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ORIGINAL ARTICLE

Groundwater Uranium Contamination in Fazilka, Punjab: A Hydro Geochemical and Risk Perspective

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KEYWORDS

Uranium concentration; Groundwater contamination; Radiological risk; Chemical risk

ABSTRACT: Groundwater is a crucial source of freshwater for agricultural, industrial, and domestic use globally, with India heavily relying on it. In Punjab, an agrarian state, groundwater is vital for both irrigation and drinking, placing immense pressure on its reserves due to rapid population growth. This necessitates sustainable management to ensure long-term water security and public health. Recent studies have identified uranium contamination in groundwater, especially in the southwestern region of Punjab. This study systematically sampled groundwater from boreholes of varying depths in Fazilka District, Punjab, to assess uranium concentrations and their associated radiological risks. The evaluation focused on lifetime dose estimates and carcinogenic risks, including cancer mortality and morbidity. Furthermore, the study addressed the chemical toxicity of uranium, which poses potential health hazards. Findings indicate that groundwater from boreholes up to 100 feet deep is within safe limits for consumption, with no immediate radiological or chemical risks to residents.

INTRODUCTION

Uranium is a naturally occurring radioactive element found in different types of rocks and soil across India. As a result, the amount of uranium in groundwater can vary, usually between 1 to 30 µg L^{-1}. In some areas, the concentration can go above the World Health Organization's (WHO) safe drinking water limit of 30 µgL^{-1}. The amount of uranium in groundwater is affected by both natural factors and human activities. Uranium is commonly found in minerals and granite rocks. Over time, weathering and leaching (the process where water carries away minerals) can release uranium into the soil and water, eventually making its way into groundwater. Regions with granite bedrock, for instance, often show higher uranium concentrations due to the inherent uranium content in these rocks [1]. In many natural water sources, uranium concentrations are perceptible, with the mean concentration in ocean water reported at an approximately 3.0 µg L^{-1} [2].

Agricultural practices significantly impact uranium levels in groundwater. The widespread use of phosphate fertilizers, which contain trace amounts of uranium, is a notable source. When these fertilizers are applied to fields, uranium can leach into the groundwater, especially in areas with high rainfall or intensive irrigation practices. Moreover, certain pesticides may indirectly mobilize uranium in the soil, further contributing to its concentration in groundwater. Industrial activities are another major contributor to uranium contamination. Uranium mining and milling operations produce waste products and tailings that often

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contain significant amounts of uranium. If these wastes are not managed properly, they can leach uranium into nearby water sources. Additionally, nuclear fuel processing facilities can release uranium into the environment through improper waste disposal or accidental releases, further contaminating water bodies.

The reliance on private wells, particularly in regions without municipal water supply, exacerbates the issue. These wells often tap into aquifers with naturally high uranium content, increasing the risk of uranium exposure for the local population. Surface water bodies near uranium mining areas or industrial zones can also become contaminated through runoff and discharges, spreading uranium contamination over larger areas. Topographical and climatic factors play crucial roles in the distribution and concentration of uranium in groundwater [3]. For instance, soil erosion and surface runoff can transport uranium from the soil into water bodies. Areas with high rainfall may experience more significant leaching of uranium from the soil into groundwater, while arid regions might see higher concentrations due to reduced dilution and increased evaporation rates.

Uranium can enter the human and animal body through ingestion, skin contact, and inhalation, with ingestion being the primary route. About 15% of uranium intake in humans comes from food, while 85% comes from drinking water [4]. The concentration of uranium in the environment varies based on the geological and topographical conditions of an area. Uranium toxicity primarily affects the kidneys and lungs due to its chemical and radiological properties [5-7]. Consuming approximately 0.1 mg of soluble natural uranium per kilogram of body weight can cause temporary kidney damage [8]. Chronic exposure to uranium through drinking water, even at low concentrations, can lead to kidney damage [9].

In a study, participants were divided into two groups based on their drinking water source and uranium exposure levels. The low-exposure group used municipal water containing less than 1 microgram of uranium per liter, while the high-exposure group used private wells with uranium levels ranging from 2 to 781 micrograms per liter. Findings indicate that chronic ingestion of uranium in drinking water, with intake levels between 0.004 to 9 micrograms per kilogram of body weight, adversely affects kidney function. The maximum recommended safe range for uranium concentration in drinking water lies in the range of 15-30 parts per billion ppb [10-12]. However, even within this range, there is still a risk of internal organ damage, and the water may not be entirely safe for consumption. Studies from adjoining states like Ferozepur, Himachal Pradesh, Haryana, and Rajasthan have shown high concentrations of uranium in the region.

The Malwa region of Punjab, a significant cotton-growing area, illustrates the cumulative impact of these factors. Decades of extensive pesticide and fertilizer use in this region have potentially increased uranium levels in groundwater. Suspected contributors include fertilizers like diammonium phosphate, cyhalothrin, urea, super phosphate, and NPK. Assessing physico-chemical parameters, such as total dissolved solids (TDS), is vital for evaluating water quality since TDS levels provide immediate insights into water's suitability for consumption. TDS, comprising inorganic salts and small amounts of organic matter dissolved in water, can stem from natural sources, sewage, urban runoff, and industrial wastewater. The concentration of TDS varies significantly across different geological regions due to the varying solubility of minerals, which may correlate with uranium levels.

This study, focusing on the Fazilka district in Punjab, aims to determine uranium concentrations in groundwater and assess the associated radiological and chemical health risks for the local population. By understanding the background values and potential contamination sources, the study seeks to inform policy decisions and health guidelines to ensure safe drinking water in the region. Such comprehensive assessments are essential for developing effective mitigation strategies and protecting public health from the hazards of uranium contamination.

MATERIALS AND METHODS

Area of study

The district is located between latitude 30°40' N and longitude 74°03' E. It has an approximate population of 1,180,483 and a literacy rate of 86.03%. [13].The district

covers an area of 3,113 square kilometers. The soil in this area is loose, sandy, calcareous, and alluvial, consisting of varying proportions of gravel, sand, silt, and clay. This supports year-round agriculture, with crops like wheat, rice, and cotton. The soil is mostly sandy loam to loamy sand, with some areas facing salinity and alkalinity issues due to poor-quality underground water. In the southwest, the alluvium is covered by fine-grained, buff-colored sand dunes. The map of Fazilka district and the geological map of Punjab are provided in Figure 1

In the calcareous soils of the study region, plant root respiration and microbial activity produce CO_2, increasing its pressure in the soil. Water percolating through the soil absorbs CO_2, forming carbonic acid. This reacts with calcium carbonates to create bicarbonate, an efficient agent for uranium leaching, potentially explaining high uranium levels in groundwater.

The study region of Punjab, a major cotton-growing area, has potentially increased uranium levels in groundwater due to decades of fertilizer and pesticide use, including substances like diammonium phosphate and NPK. Assessing TDS, which include inorganic salts and organic matter, is crucial for evaluating water quality, as TDS levels vary with geological conditions and may correlate with uranium levels. For these reasons, the Fazilka district in the Malwa region of Punjab, India, was chosen for a study on uranium levels in groundwater.

A total of 30 water samples were collected from borehole both private and public of various villages within the study region. The number of samples procured from each village varied based on the accessibility of water extraction sources. To ensure comprehensive coverage of the study area and maximize data collection, a grid map was created based on available roads and resources. A single sampling site was randomly selected from each grid cell, considering the accessibility of roads, available resources, and population density. Groundwater within the study area is primarily sourced from either manually operated shallow hand pumps or power-operated deep bore wells. Prior to conducting measurements for temperature, conductivity, and pH, as well as ensuring water stabilization, the water was allowed to flow from the sources for a duration of 10 –15 minutes.

Samples were collected in High Density Polyethylene (HDPE) bottles that had been acid-leached and rinsed twice with deionized water before sample collection on a daily basis. Each bottle was further rinsed twice with the sample water to remove any potential contaminants from the bottle. To avoid any potential contaminations, samples were retrieved by holding the bottle at its base. The bottles were labeled with details such as location, date, time, GPS coordinates, and water source (e.g., borehole) to ensure accurate identification of the sampling point.

Samples of groundwater were collected only after allowing of pumping the water for about 5–10 min and these samples were kept cold, transported to the laboratory, where they were stored in a freezer at 4°C until final chemical analysis. Following collection, the samples were promptly analyzed within a timeframe of 6 to 12 hours.

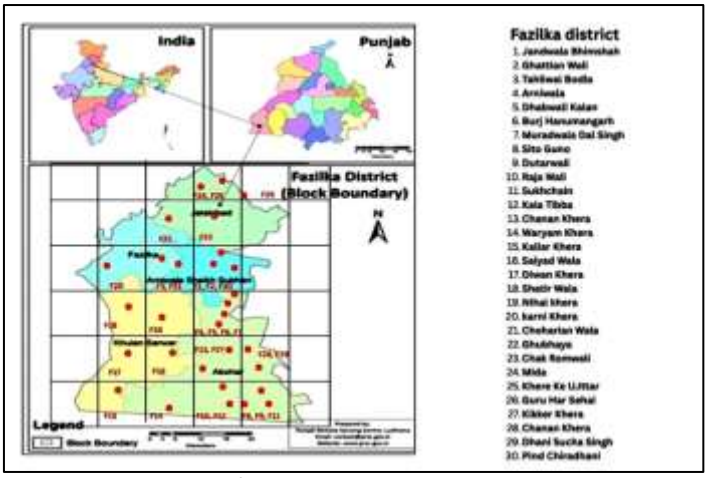


Figure 1. Map of Fazilka District showing sampling locations.

Uranium estimation

The uranium concentration in water samples is determined using the LED Fluorimeter technique, which enables the detection of ultra-trace levels of uranium in water. This technique has the capability to measure uranium concentrations ranging from 0.5 ppb to 1000 ppb with an accuracy of +/- 10% or 0.05 ppb, whichever is greater, and consistently achieves repeatability better than +/- 5%. This precision is attained by averaging measurements over 1280 pulses, with the measurement duration reduced to approximately 1 second. The instrument features a user-friendly full-color 170mm touch screen interface, providing guidance to the operator throughout the measurement process. Moreover, it has a substantial data storage capacity, capable of storing more than 100,000 measurements, which can be accessed at any time for further analysis. Natural water fluorescence primarily occurs in the blue-green region, with light wavelengths around 475 nm, and fluorescence is detected using Photo Multiplier Tubes (PMT).

In this technique, the capability to measure concentrations as low as 0.5 ppb is achieved. A buffer solution is prepared by dissolving and thoroughly mixing five grams of sodium pyrophosphate in 100 mL of double-distilled water, followed by the addition of ortho-phosphoric acid until a pH of 7 is attained. The addition of the buffer solution to the uranium sample enhances fluorescence yield. Freshly prepared buffer was used each time for sample analysis. A blank solution with zero uranium concentration is prepared by adding one mL of buffer solution to 10 mL of double-distilled water. To ensure accuracy in measurement, samples underwent filtration using Whatman filter paper with a pore size of NY0.45µm. To avoid matrix interferences, the standard spiking method for uranium quantification of water samples was employed [14]. Each sample was analyzed twice, and the presented results represent the average of these two measurements. The accuracy of results was verified using standard reference materials and repeated analyses. All glassware was cleaned with 10% HNO_3 and rinsed with double distilled water before use. A reagent blank was tested after every five samples, and its value was subtracted from the sample readings to avoid memory effects and contamination.

Dose, health risk and chemical toxicity assessment

Health risks such as lifetime chemical risk, annual radioactivity dose, cancer mortality risk, and cancer morbidity may arise in the human body as a result of radioactive materials present in drinking water. The annual radioactivity dose to humans due to uranium isotopes was computed using Equation (Eq.1).

$$\text{Annual Radioactivity Dose (mSv)} = U_a \times W_{in} \times D_{coeff} \quad (1)$$

Where U_a represents the uranium concentration activity in water Becquerels per liter (BqL^{-1}); W denotes the annual consumption of water (in liters). The water consumption rate considered was 4.05 liters per day ($Lday^{-1}$) for an adult Indian [15]. Additionally, D_{coeff} signifies the radioactivity dose conversion factor (in Sieverts per Becquerel, $SvBq^{-1}$) provided by the International Commission on Radiological Protection (ICRP).The radioactivity dose conversion factors for U-238, U-234, and U-235 are as follows: 4.5×10^{-8}, 4.9×10^{-8}, and 4.7×10^{-8}, respectively [16]. The calculated annual dose if below the WHO guideline of 0.1 $mSvy^{-1}$, the health risk is considered low and if it exceeds the recommended limit, long-term exposure may increase risks of cancer, kidney toxicity, and other radiological health effects.

To measure the Cancer risk Equation (Eq.2). [17] was used

$$\text{CancerRisk} = U_a \times RF \quad (2)$$

This equation estimates the probability of developing cancer over a lifetime due to the ingestion of uranium through water. The calculated risk if exceeds 10^{-3}, the water source is considered unsafe for long-term human consumption and may require treatment. The cancer risk calculation (Eq. 2) reflects uranium levels in water, human consumption patterns and lifetime exposure duration. U_a denotes the Uranium activity present in a specific water sample, expressed in BqL^{-1}. RF represents the Risk Factor associated with the uranium activity, also expressed in BqL^{-1} as in Equation (Eq.3).

$$RF = R_{coeffin} \times IR_w \times ET \qquad (3)$$

$R_{coeffin}$ signifies the Risk Coefficient of intake, denoting the quantitative measure of risk associated with intake. IR_w represents the rate of water intake by an adult individual residing in the studied area, established at 4.05 $Lday^{-1}$. ET denotes the Exposure Time, which was determined to be 65 years according to the parameters of the study [18]. If RF is small, the associated cancer risk will also be low. This formulation provides a direct way to link uranium activity in water with long-term exposure risk. It takes into account both individual consumption habits and lifetime duration of exposure. By doing so, it allows for a realistic estimation of cumulative health risk. The RF parameter is therefore a valuable tool in assessing the potential radiological hazards faced by populations relying on groundwater sources.

The coefficients associated with cancer mortality resulting from the ingestion of U-234, U-238, and U-235 are reported as 6.1×10^{-11} Bq^{-1}, 7.5×10^{-11} Bq^{-1}, and 6.2×10^{-11} Bq^{-1} respectively[19]. Furthermore, the coefficients for cancer morbidity are 9.5×10^{-11} Bq^{-1}, 1.2×10^{-10} Bq^{-1}, and 9.8×10^{-11} Bq^{-1} respectively.

Additionally, literature [20] presents Equation (Eq. 4), which outlines the determination of LADD concerning radioactive Uranium via water ingestion. This equation quantifies the chemical hazard level associated with uranium exposure.

$$LADD = \frac{EPC}{AT} \times \frac{IR}{BW} \times EF \times LE \qquad (4)$$

LADD measured in micrograms per kilogram per day (µgkg-1day-1). EPC denotes the Exposure Point Concentration, expressed in µg L^{-1}). Higher EPC values lead to higher LADD values..IR indicates the Water Ingestion Rate, set at 4.05 $Lday^{-1}$. EF represents the Exposure Frequency, defined as 350 days per year [21]. LE signifies Life Expectancy, determined to be 65 years. AT denotes the average Time, calculated as 23,725 days (65 years multiplied by 365 days per year). Lastly, BW represents the Body Weight, standardized at 53 kilograms for the Indian standard man [22]. This approach provides a standardized framework to estimate the daily intake of uranium across a human lifetime. It allows for comparison of uranium toxicity risk in different populations and regions. Moreover, it ensures that risk assessments remain consistent with international health safety guidelines. The equation is therefore a widely accepted tool in environmental health studies for quantifying chemical hazards from uranium ingestion.

The assessment of non-cancer-related risk has been conducted through the use of the HQ [23]. This quotient represents the ratio of the continuous daily intake of uranium to its reference level, which is established at 0.6 $\mu gkg^{-1}day^{-1}$ [24]. The reference level signifies the daily uranium ingestion threshold at which the population is exposed to any cancer risk throughout their lifetime. The Hazard Quotient (HQ) for uranium intake via water was determined using Equation (Eq 5).

$$HazardQuotient = \frac{LADD}{RFD} \qquad (5)$$

where RFD is reference dose limit as 0.6 $\mu gkg^{-1}day^{-1.}$ A Hazard Quotient greater than 1 indicates that the exposure level surpasses the safe reference dose and may pose a potential health risk. Conversely, a value below 1 suggests that the population is within the acceptable risk range. This makes HQ a practical and straightforward tool for evaluating chemical toxicity risk from uranium in drinking water. By integrating LADD with RFD, the HQ framework provides a clear measure of non-carcinogenic health impacts that can be directly compared across different regions and populations.

RESULTS AND DISCUSSION

In the study [25], it was demonstrated that local geochemistry and geology exert a significant influence on uranium concentration, which can range from sub-parts per million (sub-ppm) to parts per million (ppm) levels. The direct radiation impact of ingested uranium primarily stems from its alpha emission, which contributes to radiation exposure within the body. Within the study area, uranium concentrations in ground source samples varied from 2.33 to 217.23 μgL^{-1}, with an average value of 74.905 μgL^{-1}. It is important to note that the ratios of uranium isotopes in water samples are not always equal to 1. This is because natural uranium consists of different isotopes, namely U-238, U-235, and U-234, each present in varying amounts by weight. In this study, we focus specifically on the isotope U-238

found in the groundwater source.

The World Health Organization (WHO-2012) recommends a baseline value of 30 μgL^{-1} for uranium concentration, and upon comparing the obtained results, it was observed that 60% of the measured values exceeded this baseline limit. Conversely, if we consider the baseline value of 60 μgL^{-1} recommended by the Atomic Energy Regulatory Board [26], it was noted that 40% of the analyzed samples exceeded this prescribed limit. Figure 2 depicting the concentration of uranium distribution in ground water samples of different villages. Approximately 67% of the water samples exhibited uranium concentrations of up to 100 μgL^{-1}, while around 30% fell within the range of 101-200 μgL^{-1}, and the remaining 3% exceeded 200 μgL^{-1}. Additionally, we investigated the relationship between uranium concentration and the depth of water sources, with the findings presented in Figure 3. Analysis of the figure reveals that that up to the depth of 100 feet approximately 67% of samples are within the permissible limit of 60 μgL^{-1} (AERB, 2004) with an exception of some villages having uranium concentration more than the permissible limit. The sample which was collected from the site having depth more than 100 feet, the data reveals that the uranium concentration decreases as the depth is increased. This suggests that borehole water up to 100 feet is deemed safe for residents. A correlation coefficient of 0.5168 (r = 0.5168) indicates a positive relationship between the average uranium concentration and the depth of the water source in the region being studied.

Past geochemical investigations have revealed that increased salinity and TDS can impact the migration of radioactive material, such as uranium, in groundwater [27]. Fertilizers containing phosphate compounds have been identified as potential contributors to elevated uranium levels. Previous research indicates that phosphate rocks exhibit significant absorption capacities for radioactive materials such as thorium, uranium, radium, and their byproducts [28]. Since phosphate fertilizers are primarily derived from phosphate rocks, these fertilizers may contribute to the presence of uranium and radium in the groundwater of the studied region.

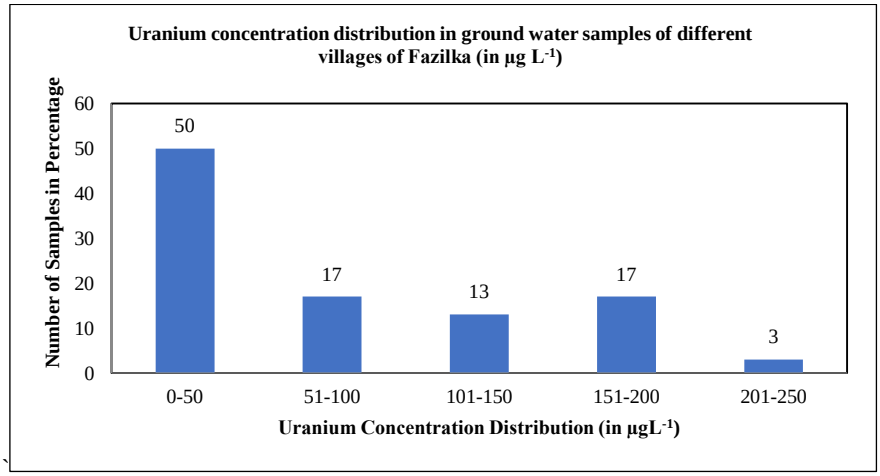


Figure 2. Uranium concentration distribution in ground water samples of different villages

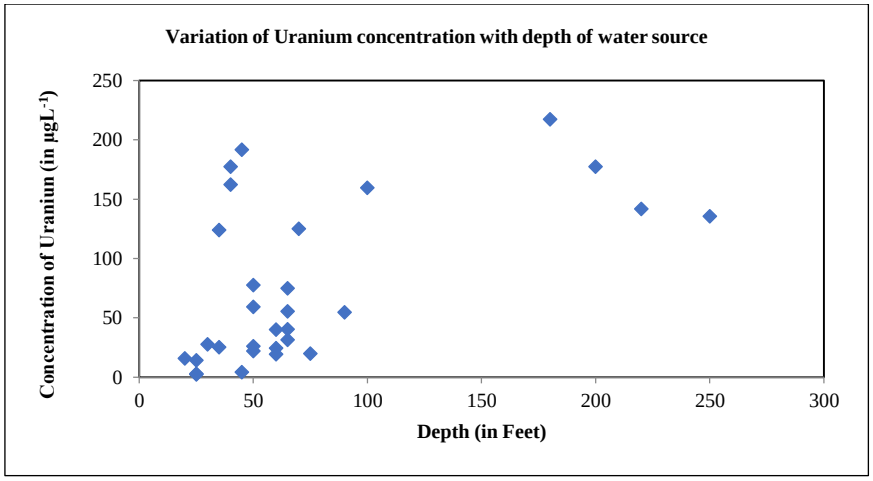


Figure 3. Variation of uranium concentration with depth of water source

Punjab's substantial contribution to the nation's food grain supply, the region heavily relies on fertilizer usage. This extensive application of fertilizers promotes the increased concentration of uranium in Punjab's groundwater. The presence of calcium carbonate (lime deposits) in the soil is another factor to consider. Carbonic acid, produced by the decomposition of carbon dioxide from plant root respiration and microbial oxidation of organic matter, reacts with calcium carbonate to generate bicarbonate, the primary product of mineral dissolution. Bicarbonate facilitates the release of adsorbed uranium from sediment, leading to higher concentrations of dissolved uranium [29-31].

Since the Fazilka district falls in the major cotton belt of Punjab (MALWA region of Punjab) and as there has been a wide spread use of pesticides/fertilizers extensively by the farmers from the last many decades, like diammonium phosphate, cyhalothrein & even fertilizers such as urea, super phosphate and NPK, which might have also contributed to certain extent towards the high concentration of uranium observed in ground water of this region

The TDS levels observed in water samples from this area are notably elevated. These values range from 1.74 x 10^{-6} to 1782 mgL^{-1}, with an average of 567.2 mgL^{-1}. Uranium concentration and TDS has positive correlation. About 53% samples exceed 500 mgL^{-1} [WHO2011] and [USEPA 2011].

Our observations indicate a general correlation between high TDS values and elevated uranium concentrations in this area, reflecting poor water quality in a significant portion of the study area .as illustrated in Figure 4.

This implies that the geochemical processes contributing to the mobilization of dissolved solids may also facilitate uranium release and persistence in groundwater. Low uranium concentrations are typically observed in water supplied by Water Works, which primarily consists of canal water, as well as in sources located in close proximity to canals or drains. Our observations suggest that the seepage of canal water into nearby areas results in the dilution of TDS and uranium concentrations in shallow groundwater. Therefore, elevated TDS is not only a measure of poor water quality but also a useful indicator of potential uranium risk in groundwater.

Other countries known to have high levels of uranium in groundwater include Canada, Brazil, Ghana, USA, Kosovo, South Korea, Norway, Mongolia, Burundi, China, and Nigeria, as documented by various authors [32-42]. These findings are comparable to uranium concentrations reported in locations such as Switzerland, Italy, Finland, Iceland, and Myanmar [43-47]. Conversely, at several locations, uranium concentrations in groundwater samples are significantly lower compared to areas such as Andhra Pradesh, Haryana, SW, Punjab, Northeast Rajasthan, Uttarakhand, Chhattisgarh, Jharkhand, and Karnataka in India [48-55] as detailed in Table1.

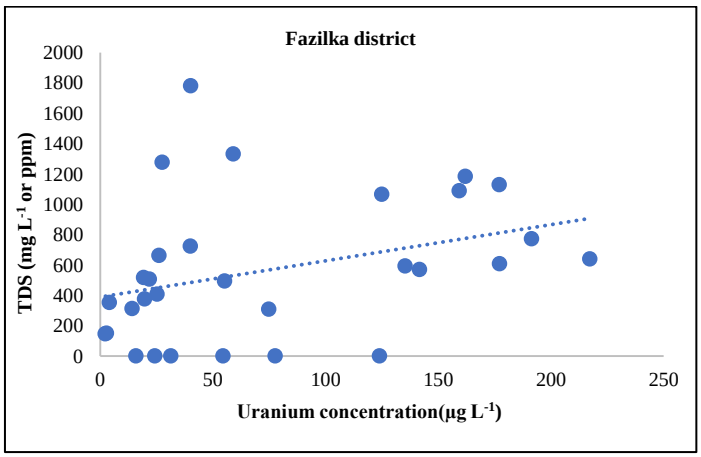


Figure 4. Variation of uranium concentration and TDS

Table 1. Uranium in groundwater and drinking water samples around the world

State/Country	Range of U concentration (µg L^{-1})	Reference
	World	
Canada, Quebec	1–845	Zamora et al., 2009 [32]
Brazil	<1–930	Godoy et al., 2019 [33]
Ghana	<0.001–266	Rossiter et al., 2010 [34]
USA New Mexico	< 5–560	Jones et al., 2020 [35]
Kosova	0.01–166	Berisha and Goessler, 2013 [36]
South Korea	0.02–1640	Cho and Choo, 2019 [37]
Norway	< 0.02–170	Frengstad et al., 2000 [38]
Mangolia	.31–200	Ariunbileg et al., 2016 [39]
Barundi	< 700	Post et al., 2017 [40]
China	< 0.02–288	Wu et al., 2014 [41]
Nigeria	20.17- 267.80	Amakom and Jibiri, 2010 [42]
Switzerland	0.05–100	Stalder et al., 2012 [43]
Italy	0.05–62	Cinti et al., 2015 [44]
Finland	0.08–34	Turtiainen et al., 2011 [45]
Iceland	0.01–0.54	Óskarsson and Stasgeirsdóttir, 2017 [46]
Myanmar	<1–45	Bacquart et al., 2015 [47]
	India	
Andhra Pradesh, India	0.0–2.0	Kumar et al., 2020 [48]
Haryana,India	0.10–223.16	Chahal et al., 2019 [49]
SW,Punjab	0.5 - 579	Bajwa et al., 2015 [50]
North east Rajasthan,India	0.89–166.89	Mittal et al., 2017 [51]
Uttarakhand,India	0.03–19.19	Mehra et al., 2018 [52]
Chhattisgarh, India	0.56–23.42	Sar et al., 2017 [53]
Jharkhand,India	0.03–11.60	Patra et al., 2013 [54]
Karnataka,India	0.3–144	Babu et al., 2008 [55]
Kerala, India	0.13 to 2.54	Prabhu et. Al., 2008 [56]
Fazilka, Punjab,India	2.33 to 217.23	Present Study

Table 2. Health Hazard data via ingestion of uranium.

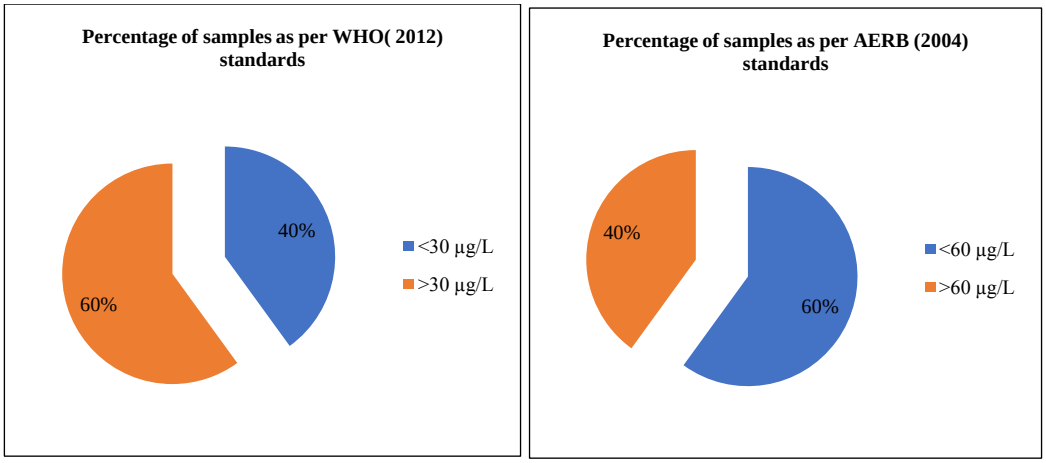
S. No	Village	Conc of Uranium (ppb)	Depth (in feet)	Activity (Bq L^{-1})	Annual Intake per person in Svdays^{-1}	Total annual ingestion dose Svyear^{-1}	Cancer mortality	Cancer morbidity	Life Time Daily Dose(LADD)μgkg^{-1}day^{-1}	Hazard Quotient (HQ)
1	Jandwala Bhimeshah	40.09	60.00	1.01	1.85E-07	6.46E-05	2.00E-08	3.20E-09	2.94	4.90
2	Ghattianwali	15.84	20.00	0.40	7.30E-08	2.55E-05	7.91E-09	1.27E-09	1.16	1.93
3	Tahliwala Bodla	4.07	45.00	0.10	1.87E-08	6.56E-06	2.03E-09	3.25E-10	0.30	0.50
4	Arniwala	123.95	35.00	3.13	5.71E-07	2.00E-04	6.19E-08	9.90E-09	9.08	15.14
5	Dhabwali Kalan	14.22	25.00	0.36	6.55E-08	2.29E-05	7.10E-09	1.14E-09	1.04	1.74
6	Burj Hanumangarh	77.62	50.00	1.96	3.58E-07	1.25E-04	3.87E-08	6.20E-09	5.69	9.48
7	Muradwala	21.87	50.00	0.55	1.01E-07	3.53E-05	1.09E-08	1.75E-09	1.60	2.67
8	Sito Gunno	74.91	65.00	1.89	3.45E-07	1.21E-04	3.74E-08	5.98E-09	5.49	9.15
9	Dutarwali	162.09	40.00	4.10	7.47E-07	2.61E-04	8.09E-08	1.29E-08	11.88	19.79
10	Rajawali	177.11	40.00	4.48	8.16E-07	2.86E-04	8.84E-08	1.41E-08	12.98	21.63
11	Sukhchain	55.27	65.00	1.40	2.55E-07	8.91E-05	2.76E-08	4.41E-09	4.05	6.75
12	Kala Tibba	54.51	90.00	1.38	2.51E-07	8.79E-05	2.72E-08	4.35E-09	3.99	6.66
13	Chanan Khera	31.43	65.00	0.79	1.45E-07	5.07E-05	1.57E-08	2.51E-09	2.30	3.84
14	Waryam khera	2.33	25.00	0.06	1.08E-08	3.76E-06	1.17E-09	1.86E-10	0.17	0.29
15	Kallar Khera	19.70	75.00	0.50	9.07E-08	3.18E-05	9.83E-09	1.57E-09	1.44	2.41
16	Siyadwala	24.32	60.00	0.61	1.12E-07	3.92E-05	1.21E-08	1.94E-09	1.78	2.97
17	Diwan Khera	26.07	50.00	0.66	1.20E-07	4.20E-05	1.30E-08	2.08E-09	1.91	3.18
18	Shatir wala	40.22	65.00	1.02	1.85E-07	6.49E-05	2.01E-08	3.21E-09	2.95	4.91
19	Nihal Khera	25.25	35.00	0.64	1.16E-07	4.07E-05	1.26E-08	2.02E-09	1.85	3.08
20	Karni khera	125.04	70.00	3.16	5.76E-07	2.02E-04	6.24E-08	9.99E-09	9.16	15.27
21	Choharian wali	27.58	30.00	0.70	1.27E-07	4.45E-05	1.38E-08	2.20E-09	2.02	3.37
22	Ghubhaya	177.27	200.00	4.48	8.17E-07	2.86E-04	8.85E-08	1.42E-08	12.99	21.65
23	Chak Romwali	159.35	100.00	4.03	7.34E-07	2.57E-04	7.95E-08	1.27E-08	11.68	19.46
24	Mida	135.41	250.00	3.42	6.24E-07	2.18E-04	6.76E-08	1.08E-08	9.92	16.54
25	Khere Ke Uttar	141.76	220.00	3.58	6.53E-07	2.29E-04	7.08E-08	1.13E-08	10.39	17.31
26	Guru Harsehai	217.23	180.00	5.49	1.00E-06	3.50E-04	1.08E-07	1.73E-08	15.92	26.53
27	Kikkar Khera	2.89	25.00	0.07	1.33E-08	4.66E-06	1.44E-09	2.31E-10	0.21	0.35
28	Chanan Khera	19.30	60.00	0.49	8.89E-08	3.11E-05	9.63E-09	1.54E-09	1.41	2.36
29	Dhani Sucha Singh	191.39	45.00	4.84	8.82E-07	3.09E-04	9.55E-08	1.53E-08	14.02	23.37
30	Pind chiragdhani	59.07	50.00	1.49	2.72E-07	9.53E-05	2.95E-08	4.72E-09	4.33	7.21

Uranium concentration for two cities of Kerala ranges from 0.132 to 2.54 μgL^{-1} Prabhu et al. [56]. In our study, the total uranium activity in water samples ranged from 0.05 to 5.49 BqL^{-1} as detailed in Table 2, with uranium concentrations ranging between 2.33 and 217.23 μgL^{-1}. Notably, Nriagu et al. [57] reported uranium levels ranging from 0.01 to 57 μgL^{-1}, significantly higher than the values reported for samples from India (Jharkhand state), which ranged from 0.03 to 11.6 μgL^{-1} [54]. Furthermore, the values reported by Nriagu et al. [57] are comparable to those obtained for samples in Italy (ranging from 0.05 to 62 μgL^{-1}) [44] and also similar to the range (<1 to 80 μgL^{-1}) reported for water samples elsewhere [58]. The annual ingestion of U-238 was estimated to be between 1.07×10^{-8} and 1.00×10^{-6} $Svday^{-1}$ for the samples under study.

The AERB, the national authority for radiological safety, has set a national limit of 60 μgL^{-1} for radiological contaminants, as detailed in Table 3. This limit is considered reasonable for two main reasons: a) the cost of reducing contaminant levels to extremely low concentrations is not justified by the associated benefits, and b) it is in line with standards adopted by other countries and recommendations from international organizations. According to AERB (2004) standards, 60% of groundwater samples fall within this permissible limit, indicating that the water is generally safe for drinking, with the exception of a few villages. Figure 5 showing the Pie chart distribution indicating the percentage of samples exceeding a) WHO limit b) AERB limit.

Table 3. Percentage result for uranium concentration

S.No	Source document	Derived water concentration of uranium µg L^{-1} as per standards	No of Samples (in Percentage) under permissible limit as per standards
1	WHO (1998)	2	---
2	WHO(2004)	15	13%
3	WHO(2012)	30	40%
4	BIS (2021)	30	40%
5	USEPA (2000)	30	40%
6	AERB (2004)	60	60%



(a) (b)

Figure 5. Pie chart indicating percentage of samples exceeding (a) WHO limit, (b) AERB limit

In this study, the cumulative intake of U-238 per year was evaluated, ranging from 3.76×10^{-6} $Svyear^{-1}$ to 3.5×10^{-4} $Svyear^{-1}$, with a mean dose of 1.2×10^{-4} $Svyear^{-1}$. Cancer mortality, defined as the death rate among individuals in the study area due to cancer, is expressed as the number per 100,000 inhabitants. For the area

under investigation, the cancer mortality attributed to U-238 intake from groundwater was estimated to be between 1.16×10^{-9} and 1.08×10^{-7}. Similarly, cancer morbidity, representing the incidence of cancer-related illness among inhabitants, was determined to be in the range of 1.86×10^{-10} to 1.73×10^{-8} due to U-238 intake from groundwater in the studied area as shown in Figure 6. These values fall well below the maximum threshold limit of 10^{-3} [24]. Table 4 shows the comparison of Radiological and chemical risk with the standard reference values.

According to the World Health Organization, the acceptable Tolerable Daily Intake (TDI) for LADD is set at 1.0 $\mu gkg^{-1}day^{-1}$ [59]. In this study, the average LADD value obtained was 5.48 $\mu gkg^{-1}day^{-1}$, with values ranging from 0.17 to 15.9 $\mu gkg^{-1}day^{-1}$. Notably, 90% of the samples analyzed exceeded the maximum permitted value. Utilizing the RfD value of 0.6 $\mu gkg^{-1}day^{-1}$, the HQ was assessed. For the study area, the HQ values ranged from 0.285 to 26.5, with an average of 9.14 $\mu gkg^{-1}day^{-1}$. As the majority of samples (more than 90%) exhibited HQ values above 1.0, it can be concluded that residents are significantly exposed to chemical toxicity hazards as depicted in Table 4.

Table 4. Comparison table of radiological and chemical risk of Fazilka District.

	For Fazilka District					
	Radiological Risk		Chemical Toxicity Risk			
	Cancer mortality	Cancer morbidity	LADD in $\mu g\ kg^{-1}\ d^{-1}$		Hazard Quotient	
Minimum	1.16×10^{-9}	1.86×10^{-10}	.171		0.285	
Maximum	1.08×10^{-7}	1.73×10^{-8}	15.91		26.52	
Average	3.74×10^{-8}.	5.98×10^{-9}	5.488		9.14	
Acceptable limit	10^{-3}	10^{-3}	0.6	2	equal to or less than one (≤1)	if HQ is greater than 1
Results	Ye-Shin et al., 2004 [24]		WHO 1998 [59]	ATSDR 1999 [5]	Indicate no appreciable health risk	Chemical toxicity exist

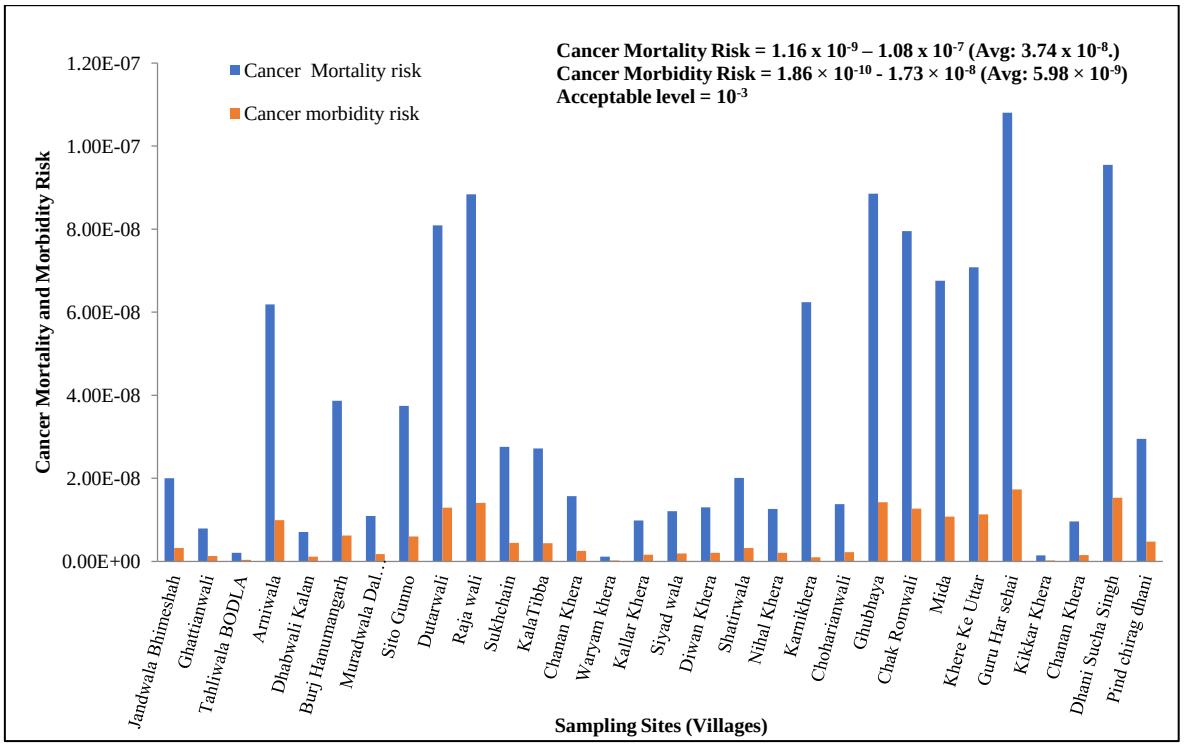


Figure 6. Cancer mortality and morbidity risk of Fazilka District.

CONCLUSIONS

This study reveals that uranium concentrations in groundwater ranges from 2.33 to 217.23 μgL^{-1}.Residents in the region experience radiological doses between 1.07×10^{-8} and 1.00×10^{-6} $Svday^{-1}$, with this exposure primarily resulting from uranium intake through groundwater sources. Importantly, the uranium levels found are within the permissible limits set by regulatory standards. The associated cancer risk, cancer mortality linked to U-238 intake from groundwater ranges between 1.16×10^{-9} and 1.08×10^{-7}. Cancer morbidity attributable to U-238 intake falls within the range of 1.86×10^{-10} to 1.73×10^{-8}. These findings indicate that the risk of cancer-related illness and mortality remains minimal and is below established reference levels, confirming that the current exposure levels are within acceptable safety thresholds.

However, the HQ and LADD values indicate a higher chemical toxicity risk due to uranium intake, with 90% of the area under study exceeding acceptable limits. In conclusion, while there are no indications of a carcinogenic threat to residents in the studied region, there are indications of non-carcinogenic risks associated with chemical toxicity due to the presence of uranium in groundwater. Findings indicate that groundwater from boreholes up to 100 feet deep is within safe limits for consumption, with no immediate radiological or chemical risks to residents. The study suggested that some policies must be set to enhance monitoring protocols, strengthen industrial regulations like waste management and emissions controls and improve water treatment guidelines. Implement updated public health advisories and adjust land use regulations to prevent contamination from industrial and agricultural activities. These measures ensure effective management and protection against uranium contamination risks. The study strongly recommended initiating research on temporal variations like seasonally, annually, or over longer periods and the adoption of preventive measures or remedial technologies in prone areas.

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Conflict of interests

All authors declare that they have no conflicts of interest.

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