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Vulnerability and risk assessment of lead (Pb) concentrations in drinking water via statistical and geostatistical analyses

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Introduction: Lead (Pb) contamination in drinking water poses serious public health risks, particularly when concentrations exceed the WHO permissible exposure limit (PEL) of 0.01 mg/L (10 ppb). This study investigates Pb levels in drinking water sources across five districts Kohat, Hangu, Dera Ismail Khan (D.I. Khan), Bannu, and Karak to assess contamination severity, spatial distribution, and potential health risks.

Methods: Drinking water samples were collected from multiple locations within the five districts and analyzed for Pb concentrations. Statistical analyses, including one-way ANOVA and the Shapiro-Wilk normality test, were conducted to evaluate variations and data distribution. Health risk assessment was performed using estimated daily intake (EDI) and hazard quotient (HQ) calculations. Additionally, geospatial analysis using Inverse Distance Weighting (IDW) modeling was employed to identify contamination hotspots.

Results: All districts exceeded the WHO PEL for Pb, with the highest mean concentrations recorded in Bannu (0.720 mg/L) and Karak (0.693 mg/L). Maximum Pb levels reached 1.809 mg/L in Bannu and 1.572 mg/L in Karak. Exceedance rates were 100% in Hangu, Bannu, and Karak. ANOVA analysis (p-value = 8.16×10^{-11}) indicated significant variations among districts, while the Shapiro-Wilk test (W = 0.742, p-value < 0.0001) confirmed non-normal data distribution. Health risk assessment revealed critical risks, particularly for children, with HQ values exceeding safe thresholds, notably in Bannu and Karak. Geospatial modeling identified contamination hotspots, including Jozara Water (Hangu), Mufti Mehmood Circuit House (D.I. Khan), and Kalanger (Bannu).

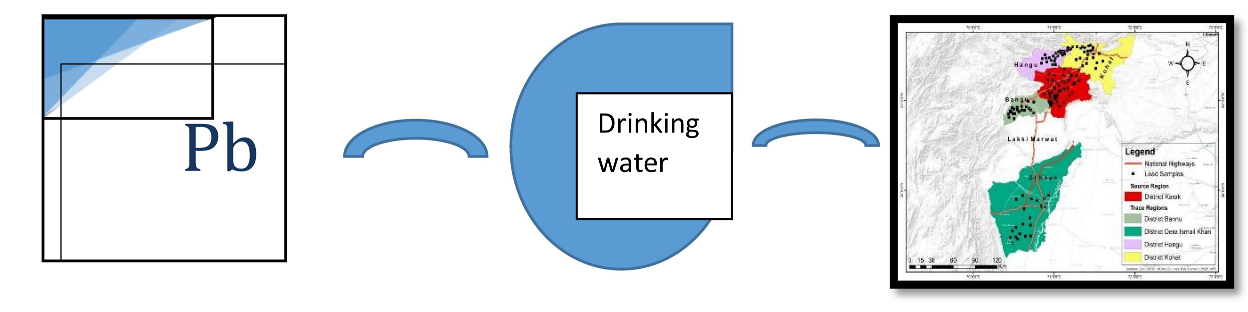
Discussion and conclusion: The findings highlight widespread Pb contamination in drinking water across the study area, posing severe health risks. Immediate intervention through advanced water treatment, stringent regulatory enforcement, and continuous monitoring is essential to safeguard public health.

KEYWORDS

lead contamination, vulnerable population, risk, prediction, good health and wellbeing, ANOVA, WHO, lead (Pb)

1 Introduction

Lead (Pb) contamination in drinking water is a critical environmental and public health issue that continues to pose significant risks worldwide (Salman et al., 2021; Jjagwe et al., 2024). Even at low concentrations, prolonged exposure to Pb can cause severe health effects, particularly in vulnerable populations such as children, pregnant women, and individuals with preexisting health conditions (Lanphear et al., 2005). The World Health Organization (WHO) has classified Pb as one of the most hazardous environmental pollutants, emphasizing the urgent need for effective



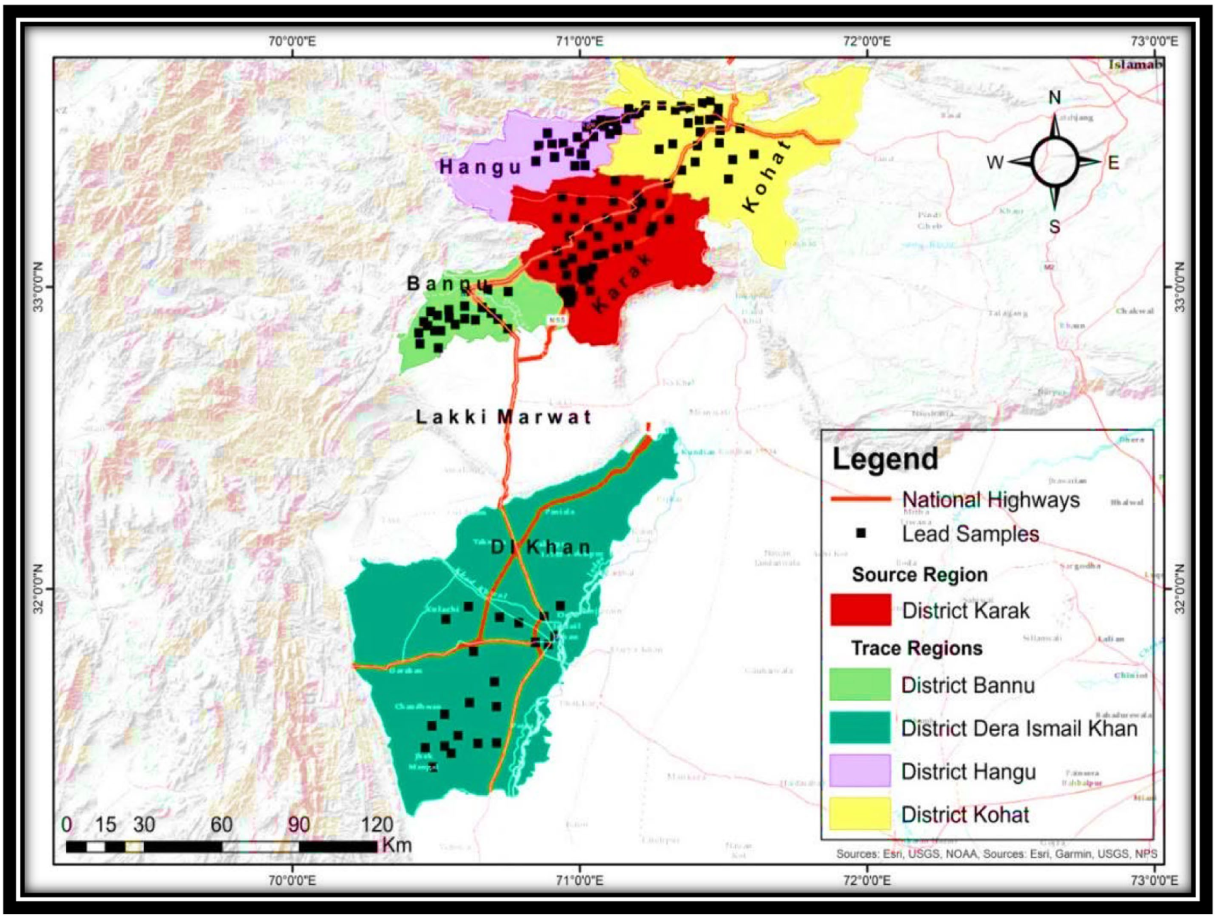
GRAPHICAL ABSTRACT

monitoring and mitigation strategies (WHO, 2022a,b). The primary sources of Pb contamination in drinking water include corroding lead-based plumbing materials, industrial discharge, mining activities, and contaminated groundwater (Triantafyllidou and Edwards, 2012). Lead pipes, solder, and brass fittings used in older water distribution systems are a significant contributor to Pb contamination (Ahmed et al., 2023), particularly in urban areas where outdated infrastructure remains in use (Roy and Edwards, 2019). Especially when the water is corrosive or has a low pH. Industrial activities such as battery manufacturing, smelting, and waste disposal sites are also significant contributors to Pb pollution, releasing Pb into surface water and groundwater systems (Reimann and de Caritat, 1998). Additionally, Pb contamination may arise from agricultural runoff containing lead-based pesticides (Ding et al., 2021), which were widely used in the past and persist in some regions (Patrick, 2006). Lead exposure has been extensively studied due to its widespread toxicity and severe health impacts (Zeng et al., 2021). Ingestion of Pb-contaminated water can result in neurological and cognitive impairments, particularly in children, who are more susceptible due to their developing nervous systems (Needleman, 2004). Studies have shown that chronic Pb exposure can lead to reduced IQ levels, attention deficits, learning disabilities, and behavioral problems in children (Lanphear et al., 2005). In adults, Pb exposure has been linked to hypertension, kidney damage, cardiovascular diseases, and reproductive issues (Navas-Acien et al., 2007). Pregnant women exposed to Pb-contaminated water face an increased risk of miscarriage, premature birth, and developmental disorders in their offspring (Bellinger, 2013). Given these health risks, it is crucial to establish stringent regulations and effective mitigation strategies to limit Pb exposure (Flores-Rojas et al., 2024). In response to the health hazards associated with Pb exposure, regulatory agencies worldwide have set permissible limits for Pb in drinking water (Xia et al., 2024). The WHO has established a maximum Pb concentration of 0.01 mg/L to minimize health risks (WHO, 2022a,b). Similarly, the United States Environmental Protection Agency (EPA) has set an action level of 0.015 mg/L under the Lead and Copper Rule (Environmental Protection Agency (EPA), 2021). However, despite these regulations, Pb contamination continues to be a persistent problem in many parts of the world, particularly in developing countries where water quality monitoring and enforcement mechanisms are inadequate (Patrick, 2006; Roy and Edwards, 2019; Chen et al., 2024). Geospatial analysis has emerged as an effective tool for assessing Pb contamination patterns and identifying high-risk areas (Goovaerts, 2001). By integrating statistical methods with geostatistical modeling techniques such as kriging and inverse distance weighting (IDW), researchers can predict spatial variations in Pb concentrations and assess population vulnerability (Griffith, 2005). These approaches facilitate targeted interventions, enabling authorities to implement site-specific remediation efforts and reduce exposure risks (Hengl et al., 2009). Statistical analyses, including correlation and regression models, are also employed to identify key factors influencing Pb levels in drinking water, such as water source type, pH, and proximity to industrial zones (Triantafyllidou and Edwards, 2012). To improve monitoring and mitigation strategies for Pb contamination in drinking water, it is essential to integrate advanced experimental and modeling techniques. Experimental validation of predictive models enhances the reliability of assessments, allowing for better forecasting of Pb contamination trends. Studies such as those by Errico et al. (2019) and Box et al. (2021) have demonstrated the importance of using flow resistance models and hydrological simulations in environmental assessments. These methodologies provide a robust foundation for understanding Pb transport dynamics and optimizing water treatment processes. Additionally, comparative analysis of modeled and measured environmental variables, as explored by Lama et al. (2019), strengthens the predictive accuracy of geospatial and hydrological models. By combining laboratory experimentation with computational modeling, researchers can develop comprehensive frameworks for assessing Pb contamination risks, ensuring effective regulatory compliance, and safeguarding public health.

In Pakistan, Pb contamination in drinking water is a growing concern due to industrialization, poor infrastructure, and inadequate water treatment facilities (Khan et al., 2013). The southern regions of Khyber Pakhtunkhwa (KP), including districts such as Kohat, Hangu, D.I. Khan, Bannu, and Karak, are particularly vulnerable due to their reliance on groundwater sources that may be contaminated by industrial effluents and natural Pb deposits (Fang et al., 2024; Muneer et al., 2025). Studies have shown that Pb concentrations in some parts of KP exceed WHO permissible limits, posing significant health risks to local communities (Shah et al., 2020). Children in these areas are at high risk of Pb exposure, which may result in long-term health complications if not addressed through proper water quality management and public health initiatives.

2 Methodology

Geographically, the study area lies between 31.8°N to 34.2°N latitude and 69.2°E to 71.5°E longitude. The region's geology consists of sedimentary and metamorphic formations, including sandstone, limestone, and shale, which influence groundwater chemistry. Mineral



MAP 1
Location map of southern Khyber Pakhtunkhwa showing lead (Pb) sampling sites.

deposits, mining, industrial discharge, and agricultural runoff contribute to contamination. Hydrogeological conditions vary, with some areas relying on deep aquifers while others depend on surface water sources. These geological and hydrological factors play a crucial role in Pb contamination distribution. The study area was selected based on factors such as population density, study area geology and reported water contamination. Kohat, Hangu, D.I. Khan, Bannu, and Karak were chosen due to their reliance on groundwater, which is vulnerable to contamination. The selection was further guided by previous studies, government reports, and community concerns. Sampling locations were strategically chosen for spatial representation, capturing variations in Pb concentrations. The study area is shown in Map 1.

2.1 Sample collection and preservation

A total of 145 drinking water samples were collected from various sources, including household tap water, public water supply systems, wells, and hand pumps. Sampling locations were strategically chosen based on population density, water source type, and proximity to industrial or mining activities. The sampling protocol followed standard guidelines set by the WHO (2022a,b) and the United States Environmental Protection Agency (USEPA) (2020). To assess Pb contamination under different conditions, three types of water samples were collected: first-draw samples, flushed samples, and source samples. First-draw samples were taken after a minimum of 6 hours of stagnation to evaluate Pb leaching from pipes and plumbing systems. Flushed samples were collected after allowing the tap to run for 2–3 min, assessing Pb concentrations in the main water supply. Source samples were directly obtained from wells, reservoirs, and water treatment plants to determine primary Pb contamination levels. Immediately after collection, samples were acidified with nitric acid (HNO_3) to a pH of <2 to stabilize Pb ions and prevent precipitation (Li et al., 2024). The acidified samples were stored at 4°C and transported to the laboratory within 24 h for analysis (Mohan et al., 2023).

2.2 Analytical techniques

Lead concentrations in the collected water samples were determined using Atomic Absorption Spectrophotometry (AAS), a highly sensitive and precise technique for trace metal detection. The analysis followed the standard procedures outlined by the American Public Health Association (APHA) (2017) to ensure reliable results. Calibration curves were established using certified Pb standards, and quality control measures, including blank sample testing, were conducted throughout the analytical process to minimize errors. The method detection limit (MDL) for Pb was set at 0.001 mg/L to ensure accurate quantification of even low Pb concentrations. Furthermore, 10% of the total samples were analyzed in duplicates to validate the consistency and reproducibility of the results (Wu et al., 2023).

2.3 Statistical and geostatistical analysis

Descriptive statistical parameters, including mean, standard deviation, minimum, and maximum values, were calculated to summarize Pb concentration levels across the study area. A one-way ANOVA test was performed to determine significant differences in Pb concentrations among the five districts. The Shapiro–Wilk test was applied to assess the normality of Pb concentration data. This test is particularly suitable for small to moderately sized datasets and provides a W statistic, where values closer to 1 indicate normality (Alshehri et al., 2021; Razali and Wah, 2011). The null hypothesis assumes that the data follow a normal distribution. If the p-value is below 0.05, the null hypothesis is rejected, indicating that the data are not normally distributed. This assessment guided the selection of appropriate parametric or non-parametric statistical techniques for further analysis (Ghasemi and Zahediasl, 2012). Additionally, correlation analyses were conducted to assess relationships between Pb levels and potential influencing factors, such as water source type and proximity to industrial zones. To visualize Pb distribution patterns, Geographic Information System (GIS) tools were employed for geostatistical mapping, identifying contamination hotspots and regions with elevated health risks (Hasan M. M. et al., 2023; Hasan M. et al., 2023; Li and Heap, 2014).

2.4 Health risk assessment methodology

The health risk assessment (HRA) of lead (Pb) contamination in drinking water across the five districts Kohat, Hangu, Dera Ismail Khan (D.I. Khan), Bannu, and Karak was conducted using the standard four-step approach outlined by the United States Environmental Protection Agency (USEPA). These steps include hazard identification, exposure assessment, dose–response assessment, and risk characterization (Mohanadas et al., 2023).

2.4.1 Hazard identification

Lead (Pb) is a toxic heavy metal with no known safe exposure level. Chronic exposure can result in severe neurological, developmental, and cardiovascular issues, particularly in children and pregnant women. The World Health Organization (WHO) and USEPA have set the permissible exposure limit (PEL) for Pb in drinking water at 0.01 mg/L and the maximum contaminant level (MCL) at 0.015 mg/L, respectively.

2.4.2 Exposure assessment

The lead concentrations in drinking water samples from each district were analyzed and compared to the regulatory limits. The mean Pb concentrations exceeded the PEL in all districts, with a 100% Exceedance rate in Hangu, Bannu, and Karak; 96% in Kohat; and 92% in D.I. Khan. The maximum recorded Pb concentration was 1.809 mg/L in Bannu, which is 180 times the PEL. The estimated daily intake (EDI) of Pb was calculated using the equation:

$$EDI = \frac{Cw \times IR}{BW}$$

Where:

- Cw = Lead concentration in water (mg/L).
- IR = Water intake rate (2 L/day for adults, 1 L/day for children).
- BW = Body weight (70 kg for adults, 10 kg for children).

Using the highest Pb concentration (1.809 mg/L), the EDI for adults and children was determined as follows:

- Adults: 0.0517 mg/kg/day.
- Children: 0.1809 mg/kg/day.

Both values significantly exceed the EPA Reference Dose (RfD) of 0.0015 mg/kg/day, indicating a substantial health risk.

2.4.3 Dose–response assessment

The EPA RfD for lead exposure indicates that adverse health effects occur at concentrations exceeding 0.0015 mg/kg/day. The calculated EDI values for all districts surpassed this threshold, with the highest exposures occurring in Bannu and Karak. Given that children are more vulnerable to lead toxicity, their exposure levels present a particularly high risk of neurodevelopmental impairments and other health complications.

2.4.4 Risk characterization

The hazard quotient (HQ) was calculated to assess the health risk using the equation:

$$HQ = \frac{EDI}{RfD}$$

- Adults: HQ = 34.47 (Bannu) and 29.93 (Karak).
- Children: HQ = 120.6 (Bannu) and 104.8 (Karak).

Since HQ values exceed 1 in all districts, significant health risks are indicated. Bannu and Karak fall into the “critical risk” category, requiring urgent intervention, while Kohat, Hangu, and D.I. Khan exhibit high to moderate risks (Table 1).

3 Results

3.1 Lead concentrations in drinking water

The assessment of lead (Pb) contamination in drinking water across the five districts Kohat, Hangu, Dera Ismail Khan (D.I. Khan), Bannu, and Karak demonstrates widespread exceedance of regulatory limits. The WHO’s Permissible Exposure Limit (PEL) for Pb in drinking water is 0.01 mg/L,

TABLE 1 Statistical analysis of lead concentration in drinking water samples.

District	Mean (mg/L)	Median (mg/L)	Standard deviation	Minimum (mg/L)	Maximum (mg/L)
Kohat	0.2757	0.051	0.3612	0.005	0.989
Hangu	0.2872	0.083	0.3157	0.012	0.981
D.I. Khan	0.1746	0.059	0.2575	0.002	0.831
Bannu	0.7203	0.820	0.4154	0.020	1.809
Karak	0.6930	0.721	0.3604	0.041	1.572

TABLE 2 Estimated daily intake (EDI) and hazard quotient (HQ) for Kohat district.

S. No.	Sample ID	Pb conc. (mg/L)	EDI adult (mg/kg/day)	EDI child (mg/kg/day)	HQ adult	HQ child
1	Koh-1	0.810	0.02314	0.0810	15.43	54.00
2	Koh-2	0.705	0.02014	0.0705	13.43	47.00
3	Koh-3	0.608	0.01737	0.0608	11.58	40.53
4	Koh-4	0.810	0.02314	0.0810	15.43	54.00
5	Koh-5	0.051	0.00146	0.0051	0.97	3.40
6	Koh-6	0.602	0.01720	0.0602	11.47	40.13
7	Koh-7	0.024	0.00069	0.0024	0.46	1.60
8	Koh-8	0.910	0.02600	0.0910	17.33	60.67
9	Koh-9	0.989	0.02826	0.0989	18.84	65.93
10	Koh-10	0.023	0.00066	0.0023	0.44	1.53
11	Koh-11	0.023	0.00066	0.0023	0.44	1.53
12	Koh-12	0.005	0.00014	0.0005	0.10	0.33
13	Koh-13	0.023	0.00066	0.0023	0.44	1.53
14	Koh-14	0.032	0.00091	0.0032	0.61	2.13
15	Koh-15	0.042	0.00120	0.0042	0.80	2.80
16	Koh-16	0.022	0.00063	0.0022	0.42	1.47
17	Koh-17	0.043	0.00123	0.0043	0.82	2.87
18	Koh-18	0.054	0.00154	0.0054	1.03	3.60
19	Koh-19	0.069	0.00197	0.0069	1.31	4.60
20	Koh-20	0.809	0.02311	0.0809	15.41	53.93
21	Koh-21	0.072	0.00206	0.0072	1.37	4.80
22	Koh-22	0.052	0.00149	0.0052	0.99	3.47
23	Koh-23	0.037	0.00106	0.0037	0.70	2.47
24	Koh-24	0.042	0.00120	0.0042	0.80	2.80
25	Koh-25	0.035	0.00100	0.0035	0.67	2.33

while the USEPA's Maximum Contaminant Level (MCL) is 0.015 mg/L. The detailed results of Pb concentrations in drinking water are presented in Tables 2–6. Among the five districts, Bannu exhibited the highest mean Pb concentration (0.720 mg/L), followed by Karak (0.693 mg/L), with maximum concentrations reaching 1.809 mg/L and 1.572 mg/L, respectively. In Hangu, the mean Pb concentration was 0.287 mg/L, and in Kohat, it was 0.2757 mg/L, both exceeding the regulatory thresholds. D.I. Khan recorded the lowest mean Pb concentration (0.1746 mg/L) yet still surpassed the permissible limits. The exceedance rates were 100% in Hangu, Bannu, and Karak, followed by 96% in Kohat and 92% in D.I. Khan, highlighting a severe public health risk and the urgent need for mitigation measures.

3.2 Statistical analysis of lead concentration in drinking water

The statistical analysis of lead concentration in drinking water samples from Kohat, Hangu, D.I. Khan, Bannu, and Karak reveals

TABLE 3 Estimated daily intake (EDI) and hazard quotient (HQ) for district Hangu.

Sample ID	Pb concentration (mg/L)	EDI (mg/kg/day) – adults	EDI (mg/kg/day) – children	HQ – adults	HQ – children
Han-1	0.939	0.0268	0.0939	18.80	65.93
Han-2	0.232	0.0066	0.0232	4.63	16.53
Han-3	0.501	0.0143	0.0501	10.00	35.80
Han-4	0.431	0.0123	0.0431	8.60	30.80
Han-5	0.231	0.0066	0.0231	4.60	16.47
Han-6	0.232	0.0066	0.0232	4.63	16.53
Han-7	0.012	0.0003	0.0012	0.23	0.87
Han-8	0.051	0.0015	0.0051	1.00	3.40
Han-9	0.062	0.0018	0.0062	1.23	4.13
Han-10	0.032	0.0009	0.0032	0.60	2.13
Han-11	0.021	0.0006	0.0021	0.40	1.40
Han-12	0.891	0.0254	0.0891	17.80	62.47
Han-13	0.721	0.0206	0.0721	14.47	50.07
Han-14	0.531	0.0152	0.0531	10.63	37.93
Han-15	0.421	0.0120	0.0421	8.40	30.13
Han-16	0.051	0.0015	0.0051	1.00	3.40
Han-17	0.021	0.0006	0.0021	0.40	1.40
Han-18	0.051	0.0015	0.0051	1.00	3.40
Han-19	0.053	0.0015	0.0053	1.00	3.53
Han-20	0.981	0.0280	0.0981	19.60	68.67
Han-21	0.032	0.0009	0.0032	0.60	2.13
Han-22	0.451	0.0129	0.0451	9.00	31.27
Han-23	0.083	0.0024	0.0083	1.67	5.77
Han-24	0.067	0.0019	0.0067	1.33	4.67
Han-25	0.082	0.0023	0.0082	1.63	5.73

significant variations in contamination levels across the districts. Kohat exhibits a mean lead concentration of 0.2757 mg/L, with values ranging between 0.005 mg/L and 0.989 mg/L, and a high standard deviation (0.3612), indicating substantial fluctuations in contamination levels. Similarly, Hangu has a comparable mean concentration of 0.2872 mg/L, but its higher median value (0.083 mg/L) suggests that a larger number of samples exceed the permissible limit (0.01 mg/L).

Among the five districts, D.I. Khan has the lowest mean concentration (0.1746 mg/L) and a lower maximum value (0.831 mg/L), yet the contamination still surpasses the WHO permissible exposure level. In contrast, Bannu presents the highest recorded lead concentration, reaching 1.809 mg/L, with a mean of 0.7203 mg/L, signifying severe contamination. Karak also exhibits alarmingly high lead levels, with an average concentration of 0.693 mg/L and a peak of 1.572 mg/L, indicating a considerable public health risk. The findings highlight that lead concentrations in all districts exceed the WHO permissible limit (0.01 mg/L), with Bannu and Karak being the most affected due to significantly elevated mean values and extreme maximum concentrations.

Table 7 shows a comparison with the permissible exposure limit (PEL) of 0.01 mg/L indicated widespread Exceedance. In Kohat, 96% of samples exceeded the PEL, while in Hangu, Bannu, and Karak, all samples (100%) surpassed the safe limit. Even in D.I. Khan, which had the lowest mean concentration, 92% of the samples still exceeded the PEL.

Table 8 analyze the ANOVA test (p-value = 8.16×10^{-11}) confirmed a statistically significant difference in lead concentrations between districts, suggesting localized factors affecting contamination levels. The results highlight an urgent need for intervention, particularly in Bannu and Karak, where lead concentrations are critically high. Immediate measures such as water treatment, improved infrastructure, and regular monitoring are necessary to mitigate the potential health risks associated with lead exposure.

3.2.1 Shapiro–Wilk test results for lead concentration data

Table 9 analyze "The Shapiro–Wilk test: conducted to evaluate the normality of lead concentration data across five districts. The results indicate that lead concentration data for Kohat, Hangu, and D.I. Khan do not follow a normal distribution ($p < 0.05$), suggesting significant deviations from normality. In contrast, the data from Bannu and Karak exhibit normal distribution ($p > 0.05$), meaning the lead

TABLE 4 Estimated daily intake (EDI) and hazard quotient (HQ) for district D.I. Khan.

Sample ID	Pb concentration (mg/L)	EDI (mg/kg/day) – adults	EDI (mg/kg/day) – children	HQ – adults	HQ – children
Di.k-1	0.576	0.0164	0.0576	11.53	40.27
Di.k-2	0.621	0.0177	0.0621	12.40	43.33
Di.k-3	0.021	0.0006	0.0021	0.42	1.47
Di.k-4	0.005	0.0001	0.0005	0.10	0.35
Di.k-5	0.002	0.00006	0.0002	0.04	0.14
Di.k-6	0.576	0.0164	0.0576	11.53	40.27
Di.k-7	0.021	0.0006	0.0021	0.42	1.47
Di.k-8	0.031	0.0009	0.0031	0.62	2.13
Di.k-9	0.052	0.0015	0.0052	1.04	3.63
Di.k-10	0.034	0.0010	0.0034	0.68	2.37
Di.k-11	0.051	0.0015	0.0051	1.02	3.57
Di.k-12	0.831	0.0237	0.0831	16.55	57.93
Di.k-13	0.741	0.0212	0.0741	14.73	51.60
Di.k-14	0.042	0.0012	0.0042	0.84	2.93
Di.k-15	0.056	0.0016	0.0056	1.12	3.87
Di.k-16	0.071	0.0020	0.0071	1.42	4.93
Di.k-17	0.071	0.0020	0.0071	1.42	4.93
Di.k-18	0.092	0.0026	0.0092	1.83	6.40
Di.k-19	0.081	0.0023	0.0081	1.63	5.63
Di.k-20	0.059	0.0017	0.0059	1.18	4.07
Di.k-21	0.092	0.0026	0.0092	1.83	6.40
Di.k-22	0.063	0.0018	0.0063	1.23	4.37
Di.k-23	0.054	0.0015	0.0054	1.08	3.73
Di.k-24	0.071	0.0020	0.0071	1.42	4.93
Di.k-25	0.051	0.0015	0.0051	1.02	3.57

concentration values in these districts follow a more symmetric distribution. The presence of non-normality in some districts suggests that non-parametric statistical tests may be more appropriate for further analysis in these areas.

3.3 Risk assessment: estimated daily intake and hazard quotient

The risk assessment of lead (Pb) contamination in drinking water across the five districts Kohat, Hangu, Dera Ismail Khan (D.I. Khan), Bannu, and Karak demonstrate significant health risks, particularly for vulnerable populations such as children. The estimated daily intake (EDI) calculations confirm that Pb exposure in all districts surpasses the EPA Reference Dose (RfD) of 0.0015 mg/kg/day, indicating potential adverse health effects. The highest EDI values were recorded in Bannu (0.0542 mg/kg/day for adults and 0.1894 mg/kg/day for children), followed closely by Karak (0.0486 mg/kg/day for adults and 0.1683 mg/kg/day for children). In contrast, D.I. Khan exhibited the lowest EDI values (0.0256 mg/kg/day for adults and 0.0895 mg/kg/day for children), yet still exceeded the recommended safe limits. The Hazard Quotient (HQ) calculations further confirm the severity of Pb contamination, with Bannu and Karak categorized under the critical risk level, posing significant long-term health hazards. These findings emphasize the urgent need for intervention, including improved water treatment systems, alternative water sources, and regulatory measures to mitigate Pb exposure risks.

The estimated daily intake (EDI) of lead in drinking water samples from Kohat District exceeded the EPA Reference Dose (RfD) of 0.0015 mg/kg/day in most cases, particularly in samples Koh-1, Koh-2, Koh-3, Koh-4, Koh-6, Koh-8, Koh-9, and Koh-20, indicating a potential health risk. The hazard quotient (HQ) values were significantly greater than 1, particularly in samples Koh-1, Koh-8, Koh-9, and Koh-20, suggesting a high to critical risk of lead toxicity. Children exhibited higher EDI and HQ values compared to adults, emphasizing their vulnerability to lead exposure. Urgent mitigation measures such as water filtration, alternative water sources, and policy interventions are strongly recommended to reduce exposure risks in this region.

The estimated daily intake (EDI) of lead in drinking water samples from District Hangu indicates significant contamination, with multiple samples exceeding the EPA Reference Dose (RfD) of 0.0015 mg/kg/day. Samples Han-1, Han-12, Han-13, Han-14,

TABLE 5 Estimated daily intake (EDI) and hazard quotient (HQ) for district Bannu.

Sample ID	Pb concentration (mg/L)	EDI (mg/kg/day) – adults	EDI (mg/kg/day) – children	HQ – adults	HQ – children
Ban-1	0.88	0.0251	0.0880	17.61	61.33
Ban-2	0.82	0.0234	0.0820	16.41	57.17
Ban-3	0.02	0.0006	0.0020	0.40	1.39
Ban-4	1.097	0.0313	0.1097	21.89	76.67
Ban-5	1.079	0.0308	0.1079	21.47	75.07
Ban-6	1.081	0.0308	0.1081	21.51	75.40
Ban-7	1.021	0.0291	0.1021	20.31	71.07
Ban-8	1.032	0.0294	0.1032	20.63	72.27
Ban-9	1.001	0.0286	0.1001	20.02	70.07
Ban-10	0.717	0.0205	0.0717	14.34	50.13
Ban-11	0.669	0.0192	0.0669	13.38	46.73
Ban-12	0.024	0.0007	0.0024	0.48	1.67
Ban-13	0.463	0.0133	0.0463	9.27	32.27
Ban-14	0.251	0.0072	0.0251	5.03	17.47
Ban-15	0.231	0.0066	0.0231	4.62	16.07
Ban-16	0.527	0.0151	0.0527	10.53	36.87
Ban-17	0.831	0.0237	0.0831	16.55	57.93
Ban-18	1.002	0.0286	0.1002	20.04	70.13
Ban-19	1.809	0.0517	0.1809	36.07	126.27
Ban-20	0.281	0.0080	0.0281	5.61	19.60
Ban-21	0.531	0.0152	0.0531	10.61	37.27
Ban-22	0.271	0.0078	0.0271	5.41	18.90
Ban-23	1.004	0.0287	0.1004	20.08	70.27
Ban-24	0.451	0.0130	0.0451	9.02	31.57
Ban-25	0.915	0.0262	0.0915	18.29	63.37

Han-20, and Han-22 exhibited notably high EDI values, suggesting potential health risks, especially for children, where exposure levels are significantly higher. The hazard quotient (HQ) values for these samples were greater than 1, indicating a high risk of lead toxicity for the local population. Samples Han-1, Han-12, Han-13, and Han-20 showed critical risk levels, where lead exposure could lead to serious health effects. Children are at the highest risk, as their HQ values are notably elevated, reflecting greater susceptibility to neurological and developmental impairments due to lead exposure.

The estimated daily intake (EDI) and hazard quotient (HQ) values for District D.I. Khan reveal elevated lead concentrations in drinking water, with multiple samples exceeding the EPA Reference Dose (RfD) of 0.0015 mg/kg/day. Critical contamination levels were found in samples Di.k-12, Di.k-13, Di.k-1, Di.k-2, and Di.k-6, where lead exposure is significantly higher. For children, the HQ values for these samples exceed 40, indicating severe potential health risks such as neurological damage, cognitive impairments, and developmental disorders due to chronic lead exposure. Although several samples had low lead levels (e.g., Di.k-3, Di.k-4, Di.k-5), over 60% of the samples exceeded the safe limit, posing serious health concerns for the local population.

The Estimated Daily Intake (EDI) and Hazard Quotient (HQ) values for District Bannu indicate severe lead contamination in drinking water, with a majority of the samples exceeding the WHO safe limit of 0.01 mg/L. Highly contaminated samples include Ban-4, Ban-5, Ban-6, Ban-7, Ban-8, Ban-9, Ban-18, Ban-19, and Ban-23, where the HQ values for children exceed 70, indicating an extreme health hazard. Ban-19 shows the highest contamination, with an HQ of 126.27 for children, which poses serious neurotoxic risks, cognitive impairments, and developmental delays. For adults, more than 70% of the samples have HQ values above 10, suggesting a high likelihood of chronic lead poisoning. Lower contamination levels were observed in Ban-3, Ban-12, Ban-14, and Ban-15, but the overall results indicate significant health risks for the population in Bannu District.

The Estimated Daily Intake (EDI) and Hazard Quotient (HQ) values for District Karak indicate significant lead contamination in drinking water, with several samples surpassing the WHO permissible limit of 0.01 mg/L. The highest levels of lead contamination were observed in samples K-W3, K-W6, K-W7, and K-W14, where HQ values exceeded 100 for children, highlighting extreme neurotoxic risks. Moderate contamination was found in samples K-W1, K-W4, K-W9, K-W10, and K-W18, with HQ values ranging between 50 and 70 for children, still posing

TABLE 6 Estimated daily intake (EDI) and hazard quotient (HQ) for district Karak.

Sample ID	Pb concentration (mg/L)	EDI (mg/kg/day) – adults	EDI (mg/kg/day) – children	HQ – adults	HQ – children
K-W1	1.019	0.0290	0.1019	20.39	71.36
K-W2	0.746	0.0213	0.0746	14.93	52.13
K-W3	1.572	0.0447	0.1572	31.44	110.86
K-W4	0.891	0.0253	0.0891	17.73	62.37
K-W5	0.671	0.0191	0.0671	13.37	46.93
K-W6	1.538	0.0437	0.1538	30.76	108.43
K-W7	1.538	0.0437	0.1538	30.76	108.43
K-W8	0.737	0.0211	0.0737	14.73	51.67
K-W9	0.871	0.0247	0.0871	17.41	61.13
K-W10	0.891	0.0253	0.0891	17.73	62.37
K-W11	0.651	0.0186	0.0651	13.03	45.43
K-W12	0.041	0.0012	0.0041	0.82	2.87
K-W13	0.051	0.0014	0.0051	1.02	3.57
K-W14	1.033	0.0295	0.1033	20.67	72.33
K-W15	0.981	0.0281	0.0981	19.63	68.63
K-W16	0.581	0.0166	0.0581	11.63	40.73
K-W17	0.472	0.0135	0.0472	9.44	33.73
K-W18	0.981	0.0281	0.0981	19.63	68.63
K-W19	0.571	0.0163	0.0571	11.41	39.93
K-W20	0.531	0.0152	0.0531	10.61	37.27
K-W21	0.761	0.0217	0.0761	15.23	53.67
K-W22	0.987	0.0283	0.0987	19.73	68.90
K-W23	0.061	0.0018	0.0061	1.22	4.30
K-W24	0.341	0.0097	0.0341	6.83	24.37
K-W25	0.631	0.0180	0.0631	12.61	44.17
K-W26	0.071	0.0020	0.0071	1.42	5.00
K-W27	0.891	0.0253	0.0891	17.73	62.37
K-W28	0.671	0.0191	0.0671	13.37	46.93
K-W29	0.310	0.0088	0.0310	6.20	22.30
K-W30	0.061	0.0018	0.0061	1.22	4.30
K-W31	0.581	0.0166	0.0581	11.63	40.73
K-W32	0.841	0.0239	0.0841	16.83	59.43
K-W33	0.721	0.0205	0.0721	14.43	50.17
K-W34	0.891	0.0253	0.0891	17.73	62.37
K-W35	0.902	0.0256	0.0902	18.04	63.13
K-W36	0.501	0.0143	0.0501	10.02	35.07
K-W37	0.721	0.0205	0.0721	14.43	50.17
K-W38	0.831	0.0237	0.0831	16.55	57.93
K-W39	0.476	0.0136	0.0476	9.52	34.07
K-W40	0.831	0.0237	0.0831	16.55	57.93
K-W41	0.541	0.0155	0.0541	10.81	37.93
K-W42	0.472	0.0135	0.0472	9.44	33.73
K-W43	0.581	0.0166	0.0581	11.63	40.73

(Continued)

TABLE 6 (Continued)

Sample ID	Pb concentration (mg/L)	EDI (mg/kg/day) – adults	EDI (mg/kg/day) – children	HQ – adults	HQ – children
K-W44	0.321	0.0091	0.0321	6.42	23.17
K-W45	0.821	0.0234	0.0821	16.41	57.17

TABLE 7 Exceedance of PEL (0.01 mg/L) in each district.

District	Total samples	Samples > PEL	% Exceedance
Kohat	25	24	96%
Hangu	25	25	100%
D.I. Khan	25	23	92%
Bannu	25	25	100%
Karak	45	45	100%

TABLE 8 ANOVA test results.

Test	*p*-value	Interpretation
ANOVA	8.16×10^{-11}	Significant differences between districts

TABLE 9 Shapiro–Wilk test for normality.

District	W-statistic	*p*-value	Normality
Kohat	0.6876	0.0000	Not normal
Hangu	0.8022	0.0002	Not normal
D.I. Khan	0.6143	0.0000	Not normal
Bannu	0.9391	0.1410	Normal
Karak	0.9422	0.1663	Normal

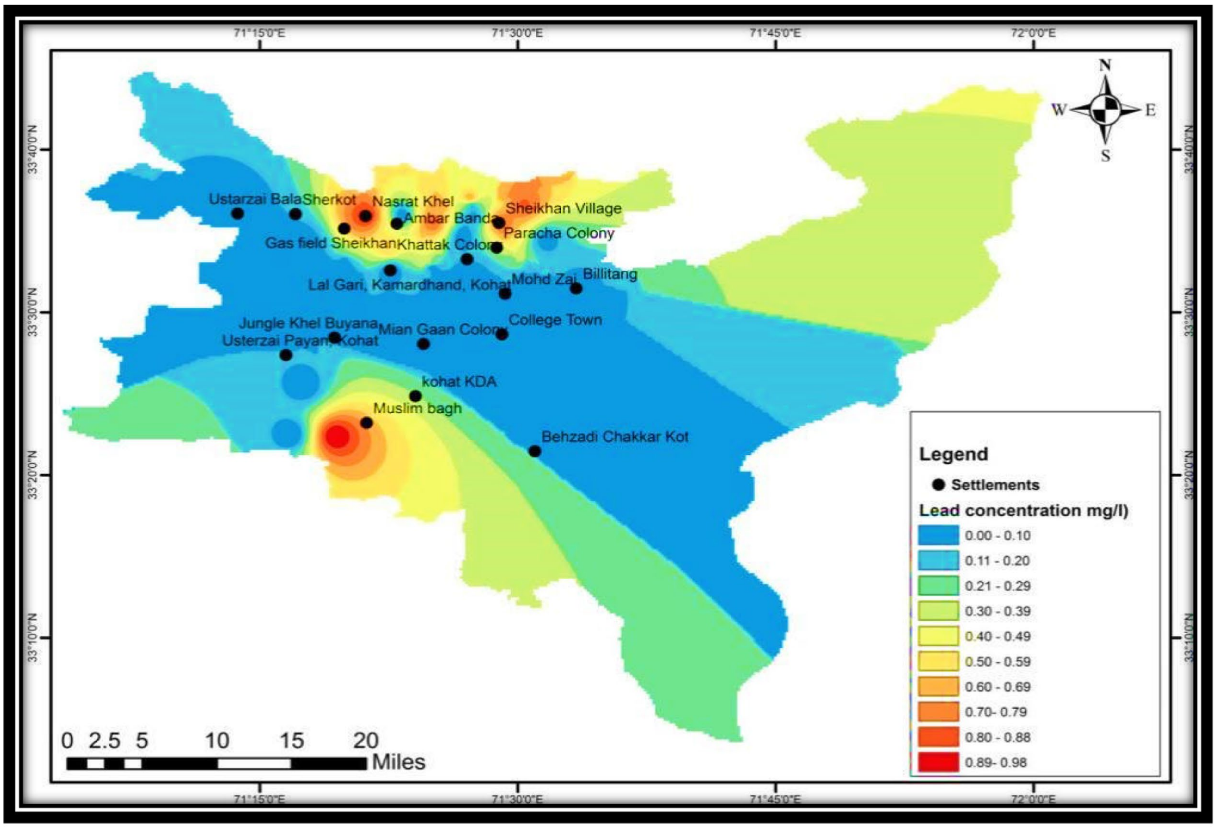
TABLE 10 Risk characterization – hazard quotient (HQ) calculation.

District	HQ (adults)	HQ (children)	Risk level
Kohat	5.27	18.4	High risk
Hangu	5.47	19.1	High risk
D.I. Khan	3.33	11.7	Moderate risk
Bannu	34.47	120.6	Critical risk
Karak	29.93	104.8	Critical risk

TABLE 11 Risk management recommendations.

Risk level	Recommended actions
Moderate risk (HQ: 1–10)	Public awareness, filtration systems, periodic monitoring.
High risk (HQ: 10–30)	Alternative water sources, strict industrial regulations, water treatment plants.
Critical risk (HQ > 30)	Immediate intervention, emergency water supply, remediation strategies.

considerable health hazards. In contrast, lower-risk samples such as K-W12, K-W13, K-W23, K-W26, and K-W30 exhibited HQ values below 5, indicating minimal health risks. These findings underscore the urgent need for water purification interventions and public awareness programs to mitigate long-term health consequences in the region. The Hazard Quotient (HQ), analyses values are shown in Table 10, which measures risk by comparing the EDI to the RfD, confirms severe health risks across all districts. The highest risk is in Bannu (HQ = 34.47 for adults, 120.6 for children) and Karak (HQ = 29.93 for adults, 104.8 for children), placing them in the critical risk category. Even in the district with the lowest mean concentration, D.I. Khan, the HQ values (3.33 for adults, 11.7 for children) still indicate moderate to high risk, warranting immediate attention (Table 11).

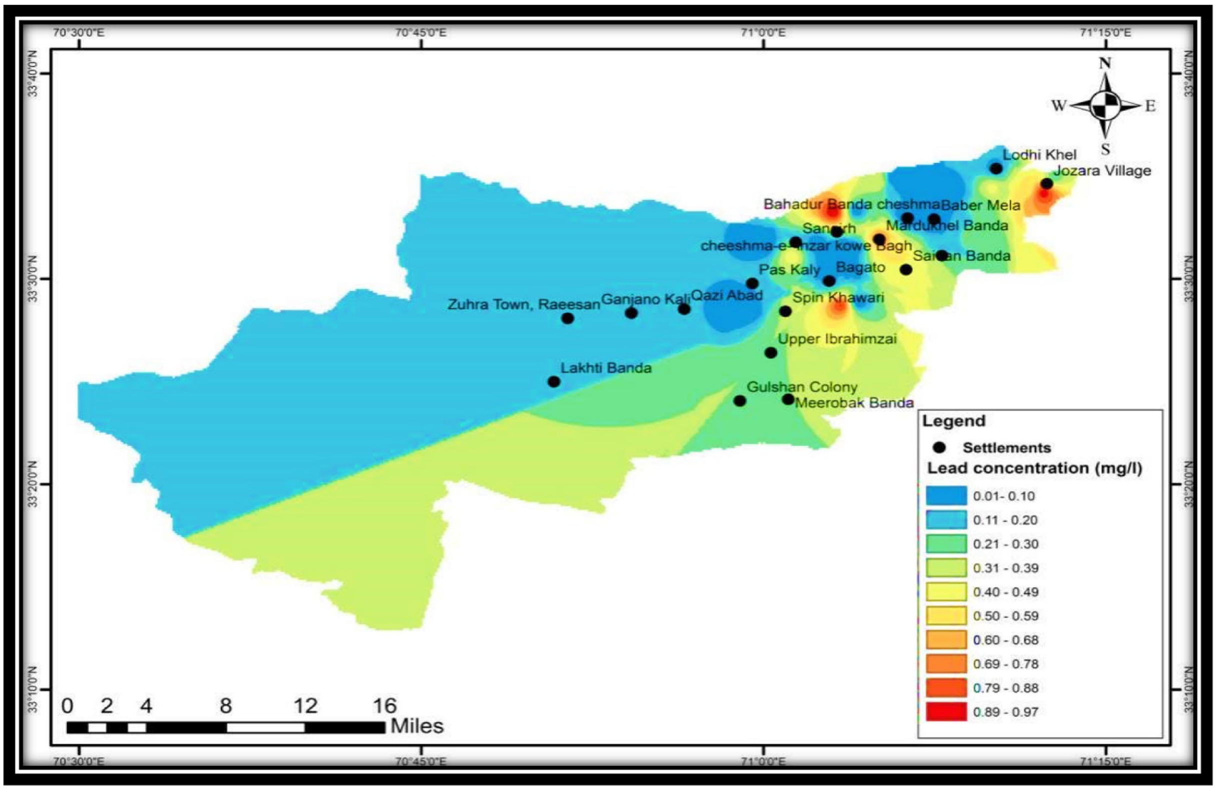


MAP 2
IDW prediction model representing lead measurements in drinking water samples from district Kohat. The blue color represents a low Pb level. The yellow color in the map represents moderate concentration; the red color represents vulnerable risk areas with the highest concentration of Pb.

Based on these findings, urgent intervention is required, particularly in Bannu and Karak, where lead contamination poses an extreme threat to public health. Immediate actions such as emergency water supply, filtration systems, and public health awareness campaigns are essential. Additionally, long-term solutions like industrial regulation enforcement, water treatment infrastructure, and groundwater remediation must be prioritized to mitigate future risks.

3.4 Risk assessment using geostatistical analysis

The Inverse Distance Weighting (IDW) modeling method was applied to predict unmeasured lead (Pb) concentrations in drinking water across the five studied districts Kohat, Hangu, D.I. Khan, Bannu, and Karak allowing for a spatial distribution analysis of contamination levels. The generated maps reveal hotspot locations with critically high Pb concentrations, where red areas indicate severe contamination, and blue areas represent lower concentrations. In Kohat, the most affected areas include Gas-filled Sheikhan, Bezadi Cheker Koti, Cheshma Zayry Dhand, Muslim Bagh Cheshma, Bahadur Baba Cheshma, and Jangel Khel Buyanya Cheshma, where Pb levels exceed 0.81 mg/L, necessitating immediate intervention to prevent neurotoxic risks, especially for children. Hangu exhibits similar contamination trends, with Jozara Water, Railway Road Hangu, Gulshan Colony Cheshma, Merobak Banda, Cheshma Inzer Kowe, and the Government Degree College for Girls experiencing Pb concentrations as high as 0.981 mg/L, indicating potential sources such as industrial discharge, deteriorating pipelines, or geological factors. In D.I. Khan, hotspot locations such as Mufti Mehmood Circuit House, Madina Colony, Imamia Colony, Gilani Town, and Keri Juma Khan were identified, with maximum Pb levels reaching 0.831 mg/L, signaling the need for continuous monitoring to prevent further contamination. Bannu presents the most critical situation, with Kalanger, Tur Kaki, Asad Kaki, and Bharat recording Pb concentrations up to 1.809 mg/L, indicating acute contamination that demands urgent water treatment and alternative water sources. Similarly, Karak is another high-risk area, with severe contamination found in Tehsil Circuit House, Surdag, Rehmat Abad, Hamadan, Thati, Chokara, and Takht-e-Nasrati, where Pb levels exceed 1.572 mg/L, suggesting widespread groundwater vulnerability. The IDW analysis confirms that geographically closer locations exhibit similar Pb trends, highlighting the importance of early identification of high-risk zones for targeted interventions, estimation of exposure in unmonitored areas, and the development of spatial risk maps (Maps 2–6) to aid policymakers in formulating effective mitigation strategies. The findings reveal that all five districts exceed the WHO permissible Pb limit (0.01 mg/L), with Bannu and Karak posing the greatest health risks due to extreme Pb concentrations. Consequently,



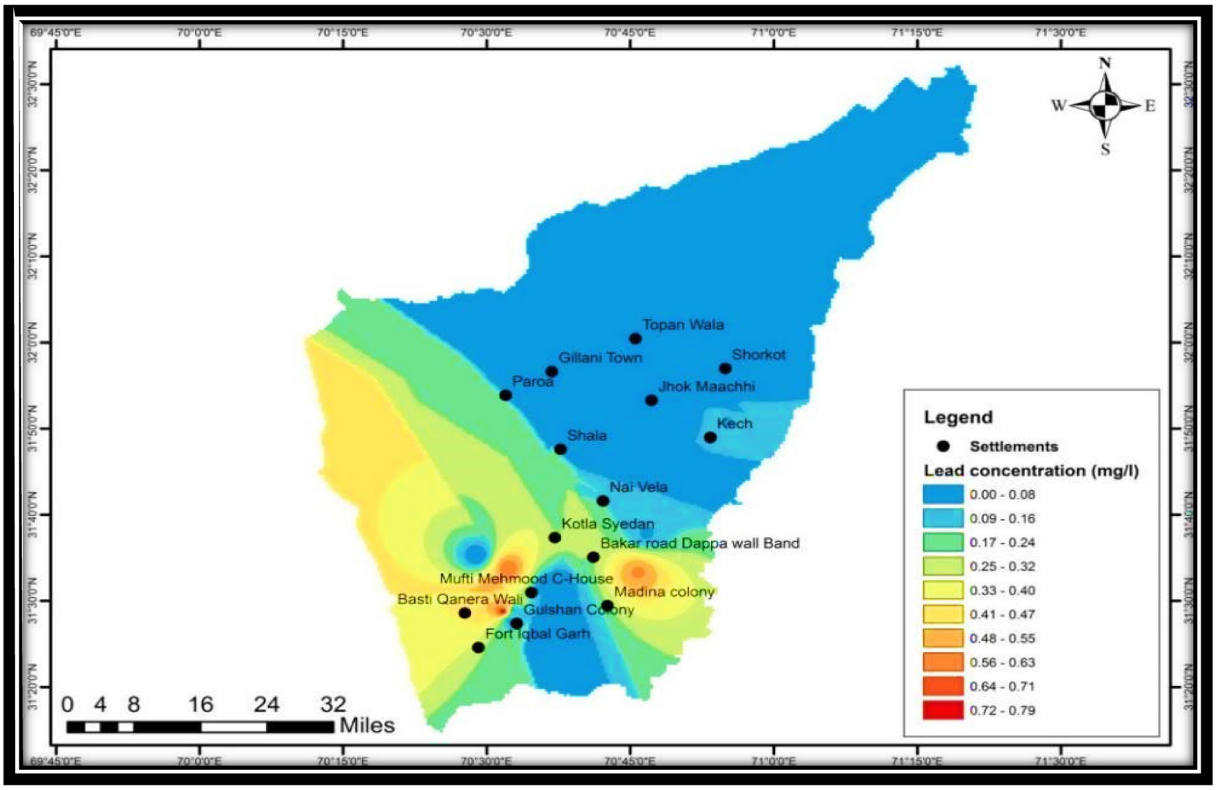
MAP 3
IDW prediction model representing lead measurements in the drinking water samples of district Hangu. The blue color represents a low Pb level. The yellow color in the map represents a moderate concentration; the red color vulnerability risk represents the area with the highest concentration of Pb.

urgent water purification measures, public awareness campaigns, and long-term environmental management strategies are imperative to safeguard public health from Pb-related hazards.

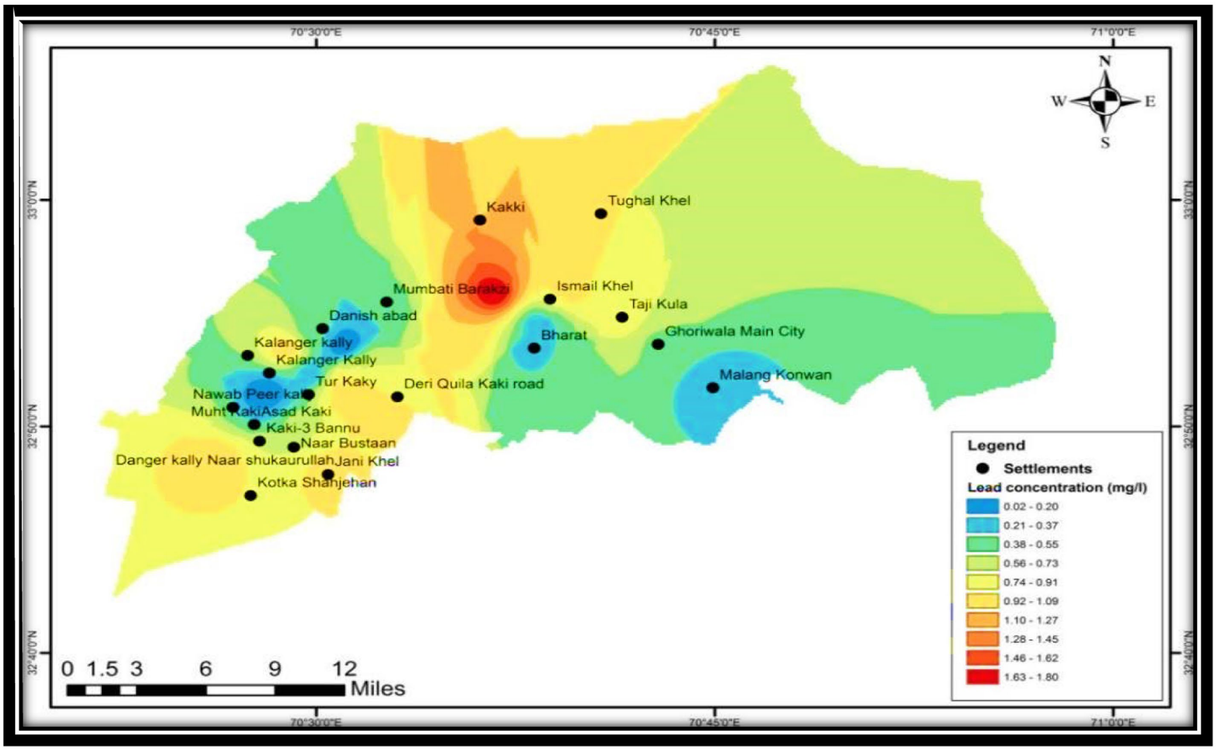
4 Discussion

The findings of this study reveal substantial variations in lead (Pb) contamination in drinking water across the five studied districts: Kohat, Hangu, Dera Ismail Khan (D.I. Khan), Bannu, and Karak. Notably, Bannu recorded the highest mean Pb concentration (0.7203 mg/L) with a peak value of 1.809 mg/L, while Karak followed closely with a mean Pb concentration of 0.693 mg/L and a maximum of 1.572 mg/L. The presence of such elevated Pb levels is alarming, as chronic exposure is associated with severe neurotoxic and developmental health effects, particularly in children (Needleman, 2004; Lanphear et al., 2005). Risk characterization using hazard quotient (HQ) calculations further substantiated the potential health threats. Bannu and Karak exhibited critical risk levels, with HQ values surpassing 100 for children, indicating extreme neurotoxic and systemic health risks (United States Environmental Protection Agency (USEPA), 2000). Kohat and Hangu were categorized as high-risk regions, with HQ values for children exceeding 10, while D.I. Khan presented a moderate risk profile. These findings underscore the urgency of implementing effective water purification measures and regulatory interventions to mitigate Pb exposure in these regions (Sharma and Rehman, 2020). Geostatistical analysis using the Inverse Distance Weighting (IDW) interpolation method identified distinct Pb contamination hotspots across all five districts. In Kohat, highly affected locations included Gas-filled Sheikhan, Bezadi Cheker Koti, and Jangel Khel Buyanya Cheshma. Hangu's contamination hotspots were concentrated around Jozara Water, Railway Road Hangu, and Gulshan Colony Cheshma. Similarly, elevated Pb levels in D.I. Khan were observed in Mufti Mehmood Circuit House, Madina Colony, and Gilani Town, while hotspot locations in Bannu included Kalanger, Tur Kaki, and Bharat. In Karak, critical contamination was recorded in areas such as Tehsil Circuit House, Surdag, Rehmat Abad, and Takht-e-Nasrati. The spatial distribution trends suggest that contamination sources are likely linked to local industrial activities, mining operations, and inadequate waste management practices (Nriagu, 1996; Xiao et al., 2019).

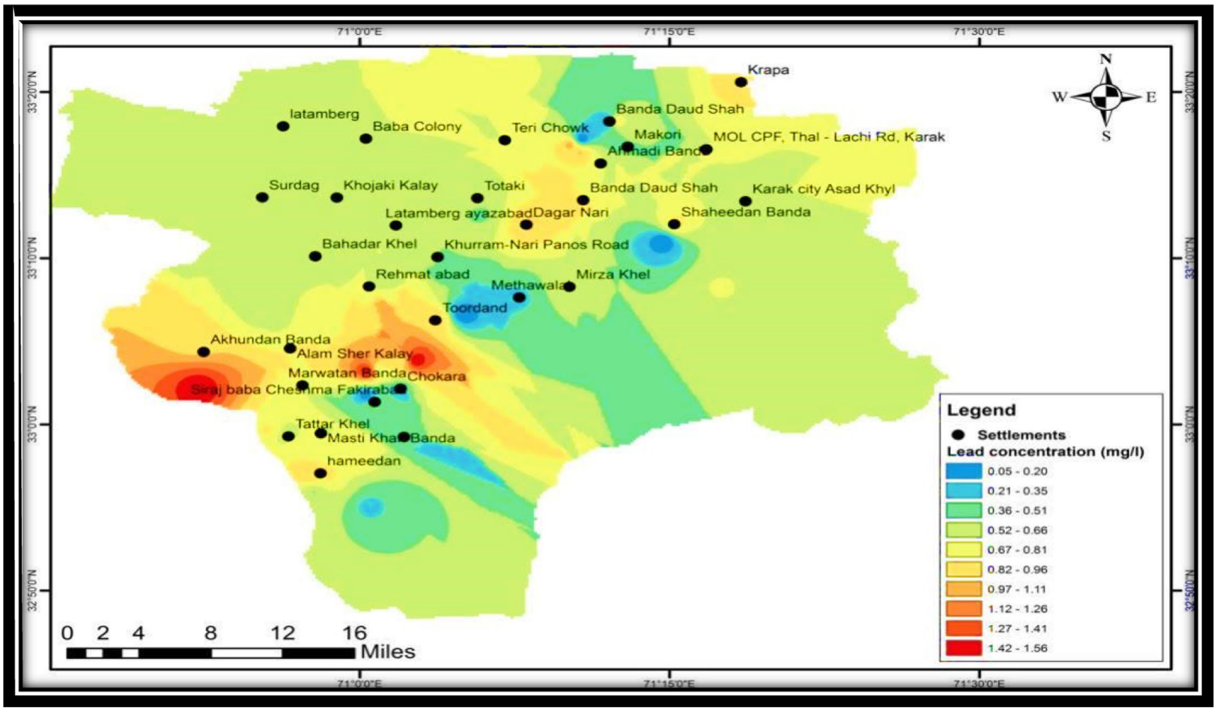
The IDW modeling results support previous research indicating that Pb contamination is often influenced by topography, industrial proximity, and natural geochemical processes (Li and Heap, 2014). Notably, areas at higher altitudes and near industrial zones exhibited relatively higher Pb concentrations, highlighting the need for targeted mitigation strategies. Studies have shown that such contamination often arises from anthropogenic sources, including industrial discharge, corrosion of lead-based plumbing materials, and atmospheric deposition from vehicular emissions (Goyer, 1996). Given that Pb has no known biological function and is toxic even at low concentrations, the long-term implications of exposure necessitate urgent intervention. Overall, the study underscores the critical need for regulatory oversight and remedial action in these high-risk regions (Xiao et al., 2019).



MAP 4
Predication model represents lead measurements in drinking water samples from district D.I. Khan. The blue color represents a low Pb level. The yellow color in the map represents a moderate concentration; the red color vulnerability risk represents the area with the highest concentration of Pb.



MAP 5
IDW prediction model representing lead measurements in the drinking water samples of district Bannu. The blue color represents a low Pb level. The yellow color in the map represents a moderate concentration; the red color vulnerability risk represents the area with the highest concentration of Pb.



MAP 6
IDW prediction model representing lead measurements in drinking water samples from district Karak. The blue color represents a low Pb level. The yellow color in the map represents a moderate concentration; the red color vulnerability risk represents the area with the highest concentration of Pb.

5 Conclusion

The findings of this study emphasize the critical issue of lead (Pb) contamination in drinking water across the five districts Kohat, Hangu, Dera Ismail Khan (D.I. Khan), Bannu, and Karak. The analysis revealed that Pb concentrations in all districts exceeded the WHO permissible exposure limit (0.01 mg/L), posing significant health risks. Among the areas studied, Bannu and Karak exhibited the highest contamination levels, with Pb concentrations reaching 1.809 mg/L and 1.572 mg/L, respectively. The hazard quotient (HQ) values for children in these districts exceeded 100, indicating extreme neurotoxic risks. The geostatistical analysis using the IDW modeling method effectively identified contamination hotspots, highlighting specific locations with elevated Pb levels. The high Pb concentrations observed suggest potential sources such as industrial emissions, mining activities, aging water supply infrastructure, and natural geochemical processes. The results emphasize the need for immediate intervention, including the implementation of advanced water treatment systems, strict regulatory measures to control Pb pollution, and public awareness campaigns on the dangers of lead exposure. Furthermore, continuous monitoring and predictive modeling using geostatistical techniques can aid in assessing long-term trends and ensuring sustainable water quality management. In conclusion, this study highlights the urgency of addressing Pb contamination in drinking water, particularly in high-risk areas like Bannu and Karak. The integration of geostatistical analysis provides a valuable approach for identifying contamination trends and guiding targeted mitigation strategies. Future research should focus on source apportionment studies and the development of cost-effective remediation technologies to ensure safe drinking water for affected populations.

6 Recommendation

To mitigate lead contamination in drinking water, immediate and long-term measures are essential. Short-term actions should include public awareness campaigns, provision of alternative water sources, installation of filtration systems, and regular water quality monitoring. In the long run, strict industrial regulations, infrastructure improvements, groundwater remediation, and integrated water resource management should be implemented. Government policies must enforce compliance, while community-based monitoring can enhance local engagement. Advanced research, geostatistical modeling, and epidemiological studies should be conducted to assess health risks and improve predictive analysis. International collaboration and funding from global organizations can further support sustainable solutions to ensure safe drinking water in affected regions.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

HS: Investigation, Methodology, Conceptualization, Resources, Supervision, Formal analysis, Software, Data curation, Writing – review & editing, Writing – original draft. FA: Data curation, Validation, Project administration, Funding acquisition, Writing – review & editing. MS: Conceptualization, Resources, Supervision, Formal analysis, Software, Data curation, Writing – original draft, Writing – review & editing. FAA: Funding acquisition, Writing – review & editing. LA: Data curation, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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