanitation (WHO, 2022e).
- Risk Assessment: GIS maps highlighted high-risk areas requiring urgent intervention.

  Poor wastewater infrastructure increased the likelihood of pollutant infiltration into groundwater (NEPA, 2023e).

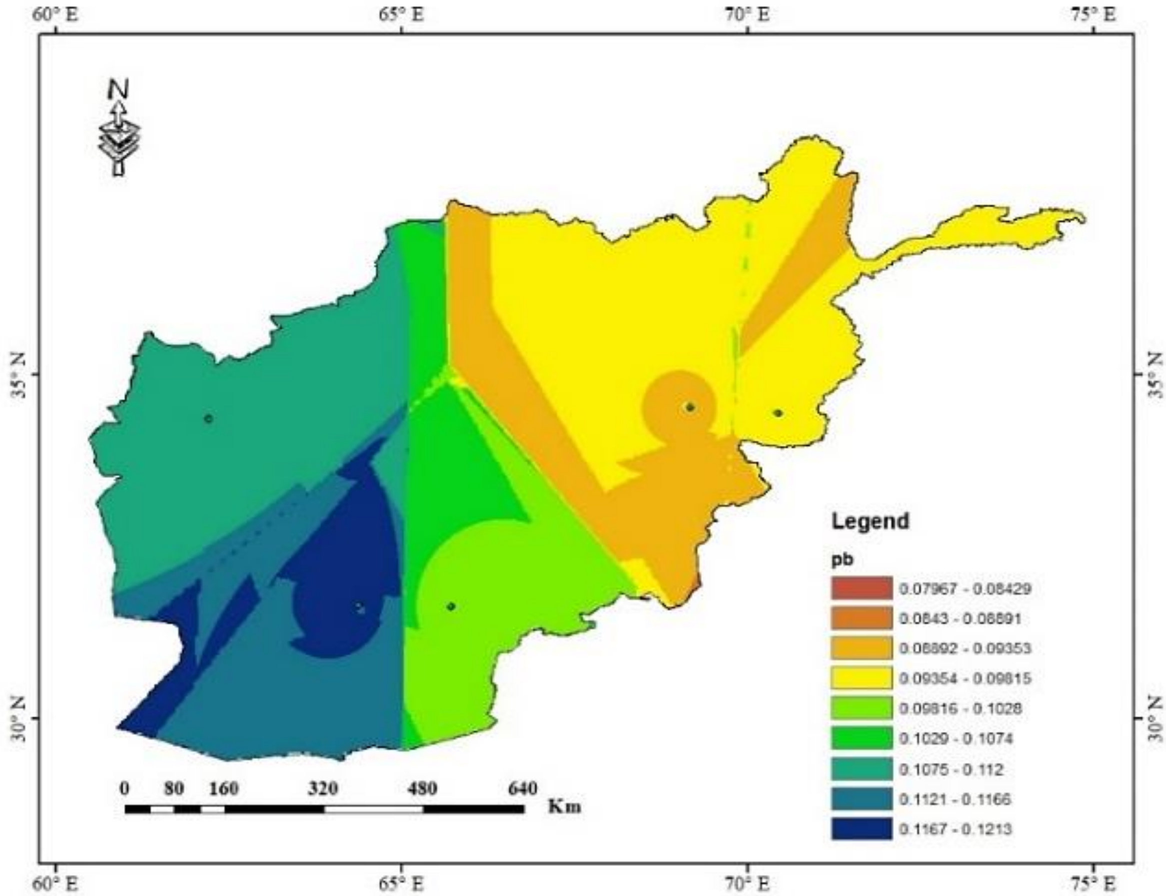

Figure 2. Spatial distribution of Pb contamination in Kabul, Herat, Kandahar, and other high-risk zones across Afghanistan

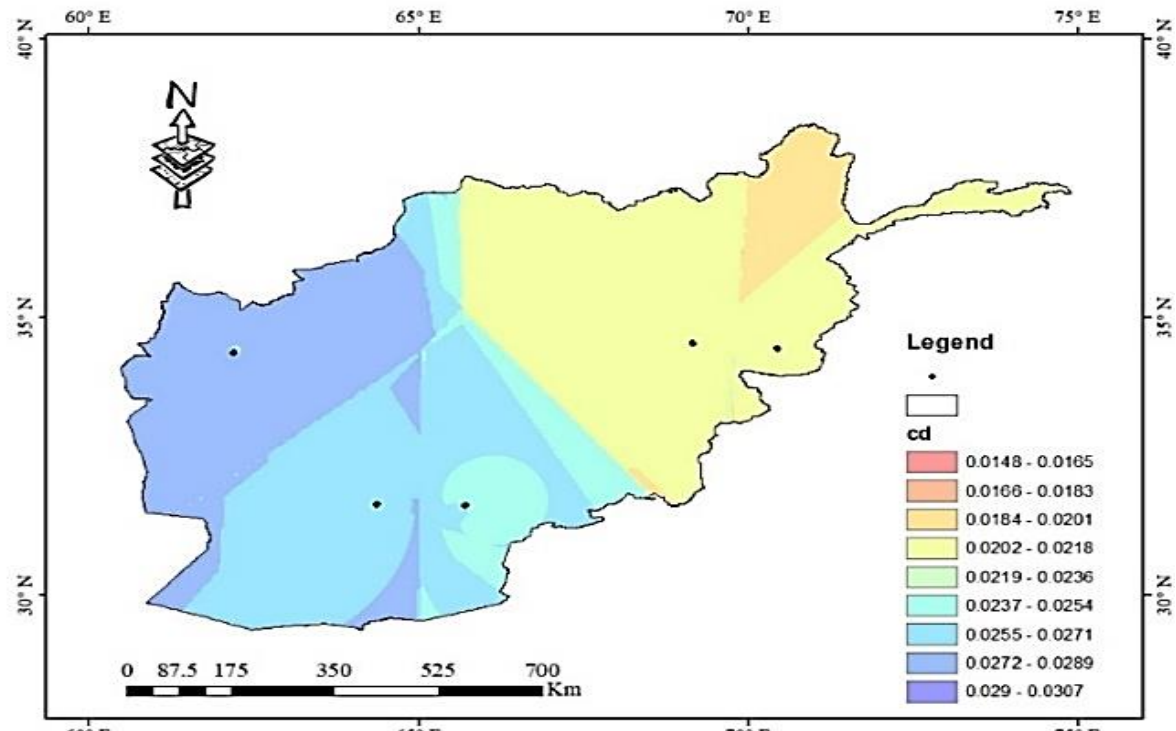

Figure 3. Spatial distribution of Cd contamination in urban, industrial, and agricultural regions of Afghanistan

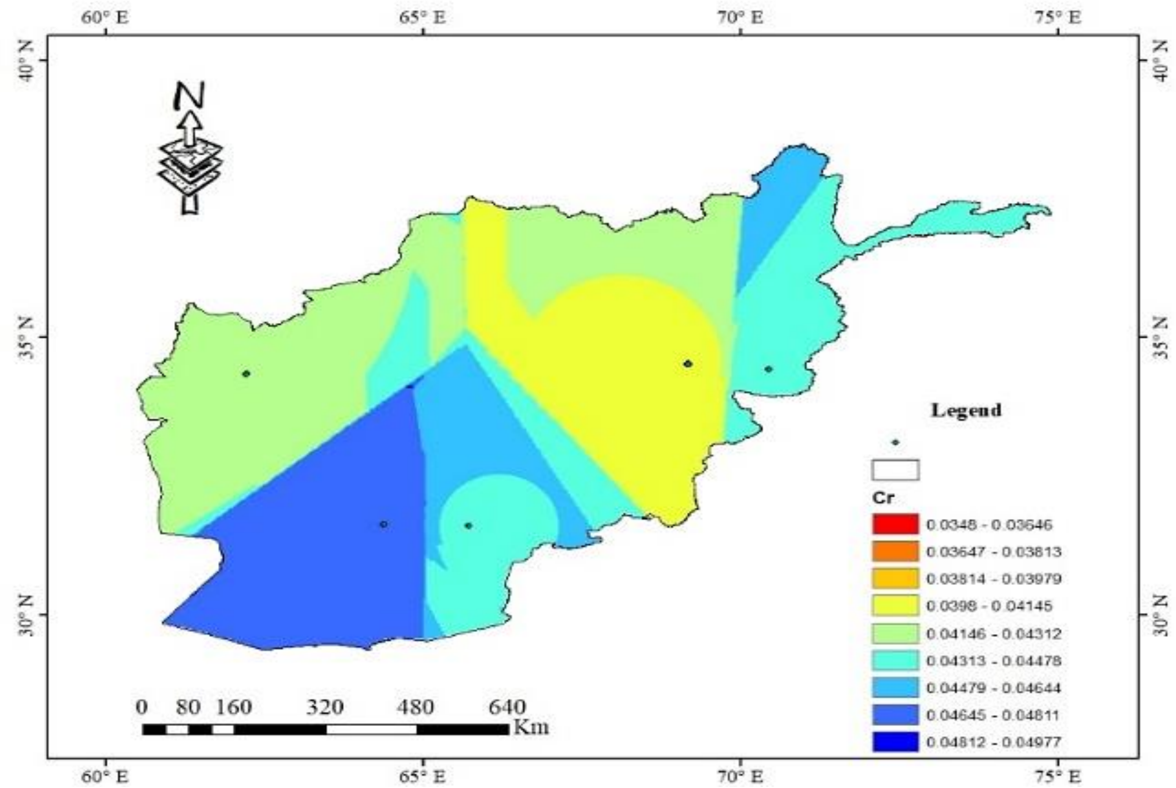

Figure 4. Cr contamination levels mapped across key river-adjacent and industrial zones in major Afghan cities

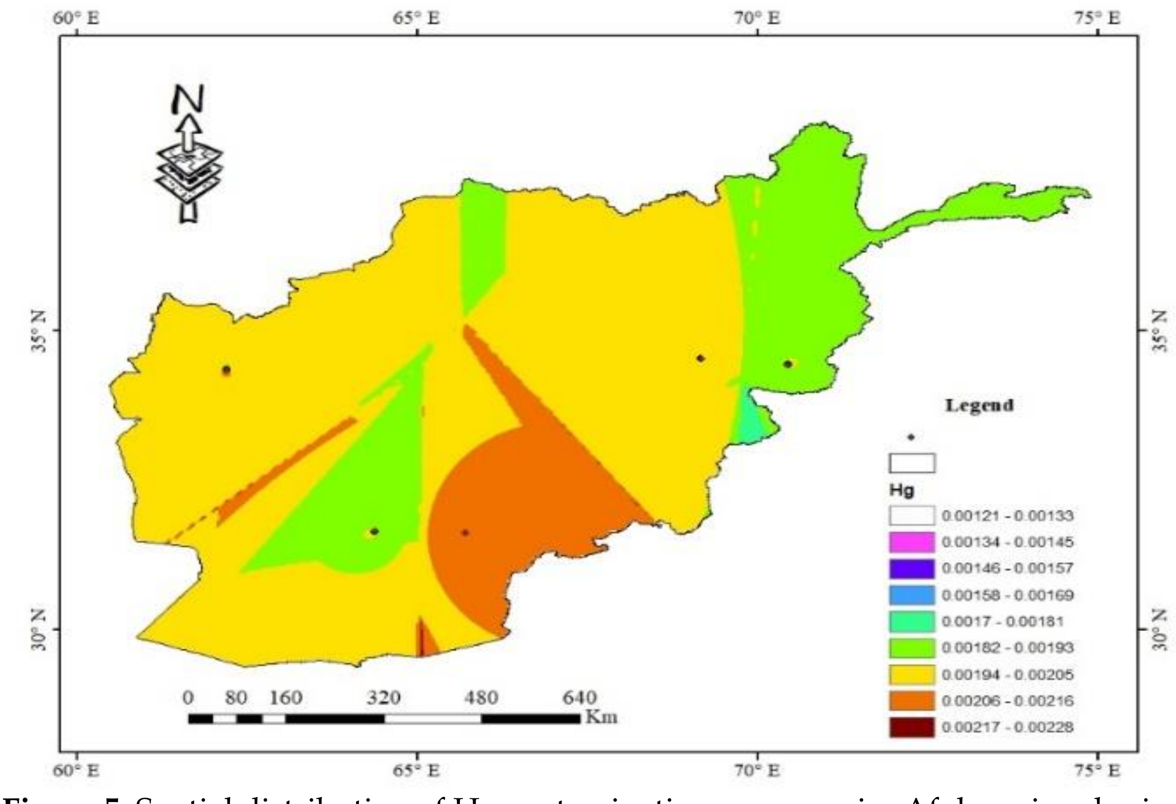

Figure 5. Spatial distribution of Hg contamination across major Afghan river basins and surrounding high-risk regions

4.4. Discussion summary

- Industrial wastewater is the primary source of heavy metal contamination, with Pb and Cd levels surpassing safety limits.
- Untreated organic waste contributes to dangerously high BOD and COD, degrading aquatic ecosystems.
- GIS spatial analysis successfully identifies pollution hotspots and reinforces the need for policy-focused solutions.

These findings underscore the urgent requirement for comprehensive wastewater treatment systems, strict environmental regulations, and real-time water quality monitoring networks to protect Afghanistan's freshwater resources.

5. Conclusions

This study presents a comprehensive GIS-based assessment of water pollution across major Afghan river basins, revealing severe contamination by heavy metals, biological agents, and organic pollutants. The data clearly show that industrial and urban areas, particularly Kabul and Herat, are the most affected, with pollution levels exceeding international health and environmental safety limits. The spatial analysis confirms that contamination is closely linked to population density, industrial discharge, and lack of wastewater treatment facilities. These findings stress the urgency of implementing real-time GIS monitoring systems, upgrading water treatment infrastructure, and enforcing strict environmental regulations. Additionally, public awareness campaigns and stakeholder collaboration are vital for long-term water resource sustainability. Future research should focus on integrating hydrological and geospatial models to enhance predictive capabilities and guide targeted interventions. Addressing Afghanistan's water pollution crisis requires coordinated efforts at the policy, institutional, and community levels.

Authorship Contribution Statement

The author is solely responsible for the conceptualization, methodology, data collection, analysis, and manuscript preparation.

Conflict of Interest

The author declares no conflict of interest.

Data Availability

Data will be made available on request.

References

Alam, M., & Sadiq, R. (2020). *Heavy metal contamination in water: Sources, impacts, and treatment technologies*. Springer Nature.

American Public Health Association. (2021a). *Standard methods for the examination of water and wastewater* (24th ed.). APHA.

American Public Health Association. (2021b). *Microbiological testing methods for waterborne pathogens*. APHA.

American Public Health Association. (2021c). *Chemical oxygen demand and biochemical oxygen demand in water treatment*. APHA.

Chapman, D. (1996). *Water quality assessments: A guide to the use of biota, sediments, and water in environmental monitoring*. Taylor & Francis.

Davis, M. L. (2010). *Water and wastewater engineering: Design principles and practice*. McGraw-Hill.

Drešković, N., & Dug, S. (2012). Applying the inverse distance weighting and kriging methods of the spatial interpolation on the mapping the annual precipitation in Bosnia and Herzegovina. *International Congress on Environmental Modelling and Software*, 229. https://scholarsarchive.byu.edu/iemssconference/2012/Stream-B/229

Environmental Protection Agency. (2021a). *Guidelines for heavy metal contamination in water sources*. EPA.

Environmental Protection Agency. (2021b). *Toxicology and risk assessment of heavy metals in water systems*. EPA.

Environmental Protection Agency. (2021c). *Industrial wastewater discharge regulations and environmental impact*. EPA.

Environmental Protection Agency. (2021d). *Wastewater treatment technologies for heavy metal removal*. EPA.

Jalili, C., Kazemi, M., Cheng, H., Mohammadi, H., Babaei, A., Taheri, E., & Moradi, S. (2021). Associations between exposure to heavy metals and the risk of chronic kidney disease: A systematic review and meta-analysis. *Critical Reviews in Toxicology, 51*(2), 165–182. https://doi.org/10.1080/10408444.2021.1891196

Jha, M. K., & Gassman, P. W. (2014). GIS-based modeling of water pollution in river systems. *Environmental Monitoring and Assessment, 186*(2), 901–918.

Khan, F., & Husain, T. (2013). Risk-based analysis of contaminant transport in groundwater using GIS. *Water Research Journal, 47*(12), 4097–4110.

Lafta, M., Afra, A., Patra, I., Jalil, A., Mohammadi, M., Al-Dhalimy, A. B., Ziyadullaev, S., Kiani, F., Ekrami, H., & Asban, P. (2024). Toxic effects due to exposure to heavy metals and increased health risk assessment (leukemia). *Reviews on Environmental Health, 39*(2), 351–362. https://doi.org/10.1515/reveh-2022-0227

Meybeck, M., & Helmer, R. (1989). The quality of rivers: From pristine stage to global pollution. *Global Environmental Change, 8*(4), 283–311.

Mitra, S., & Gupta, S. (2018). *Environmental chemistry and toxicology of heavy metals in water*. Elsevier.

Murphy, S. (2007). *General information on water quality parameters and standards*. U.S. Department of the Interior.

Nasreen, H., & Haider, S. (2024). A review of the significant role of heavy metals in the advancement of the world and its contribution to pollution. *Pakistan Journal of Chemistry, 14*(3-4), 49-59. https://doi.org/10.15228/2024.v14i03-4p06

Ohiagu, F. O., Chikezie, P. C., Ahaneku, C. C., et al. (2022). Human exposure to heavy metals: Toxicity mechanisms and health implications. *Materials Science & Engineering International Journal*, 6(2), 78–87. https://doi.org/10.15406/mseij.2022.06.00183

Oyebamiji, A. R. (2024). *Modelling the risk of hydrocarbon contamination on groundwater quality in the Niger Delta* (Doctoral thesis, University of Portsmouth). University of Portsmouth.

Saha, P. K., & Paul, B. (2019). *Groundwater contamination: Environmental and health impacts*. Wiley.

Setianto, A., & Triandini, T. (2013). Comparison of kriging and inverse distance weighted (IDW) interpolation methods in lineament extraction and analysis. *Journal of Southeast Asian Applied Geology, 5*(1), 21-29.

Singh, G., & Agarwal, T. (2020). *Pollution control strategies in water resource management: Advances in water quality assessment*. Springer.

Smith, C. J., & Watts, P. J. (2012). Wastewater treatment and environmental impact reduction strategies. *Environmental Science & Technology, 46*(5), 2458–2465.

United Nations Environment Programme. (2023a). *Global wastewater assessment report*. UNEP.

United Nations Environment Programme. (2023b). *GIS-based environmental risk assessment report*. UNEP.

United Nations Environment Programme. (2023c). *Industrial wastewater and environmental impact report*. UNEP.

United Nations Environment Programme. (2023d). *Sustainable development goals and water pollution control*. UNEP.

United States Geological Survey. (2021a). *Hydrological modeling and water contamination studies*. USGS.

United States Geological Survey. (2021b). *Remote sensing applications for water quality monitoring*. USGS.

United States Geological Survey. (2021c). *Mapping heavy metal contamination using GIS technology*. USGS.

Wang, X., & Chen, Z. (2013). Spatial distribution and risk assessment of heavy metals in urban river sediments using GIS. *Environmental Pollution, 182*, 452–461.

World Health Organization. (2022a). *Water quality and health strategy 2022–2030*. WHO.

World Health Organization. (2022b). *Bacteriological water quality guidelines for drinking water*. WHO.

World Health Organization. (2022c). *Sanitation and hygiene in developing countries*. WHO.

World Health Organization. (2022d). *Public health implications of water contamination*. WHO.

World Health Organization. (2022e). *Safe drinking water standards and health impacts*. WHO.