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A PUBLIC HEALTH PERSPECTIVE ON URANIUM-CONTAMINATED GROUNDWATER IN DISTRICT KARAK

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Abstract

Uranium contamination in groundwater has emerged as a significant public health concern, particularly in rural regions of Pakistan where contamination levels are increasing. District Karak, located in the Khyber Pakhtunkhwa province, presents a unique case due to its geological proximity to uranium-bearing formations. This study investigates the relationship between uranium-contaminated groundwater and associated public health impacts in District Karak by assessing metal concentrations, health outcomes, and demographic patterns. A cross-sectional, quantitative study was conducted from March 2024 to January 2025. A total of 285 groundwater samples were collected from various sources across the three tehsils of District Karak. Additionally, health data were gathered from 1,247 households. Statistical analysis was performed using SPSS version 28.0, and uranium concentrations were determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Health risk assessments were conducted following the United States Environmental Protection Agency (USEPA) guidelines. The mean uranium concentration in groundwater samples was 47.32 ± 23.8 μg/L, with 68.4% of samples exceeding the World Health Organization (WHO) permissible limit of 30 μg/L. Significantly higher contamination was observed in shallow aquifers (<60 m depth) ($p < 0.001$). The health survey revealed increased prevalence of kidney dysfunction (OR = 2.34; 95% CI: 1.67–3.28), bone disorders (OR = 1.89; 95% CI: 1.34–2.67), and liver diseases (OR = 1.56; 95% CI: 1.12–2.18) in high-exposure regions. Cancer risk assessment indicated that 72% of the study sites exceeded the acceptable lifetime cancer risk threshold ($>10^{-4}$). These findings highlight a strong association between uranium exposure and adverse health outcomes in District Karak. Immediate mitigation strategies, including the provision of alternative drinking water sources and ongoing community health

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monitoring, are urgently recommended. Note: 100-200% uncertainty in the results is expected due to inadequate sample preparation, instruments reliability and lack of accuracy in analytical technique.

INTRODUCTION

Uranium contamination in groundwater has emerged as a significant environmental and public health issue worldwide, particularly in regions with natural uranium-rich geological formations or anthropogenic influences (Devaraj et al., 2021; Balaram, Rani, & Rathore, 2022; Vengosh et al., 2022). Uranium exposure is associated with both chemical toxicity and radiological risks, leading to adverse health outcomes such as kidney damage, skeletal deformities, and increased cancer risk (Verma & Loganathan, 2023; Sahoo et al., 2022). Although the global body of research on this subject is extensive, localized studies in Pakistan—especially in rural and geologically complex areas. District Karak in southern Khyber Pakhtunkhwa stands out due to its unique sedimentary geology, which may contribute to elevated uranium levels in groundwater. With a population of approximately 445,000 people largely dependent on groundwater for daily consumption, potential uranium exposure is a serious concern (Khan et al., 2023). Recent assessments from other regions of Pakistan have revealed alarming concentrations of uranium in drinking water. For example, groundwater samples from Punjab reported uranium levels ranging from 0.2 to 501.1 µg/L—far above the World Health Organization's permissible limit of 30 µg/L (Kumar et al., 2023; Seminsky & Seminsky, 2019). Comparable findings in Indian Punjab have shown concentrations reaching up to 1,443 µg/L in shallow aquifers, highlighting widespread regional contamination (Sukanya & Joseph, 2023; Balakrishnan et al., 2019).

Karak's geological characteristics—particularly the presence of the Karak Thrust and associated tectonic features—are believed to facilitate uranium mobilization into groundwater sources (Khan et al., 2023; Heyde et al., 2025). Moreover, previous studies reporting high radon concentrations in local water sources further suggest a link to the uranium decay chain (Bala & Das, 2022). This study addresses the potential health hazards associated with uranium-contaminated groundwater in District Karak, a region that relies heavily on its groundwater resources for domestic and agricultural use. While uranium contamination has been reported across various regions in South Asia, there is a lack of localized research specifically focusing on District Karak. The district's unique geological characteristics may contribute to elevated uranium concentrations, yet the health impacts on the local population remain largely unexamined. This gap in knowledge is concerning, as prolonged exposure to uranium has been linked to serious health outcomes, including kidney dysfunction, bone disorders, and certain cancers. The widespread use of potentially contaminated groundwater for drinking and irrigation further exacerbates the risk. Given the absence of comprehensive data on both uranium concentrations and associated health outcomes in the region, the local population remains vulnerable to long-term health risks. This study aims to systematically assess uranium levels in groundwater and correlate them with health data from the affected communities. The findings will provide evidence-based recommendations for risk mitigation and inform public health interventions, ultimately contributing to the protection of community health and well-being.

Uranium exposure as a result of drinking water is both a radiological and chemical hazard to health. Chemical toxicity of Uranium is mainly exerted on the kidneys, where acute effects may result in a blocked up of tubules (tubular necrosis), whereas chronic effects may include dysfunction of glomeruli (Kurttio et al., 2002). Uranium urinary accumulation levels can accumulate in the skeletal tissues, leading to osteoporosis and bone fractures (McDiarmid et al., 2000). New epidemiological research has obtained important links between the effect of uranium exposure and health results. A recent extensive meta-analysis study conducted by Li et al. (2021) showed a greater likelihood of chronic kidney disease (RR=1.43, 95% CI: 1.18-1.73) and bone disorders (RR=1.28, 95%CI: 1.09-1.51) persons exposed to the uranium-contaminated drinking water.

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Despite growing evidence of uranium contamination in South Asian groundwater, no comprehensive study has yet been conducted in District Karak—an area with unique geological features and heavy reliance on groundwater. This research aims to evaluate the extent of uranium pollution in Karak's groundwater and investigate its potential health impacts on the local population. Specific objectives include: (1) quantifying uranium concentrations in groundwater wells, (2) analyzing the spatial and temporal patterns of contamination, (3) assessing health risks linked to uranium exposure, (4) exploring correlations between exposure levels and health outcomes, and (5) proposing evidence-based strategies for risk mitigation and public health intervention.

Methods and Materials

Setting of the Study

The district Karak, Khyber Pakhtunkhwa, Pakistan, was involved in this cross-sectional quantitative study, which was carried out between March 2024 and January 2025. District Karak spans 3,372 km 2 and includes three tehsils, namely Karak, Takht-e-Nasrati, and Banda Daud Shah. The geology of the district depicts a region of sedimentary rocks of Cretaceous to Tertiary age with possible uranium content found in lithologies.

Selection of Sampling

A stratified random sampling strategy was used to cover the entire Universal Stratification to include all tehsils and all types of water sources. Considerations were given on the determination of sample size based on cross-sectional studies that had an expected prevalence of 60 percent about the presence of Uranium exceeding WHO guidelines, 95 percent confidence level, and a margin of error of 5 percent, giving a total of 277 as the minimum number of samples of groundwater to be used.

The number of samples of groundwater that were collected is 285, and they were based on different sources:

- Tube wells (n=142, 49.8%)
- Hand pumps (n=89 31.2%).
- Springs (n=54; 18.9)

GPS coordinates were used to pick sampling locations, and it was evenly spread in the soil depending on population density and the availability of water sources.

Sampling of Water and assembling of water

The water samples were taken in 500 mL polyethylene bottles that had been washed according to the USEPA methods. To avoid precipitation, uranium samples were acidified to PH<2 with concentrated HNO 3 and kept at 4 C in the refrigerator until analysis. Calibrated and portable instruments were used to measure field parameters, such as pH, electrical conductivity (EC), total dissolved solids (TDS), and temperature. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) was used to study Uranium at the National Centre of Excellence in Analytical Chemistry, University of Sindh. Quality assurance entailed analysis of certification reference materials (NIST SRM 1643f) and rolls of replicas (10 percent of total analysis).

Health Survey and Data Collection

One thousand two hundred and forty-seven houses were chosen using the systematic random sampling approach in all the areas of the study using a structured questionnaire. In the questionnaire, there were multiple areas in which detailed information was to be obtained. It contained the demographics of the age, gender, education, and occupation, which gave a basic background about the subjects. It also identified the trends and origin of water consumption, which is essential to determine the possibility of exposure to Uranium. The questionnaire also inquired about the health history of the respondents and their health status at the time they were answering the questionnaire and enabled them to have a good feel of whatever health conditions they had. Moreover, it also explicitly considered the uranium toxicity-related symptoms, which could help get an insight into the health-related effects of exposure to Uranium. Finally, the questionnaire included questions concerning medical reports and the results of diagnostic tests, which made it a complete approach to the health profile of the participants. This complex methodology endeavored to gather helpful information in the examination of the associations existing among water quality, health status, and uranium exposure.

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Risk of Health Assessment

The National Center for Health Risk assessed it according to USEPA- guidelines for carcinogenic and non-carcinogenic risk assessment. Average daily dose (ADD) was determined as follows:

ADD = (CREATED) / (BW)

Where:

C = the concentration of Uranium in water (ug/L)

IR = ingestion rate (adults- 2 L/day)

- EF = frequency of exposure (350 days/year)
- ED = increased exposure (30 years)
- BW = body weight (70kg in adult)

i. AT = averaging time = 25,550 days (cancer risk)

The Risk of cancer was estimated as follows: Cancer Risk = ADD SF Where SF (slope factor) = 1.5 times 10-3 (mg/kg-day)-1

The Hazard Quotient (HQ) evaluated non-cancer risk H Q = ADD / RfDRfD (reference dose) = 3.0 x 10 13 mg/kg -day

Data Analysis

Data analysis was performed using SPSS version 28.0 and R software version 4.3.0. Descriptive statistics were applied to summarize uranium concentrations and health-related variables. The Shapiro-Wilk test was used to assess the normality of data distribution. Associations between uranium exposure levels and health outcomes were analyzed using several statistical methods. Chi-square tests were employed for categorical variables, while the Mann–Whitney U test was used for continuous variables that were not normally distributed. Logistic regression analysis was conducted to estimate odds ratios (ORs) with 95% confidence intervals (CIs) for various health outcomes.

Spatial patterns of contamination were examined using Geographic Information System (GIS) software (ArcGIS version 10.8). A p-value of less than 0.05 was considered statistically significant, and Bonferroni correction was applied to adjust for multiple comparisons.

Results

Groundwater Uranium Levels

Uranium contamination in the District Karak was evidenced by the analysis of 285 of its groundwater samples that showed uranium contamination. The average concentration of Uranium was 47.3 \23.8 \mu g/L (r: 8.2156.7 \mu g/L); 195 samples (68.4%) have higher contents than the recommended guidelines by the WHO of 30 \mu g/L.

Table 1: Uranium Concentrations by Water Source Type

Source Type	N	Mean ± SD (µg/L)	Median (µg/L)	Range (µg/L)	>30 µg/L (%)
Tube wells	142	52.3 ± 26.1	48.7	12.4-156.7	74.6
Hand pumps	89	45.8 ± 22.4	42.1	8.2-124.3	65.2
Springs	54	35.9 ± 18.7	33.2	11.7-89.4	55.6

The table is presented that allows us to characterize uranium concentrations that are divided into various types of water sources, including the description of sample size (n), mean concentration with a standard deviation (SD), median, range, and percentage of samples that differ above 30ug/l. In the case of tube wells, the number of samples is 142, the average concentration is 52.3 +/- 26.1 u g/L, and the median is 48.7 u g/L. The scope of the uranium concentration in tube wells varies between 12.4 and 156.7 mu g/L, and 74.6 percent of the samples are more than 30 mu g/L, implying the high prevalence of the uranium concentration above the standard.

When hand pumps are considered, eighty-nine samples were analyzed, and the average value of analytical concentration is 45.8 +/- 22.4ug/L, with 42.1 ug /L being the median. The highest values (8.2-124.3 µg/L) are found in uranium 65.2 percent of samples are treated to be higher than 30 µg/L, followed by springs with the lowest mean (35.9 18.7 µg/L) among 54 samples with a median of 33.2 µg/L with a range of 11.7 to 89.4 µg/L and 55.6 percent of springs exceed 30 µ The following information brings to focus the different grades of uranium contamination in various water sources.

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Distribution of Contamination by Spaces

The spatial analysis also indicated that there was an extreme geographic disparity in the contamination of uranium in District Karak. The peak levels were found in the central and southwest parts, especially in Takht-e-Nasrati and Banda Daud Shah tehsils.

Table 2: Uranium Concentrations by Tehsil

Tehsil	N	Mean ± SD (µg/L)	>30 µg/L (%)	>100 µg/L (%)
Karak	68	42.1 ± 20.5	61.8	4.4
Takht-e-Nasrati	74	56.8 ± 27.9	78.4	13.5
Banda Daud Shah	61	51.2 ± 24.6	73.8	9.8

The table highlights uranium concentrations in three tehsils in the categorization of the number of samples (n), mean concentration of uranium with the standard deviations (SD), and also the percentage of samples that were above the stipulated concentrations. The 68 samples found in Karak have a mean concentration of 42.1 or 20.5 0g/L; 61.8 percent of the sample measures above 30 0g/L, with 4.4 percent above 100 0g/L.

Takht-e-Nasrati yields the largest mean concentration of 56.8 27.9 mu g/ L in 74 samples with 78.4 percent aside of 30 mu g/ L and 13.5 percent separate 100 mu g/ L. In Banda Daud Shah, the average level is 51.2 24.6 ug/L among 61 samples, with 73.8 percent and 9.8 percent exceeding 30 and 100 ug/L, respectively.

Unique Hydro geochemistry

There were significant correlations between water quality parameters and levels of uranium. Uranium mobility was related to alkaline pH conditions (mean pH = 7.80 +- 0.60) and elevated TDS conditions (mean values = 1, 247 +- 534 mg/L).

Table 3: Correlation between Uranium and Water Quality Parameters

Parameter	Mean ± SD	Correlation with U	p-value
Ph	7.8 ± 0.6	0.431	<0.001
EC (µS/cm)	1,856 ± 798	0.378	<0.001
TDS (mg/L)	1,247 ± 534	0.356	<0.001
HCO_3^- (mg/L)	298 ± 127	0.445	<0.001
SO_4^{2-} (mg/L)	234 ± 156	0.289	<0.001

The table shows different measures of water quality as well as its mean, standard deviations (SD), correlations with uranium concentrations, and p-values. The pH is 7.8 0.6 with a significant positive correlation with the concentration of uranium with a p- 0.431 value, which is also statistically significant with a p- p-value of less than 0.001. Electrical conductivity (EC) is 1,856 +/- 798 micro-Siemens per centimeter, which has a 0.378 correlation coefficient with U, which again is significant where p < 0.001. In the same way, total dissolved solids (TDS) with 1,247 +/- 534 mg/L and U 0.356, p-value 0.0009 have a correlation. The mean value of bicarbonate (HCO 3 -) is 298 +/- 127 mg/L and significant with a 0.445 correlation coefficient, and with U is even more significant at p < 0.001. Finally, the average range of sulfate (SO 4 2 -) is 234 +/- 156 mg/L, the correlation is 0.289, and the p-value is less than 0.001. In general, these results indicate a high correlation between water quality parameters and uranium levels.

The Results of Health Survey

This health survey was done on 1,247 households that involved a total of 6,847 people in the District Karak. Table 4 portrays the demographic features of the populace in the study.

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Table 4: Demographic Characteristics of Study Population

Characteristic	n (%) or Mean ± SD
Total individuals	6,847
Age groups	
0-14 years	2,395 (35.0)
15-29 years	1,918 (28.0)
30-44 years	1,438 (21.0)
45-59 years	753 (11.0)
≥60 years	343 (5.0)
Gender	
Male	3,526 (51.5)
Female	3,321 (48.5)
Education level	
No formal education	2,809 (41.0)
Primary	1,917 (28.0)
Secondary	1,438 (21.0)
Higher education	683 (10.0)
Primary water source	
Tube well	3,423 (50.0)
Hand pump	2,123 (31.0)
Spring	1,301 (19.0)

A summary table shows the demographic features of 6,847 people on topics such as age group, gender, level of education, and source of main water supply. By age distribution, the 0-14 years age group takes the top role, with the population estimated to be 2,395 (35.0%), followed by those of 15-29 years with 1,918 (28.0%) and 30-44 years 1,438 (21.0%), 45-59 years 753 (11.0%), and the 60 years and above at 343 (5.0%).

Concerning gender, it is characterized by slight male dominance of 3526 (51.5) as opposed to 3321(48.5) female members. The education level also stands out in the table, and it emerges in the table that a significant percentage of the population has no formal education, as 2,809 people (41.0%) have no formal education. Primary education is received by 1,917 people (28.0%), 1,438 people (21.0%) are educated one level higher, and the number of persons with higher education accounts only for 683 (10.0%).

Finally, there is the listing of the primary water sources, of which the most common are the tube wells serving 3,423 people (50.0 percent), hand pumps for 2,123 people (31.0 percent), and springs for 1,301 people (19.0 percent). The thorough disaggregation gives a clue about the demography and living conditions of the population.

Uranium and Health Effects

The analysis of health outcomes was carried out according to the categories of uranium exposure: low (<30 0g/L), moderate (30-60 0g/L), and high (>60 0g/L). Strong correlations were found between the level of exposure to uranium and a number of health states.

Table 5: Health Outcomes by Uranium Exposure Categories

Health Outcome	Low Exposure n=2,167 (%)	Moderate Exposure n=2,845 (%)	High Exposure n=1,835 (%)	p-value	OR (95% CI)*
Kidney dysfunction	187 (8.6)	398 (14.0)	429 (23.4)	<0.001	2.34 (1.67-3.28)
Bone disorders	298 (13.8)	487 (17.1)	367 (20.0)	<0.001	1.89 (1.34-2.67)

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Liver abnormalities	156 (7.2)	267 (9.4)	198 (10.8)	0.003	1.56 (1.12-2.18)
Reproductive issues	89 (4.1)	142 (5.0)	117 (6.4)	0.021	1.43 (0.98-2.09)
Cancer cases	12 (0.6)	34 (1.2)	29 (1.6)	0.037	2.78 (1.34-5.76)

High vs. Low exposure group, with adjustment of age, gender, and socioeconomic status

The table lines out data on several outcomes of health such as kidney dysfunction, bone disorders, liver abnormalities, reproductive problems, and cancer cases grouped by the level of exposure: low, moderate, and high. Regarding kidney dysfunction, the prevalence considerably rises with exposure and indicates the prevalence of 8.6 percent in low exposure (n=2,167), 14.0 percent in moderate exposure (n=2,845), and 23.4 percent in high exposure (n=1,835), where the p-value indicates less than 0.001 makes it strong enough to be statistically significant. The odds ratio (OR) of 2.34 (95% CI: 1.67-3. 28) indicates a greater than increased risk of high exposures among the individuals. Likewise, in the case of bone disorders, the prevalence increases with 13.8% low exposure at 20.0% high exposure, the p-value is less than 0.001, and there is an OR of 1.89 (95% CI: 1.34-2.67). The abnormalities in the liver have the same pattern where the frequencies are rising with the amount of exposure (7.2% to 10.8%) with a p-value of 0.003 and OR of 1.56 (95% CI: 1.12-2.18). Increased exposure is also seen in reproductive problems and cancer incidences, though to a smaller extent and magnitude. On the whole, these results highlight the negative health consequences related to the increased level of exposure to various health conditions.

Analysis age and gender-specific

Stratification by age demonstrated that people were dissimilarly subject to the health impacts of uranium. Kidney dysfunction revealed the highest prevalence in the group of adults aged 45-59 years (18.7%), whereas in the case of bone disorders, they were reported in 22.3 percent.

Table 6: Health Outcomes by Age Groups in High-Exposure Areas

Age Group	Kidney Dysfunction (%)	Bone Disorders (%)	Liver Abnormalities (%)
0-14 years	12.4	8.9	4.2
15-29 years	18.9	16.7	8.9
30-44 years	24.6	19.8	11.3
45-59 years	28.7	22.3	14.2
≥60 years	31.2	25.8	16.7

The table presents the incidence of kidney dysfunction, bone diseases, and liver disorders in various ages. There is kidney dysfunction affecting 12.4 percent, bone disorder at 8.9 percent, and abnormality of the liver at 4.2 percent of the population occupying the 0-14 years group. The prevalence of these conditions is more common as age advances. Among 15-29 years, there is an increment of kidney dysfunction to 18.9%, bone disorders to 16.7%, and liver abnormalities to 8.9. This is also followed in the 30 44 years group, whereby kidney dysfunction is 24.6, bone 19.8, and liver abnormalities 11.3. Among the ages 45-59, 28.7 percent have kidney problems, 22.3 percent have bone ailments, and 14.2 percent have liver cases. Lastly, in patients aged 60 years and above, 31.2 percent have dysfunction of the kidneys, 25.8 percent have bone diseases, and 16.7 percent have abnormalities in their livers, showing health risks on the rise as age increases.

Gender analysis indicated kidney dysfunction was more common in males (25.8% vs. 20.9%, p=0.003) and bone disorders in females (22.1% vs. 17.8%, p=0.008) when the area of residence was categorized into high-exposure areas.

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Risk assessment

Cancer risk estimation indicated alarming forms of lifetime cancer exposure to the entire District of Karak. The average cancer risk was 7.1 x 10-4, where 72 percent of locations within a study area recorded more risk than the acceptable cancer risk of 10-4.

Table 7: Cancer Risk Assessment Results

Risk Category	Cancer Risk Range	Locations (%)	Population at Risk (%)
Low risk	$<10^{-4}$	28.1	31.5
Moderate risk	10^{-4} - 10^{-3}	58.9	52.3
High risk	$>10^{-3}$	13.0	16.2

The table classifies cancer risk levels to environmental exposure. Low-risk class, which can be characterized as cancer risk smaller than 10 14, covers 28.1 percent of locations and covers 31.5 percent of the affected population. The representation of moderate threats (10 1 4 to 10 1 3) amounts to 58.9 percent of the locations and contains 52.3 percent of the at-risk population. Last but not least, the high-risk category that includes more than 10 13 cancer risks covers 13.0 percent of locations and 16.2 percent of the population. Such distribution emphasizes the different cancer risk levels in other regions and lands. The table classifies cancer risk levels with regard to environmental exposure. Low-risk class, which can be characterized as cancer risk smaller than 10 14, covers 28.1 percent of locations and covers 31.5 percent of the affected population. The representation of moderate threats (10 1 4 to 10 1 3) amounts to 58.9 percent of the locations and contains 52.3 percent of the at-risk population.

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Table 8: Non-Cancer Risk Assessment (Hazard Quotients)

Exposure Group	Mean HQ	HQ>1 (%)	Health Implications
Low exposure	0.67	23.5	Minimal risk
Moderate exposure	1.34	78.9	Moderate risk
High exposure	2.89	100.0	High risk

Temporal Trends

Analysis of uranium concentrations over the study period (March 2024 - January 2025) revealed seasonal variations, with higher concentrations during pre-monsoon periods (April-June) and lower concentrations during post-monsoon periods (September-November).

Table 9: Seasonal Variation in Uranium Concentrations

Season	Mean U (μg/L)	SD	Range (μg/L)
Pre-monsoon	52.8	26.4	9.8-167.3
Monsoon	45.7	22.1	7.4-142.6
Post-monsoon	42.1	20.8	6.9-134.2
Winter	48.9	24.5	8.7-159.4

The table indicates seasonal differences in mean uranium (U) concentrations in the unit of micrograms per liter (ug/L). The highest mean concentration of 52.8 26.4 and a range between 9.8 and 167.3 in terms of standard deviation was obtained during the pre-monsoon season. In the monsoon, the average decreases to 45.7ug/l with a standard deviation of 22.1, and the extreme is between 7.4 and 142.6ug /l. The lowest mean is registered in the post-monsoon season at 42.1 0g/L (SD: 20.8, range: 6.9-134.2 0g/L) and in winter with a mean of 48.9 0g/L (SD: 24.5, range: 8.7-159.4 0g/L).

Discussion

This study highlights significant uranium contamination in the groundwater of District Karak, with 68.4% of samples exceeding the WHO guideline of 30 μg/L and an average concentration of 47.3 μg/L. Spatial analysis showed higher contamination in Takht-e-Nasrati and Banda Daud Shah, likely due to their proximity to uranium-rich geological formations and tectonic activity. Uranium levels were significantly higher in shallow wells (<60 m), indicating surface geogenic sources as the primary contributors. The chemical behavior of uranium in groundwater was influenced by geochemical conditions. Positive correlations with pH, bicarbonate, and electrical conductivity suggest that carbonate complexation enhances uranium mobility.

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Alkaline pH levels facilitated the formation of soluble uranium-carbonate complexes, while high total dissolved solids further promoted transport in the aquifer. Health data revealed strong associations between uranium exposure and kidney dysfunction (OR = 2.34), bone disorders (OR = 1.89), and liver issues (OR = 1.56). Cancer risk assessments indicated that 72% of surveyed areas exceeded the acceptable lifetime risk threshold (>10^{-4}). Children and middle-aged adults were particularly vulnerable, likely due to cumulative exposure and physiological sensitivity. Seasonal variation showed elevated uranium levels during dry periods, with slight dilution during monsoons. However, contamination remained above safe limits year-round, suggesting continuous leaching from natural sources. Comparisons with global data show similar contamination trends and health impacts, consistent with studies from Finland and India. Despite its strengths, the study is limited by its cross-sectional design and reliance on self-reported health data. Future longitudinal studies with biomarker-based exposure assessments are needed to strengthen causal links. These findings underscore the urgent need for intervention. Immediate actions should include the provision of alternative water sources, installation of uranium-removal treatment systems, health surveillance programs, and public awareness initiatives. Long-term policies for groundwater monitoring and regulation are essential to safeguard public health in Karak and similarly affected regions.

Note: 100-200% uncertainty in the results is expected due to inadequate sample preparation, instruments reliability and lack of accuracy in analytical technique.

Conclusions

This study provides a comprehensive assessment of uranium contamination in the groundwater of District Karak and its associated public health implications. It reveals that 68.4% of groundwater samples exceeded the World Health Organization's recommended limit of 30 µg/L, with an average concentration of 47.3 µg/L, indicating widespread contamination. Spatial analysis identified Takht-e-Nasrati and Banda Daud Shah tehsils as the most affected areas, likely due to underlying geological formations and tectonic activity. Uranium levels were found to be significantly higher in shallow aquifers (<60 meters) compared to deeper sources, suggesting a depth-dependent pattern of contamination. The study also established strong associations between uranium exposure and adverse health outcomes. Individuals in high-exposure areas exhibited increased risks of kidney dysfunction (OR = 2.34), bone disorders (OR = 1.89), and liver abnormalities (OR = 1.56). Furthermore, cancer risk assessments indicated that 72% of the surveyed sites exceeded the lifetime acceptable risk threshold (>10^{-4}). Children and middle-aged adults emerged as the most vulnerable populations to uranium-related health effects. These findings highlight the urgent need for intervention. The data serve as a critical baseline for designing targeted mitigation strategies and establishing long-term groundwater monitoring and public health surveillance programs in the region.

Note: 100-200% uncertainty in the results is expected due to inadequate sample preparation, instruments reliability and lack of accuracy in analytical technique.

Recommendations

Based on the findings, several urgent actions are recommended to mitigate the health risks associated with uranium-contaminated groundwater in District Karak. Emergency water supply systems should be established in areas identified with high levels of contamination to ensure access to safe drinking water. Health screening programs must be initiated for affected populations to detect and manage uranium-related health conditions early. Additionally, a comprehensive water quality monitoring network should be implemented to enable continuous assessment and timely response to contamination. Community-based water treatment solutions should also be introduced to empower local residents with accessible and sustainable methods for reducing uranium levels in household water supplies.

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