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Research Article

Evaluating Spatio-Temporal Trends of Uranium in Shallow Aquifers of Delhi NCR: Implications for Groundwater Quality

Shubhi Khare[1*], Deepak Kumar[1], Sandhya Kurre[1]

[1]Department of Soil & Water Conservation Engineering, GBPUAT Pantnagar, Uttarakhand- India

*** Corresponding Author's E-mail:** eshubhi259@gmail.com

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Abstract

Uranium contamination in groundwater has emerged as a significant water quality and public health concern in the National Capital Territory (NCT) of Delhi, India, where groundwater serves as an important supplementary source for domestic and municipal use. This study examines the occurrence, spatial variability, and hydrogeochemical processes controlling Uranium mobilization in shallow and deeper aquifers across urban and peri-urban regions of Delhi using data of Central Groundwater Board (CGWB). The geogenic contribution from Uranium-bearing alluvial sediments is further influenced by anthropogenic pressures such as intensive groundwater abstraction, urbanization, and infiltration of treated and untreated wastewater. Results indicate that Uranium concentrations at several sites exceed the World Health Organization (WHO) guideline value of 30 µg L^{-1}.The findings provide a scientific basis for targeted groundwater monitoring, risk assessment, and sustainable aquifer management strategies aimed at safeguarding drinking water quality in Delhi and similar rapidly urbanizing regions.

Key words: Uranium, Groundwater quality, Delhi aquifer, urban water management

Introduction :

Groundwater is one of the most crucial natural resources nowadays and needs to be managed efficiently for sustainable use.A significant percentage of the world population depends on groundwater as their source of drinking and irrigation water, especially arid and semi-arid areas where surface water resources are scarce. Nevertheless, the impact of naturally occurring and anthropogenically mobilized contaminants is a challenge to the quality of groundwater and human health. Uranium is a naturally occurring radioactive heavy metal existing largely as the U(IV) and U(VI) ions in subsurface environment (Balaram et. al., 2022).U(IV) is often referred as the 'Stuck State' since in deep, oxygen-poor environments, U(IV) (e.g., Uraninite, UO_2) is insoluble and stays effectively "glued" to the rock, while U(VI) is considered to stay in the 'Mobile State' since when oxygen enters the aquifer (due to over-pumping or shallow water tables), U(IV) oxidizes to Uranium (VI) (Waseem et. al., 2015; Papageorgio et. al., 2022). This forms the Uranyl ion (UO_2^{2+}), which dissolves easily in water.If the water is rich in bicarbonates (HCO_3^-) and carbonates (CO_3^{2-}), they bond with the uranyl ion to form negatively charged complexes (like Uranyl Carbonate) as shown in Equation 1.Since soil particles are also negatively charged, they repel these complexes and hence Uranium floats in the aquifer unhindered.This Uranium rich water then comes in the supply chain and is consumed by the human body (Srivastava et. al., 2022).

$$UO_2{}^{2+} + 2CO_3{}^{2-} \rightarrow [UO_2(CO_3)_2]^{2-} \quad (1)$$

The sources of Uraniumas shown in Fig.1 can be natural or anthropogenic depend on the site condition. The geogenic sources of Uranium in groundwater might be due to the presence of genetic terrain over the area or due to the prevalence of high saline conditions in the soil (Kumari et. al., 2026). Land use changes significantly impact groundwater recharge and quality. Utilizing a Remote Sensing and GIS approach allows researchers to track urban land-use dynamics and their subsequent pressure on water systems(Ghildiyal et. al., 2026). The anthropogenic reasons for the presence of Uranium contamination in soil and then groundwater relies on a number of human induced activities such as agriculture where the leaching of phosphate fertilizers enhances the amount of Uranium contamination present in the groundwater. Also, due to several human activities such as improper solid waste management, leakage in sewer or septic tanks and even manure produces by the livestock farming can cause the nitrate pollution in groundwater (Tiwari et. al., 2026). Also, the over extraction of groundwater due to the complex human use night result in the oxidation of Uranium ion and thus converting U(IV) ion to U(VI) ion (Sidhar et. al., 2025; Abolli et. al., 2024).

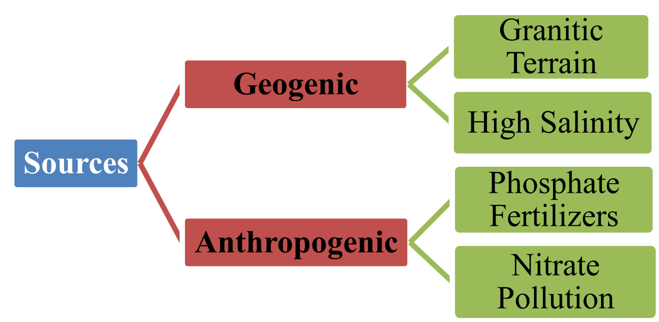


Fig. 1. Sources of Uranium in Groundwater

While compared to the other pollutants,Uranium being a radioactive substance, poses highly potential and vastly expanded effect on environment. Uranium contaminated water groundwater is severely toxic in nature and can cause severe health impact on human including illnesses like cancer. In view of this, different agencies with respect to the different uses of Uranium have framed different concentration of Uranium in groundwater (Liu et.al., 2025). Table 1 below shows the permissible limit of Uranium in groundwater according to the different agencies (AERB 2004; BIS 2012; USEPA 2004; WHO 2011). This calls for the reliable management of land and water resources which requires advanced modeling, yet these models possess inherent limitations that must be accounted for in sustainable planning (Khare et.al., 2026).

Table 1. Permissible Limit of Uranium in Groundwater

Sr. No.	Agency	Value	Unit
1	World Health Organization (WHO)	30	µg/L (ppb)
2	Bureau of Indian Standards (BIS)	30	µg/L
3	Atomic Energy Regulatory Board (AERB)	60	µg/L
4	United States Environment Protection Agency (USEPA)	30	µg/L

Chronic exposure to Uranium through drinking water poses a dual threat to human health, acting as both a chemical toxin and a radiological hazard. While radioactivity is a concern, its chemical toxicity, specifically the affinity for the kidneysis often the more immediate clinical issue. Once ingested, Uranium can accumulate in the renal tubules, potentially leading to nephrotoxicity and chronic kidney disease. Beyond renal health, emerging research suggests that prolonged consumption can interfere with bone metabolism by displacing calcium, leading to increased bone fragility. Additionally, because Uranium can act as an endocrine disruptor, long-term exposure has been linked to reproductive developmental issues and an increased risk of certain cancers, making its presence in shallow aquifers a significant public health priority (Khare et. al., 2025).

Effective management of uraniumcontaminated aquifers requires a synthesized approach that integrates advanced data analytics with physical and legal interventions. The handling of Big Data through Remote Sensing and GIS is foundational to this process, as it allows for the monitoring of land-use dynamics and the quantification of environmental stressors like salinity that correlate with contamination(Khare et. al., 2025). Once high-risk zones are identified, in situ remediation technologies offer a localized solution for subsurface management, though their implementation must be guided by rigorous cost-benefit analyses to ensure economic sustainability (Khare and Kumar, 2025). However, technical success is deeply intertwined with social and legal frameworks which requires active public participation for the long-term stewardship of a contaminated aquifer, ensuring that community needs and health impacts are addressed (KumarandKhare, 2025). Furthermore, the mitigation of lossboth in terms of water quality and public healthmust be supported by constitutional laws specifically designed to address subsurface water pollution and enforce environmental accountability(Maurya et. al., 2025). Keeping all these things in mind, the present study aims to assess the Uranium concentration at various sites in Delhi using the contamination data from CGWB of year 2023 and 2025. The study objects to monitor the various high concentration sides and the rate of increase of Uranium in the year 2025 compared to 2023. Also, the study focuses to identify the land use of the highly Uranium contaminated sites and the possible reasons for high Uranium contamination.

1. Indian and global problems of Uranium in Groundwater

According to a study by Wu et. al., 2014 which investigated the Uranium occurrence of Datong basin of Northern China. The study observed that the Uranium contents were generally more than 1 mg/kg for the igneous rocks, typically 2 to 5 mg/kg for Carboniferous and Permian sedimentary rocks while around 3 mg/kg for sedimentary rocks. The results suggested that about 24% of the investigated bore holes were above the WHO provisional guidelines for Uranium in drinking water in China within average value of 24 gram/litre. The average Uranium concentration for surface water was observed as 5.8 µg/l. The study observed high Uranium concentration in groundwater at the alluvial plains of the study area and the possible reason suggested was due to intermediate redox and enhanced alkaline conditions. Also, the abnormally high Uranium concentration in groundwater was found in the west and will planes of the study area. The overall paper suggested that the high levels of Uranium present in the study area were due to the geogenic conditions of the study area.

In a study by Nizam et. al., 2022, the analysis of toxic trace elements in surface and groundwater of Kanpur Nagar and Kanpur Dehat regions of Uttar Pradesh. A total of 172 groundwater samples were collected from the India Mark II hand-powered pumps from both the districts, and 21 surface water samples were collected from rivers, canals, ponds, and lakes of the Kanpur Dehat district only. All the sample analysis for total alkalinity, pH, trace elements and ions were carried out in the Environmental and Low-Temperature Geochemistry Lab of Indian Institute of Technology Kanpur, India. The alkalinity was measured using standard protocol, pH was measured using YSI water quality probe. and ions (chlorine, nitrate and sulfate) were analyzed using ion chromatography. The trace elements ((Li, V, Cr, Mn, Co, Ni, Sr, Rb, Cd, Ba, Pb, and U) were measured using Agilent Triple Quadrupole Inductively Coupled Plasma Mass Spectrometer (QQQ-ICP-MS). The result of the study concluded that the dissolved groundwater Uranium and NO_3^- concentrations exceeded their provisional guideline values of 30 μ g/L in 17% (n = 29) and 45 mg/L in 18% (n = 31) prescribed by WHO and BIS respectively, while the groundwater heavy metal concentrations namely Cr, Ni, Pb and Cd were within the guideline value outlined by WHO and BIS.

Zielinski et. al., 1997 demonstrated that $^{235}U/^{238}U$ alpha activity ratio (AR) can be used as an environmental tracer to map groundwater contamination from a Uranium mill near Cañon City, Colorado. By analyzing 47 samples, researchers successfully distinguished between mill-derived liquid waste (raffinate), which typically has a narrow AR of 1.0–1.06, and natural alluvial groundwater, which features higher AR values of 1.3–1.5. The study identifies a contaminant plume originating from old tailings ponds that migrates north-northeast through the Sand Creek drainage into the Lincoln Park residential area. While Uranium and molybdenum concentrations are highly correlated, isotopic data revealed that molybdenum is often more mobile than Uranium, which can be retarded by sorption onto iron and manganese oxyhydroxides despite the well-oxygenated state of the aquifer. Ultimately, the methodology provides a robust framework for assessing mixing proportions and the ultimate fate of Uranium at similar mining or processing sites, provided the introduced contamination is isotopically distinct from local groundwater.

The study by Deng et. al., 2025 explored the use of Microbial-Induced Carbonate Precipitation (MICP) as a green, low-cost solution for treating Uranium-contaminated water in tailings pond areas. Researchers isolated and domesticated an indigenous urealytic strain, HK-1 (Sporosarcina sp.), which utilizes urease to hydrolyze urea and produce carbonate ions that combine with calcium to form stable mineral precipitates. Under optimized culture conditions, including a pH of 7.9 and a temperature of 30°C, the domesticated strain achieved a Uranium fixation efficiency of 86.14%, significantly outperforming undomesticated control groups. Microscopic analysis confirmed that Uranium is immobilized through a combination of biosorption onto bacterial functional groups, interfacial coordination on carbonate minerals, and coprecipitation via lattice substitution and encapsulation. Furthermore, stability tests demonstrated that these mineralized products effectively inhibit the secondary release of Uranium even in acidic environments, providing a robust technical basis for the ecological restoration of radioactively contaminated sites.

Ibrayeva et. al., 2025 preliminary study investigates radioactive water contamination in settlements near Uranium mining areas in Northern Kazakhstan, revealing significant public health risks from untreated groundwater. While centralized water systems drawing from the Stepnogorsk Reservoir meet safety standards, private wells and boreholes in settlements like Kvartsitka and Saumalkol exhibit alarming levels of alpha and beta activity, with some exceeding intervention limits by two orders of magnitude. Notably, radon concentrations in Saumalkol boreholes reached up to 1200 Bq/L, surpassing permissive levels by an order of magnitude due to the proximity of dormant mines and the disturbance of natural geological barriers. The study highlights a distinct lack of secular equilibrium, as high radon levels persist despite relatively low radium concentrations, driven by radon's high mobility in fractured rock systems. These findings underscore the urgent necessity for advanced water treatment, routine radionuclide monitoring, and public education to protect local communities from chronic exposure risks such as kidney damage and cancer.

The study by Shalumon et. al., 2021 examines microbial-induced calcium carbonate precipitation (MICP) as a sustainable, "green" biotechnology for remediating heavy metals and radionuclides from the environment. The process relies on urealytic bacteria, such as Sporosarcinapasteurii, which secrete urease to hydrolyze urea and generate carbonate ions that combine with calcium to form stable mineral precipitates. Contaminants like strontium-90 and Uranium are effectively immobilized through a combination of biosorption onto microbial cell surfaces, surface adsorption onto newly formed crystals, and coprecipitation via lattice substitution or encapsulation within the growing mineral matrix. The efficiency of this biomineralization is highly dependent on environmental factors such as pH, temperature, and nutrient concentration, which must be optimized to ensure high microbial activity and stable mineral formation. Ultimately, the study highlights MICP as a cost-effective and environmentally friendly alternative to traditional remediation methods, though it emphasizes the need for further research to transition from laboratory success to large-scale field applications.

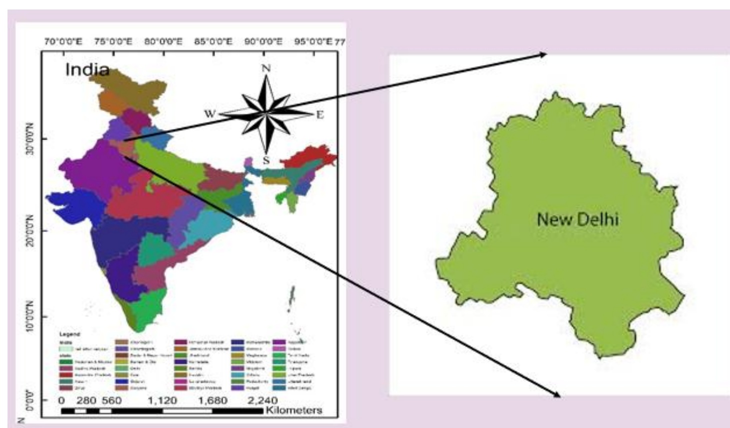
Srivastava et. al., 2017 utilized Electron Paramagnetic Resonance (EPR) spectroscopy of tooth enamel to retrospectively reconstruct radiation doses for 21 workers at a Uranium hydrometallurgical plant in Northern Kazakhstan. By analyzing 26 tooth samples from staff employed between 1960 and 2011, researchers identified an average excess radiation dose of approximately 58 mGy above the natural background. The findings demonstrate that EPR dosimetry serves as a high-precision "biological dosimeter," offering a more reliable assessment of long-term occupational exposure than historical records, especially for the early decades of the plant's operation. This quantitative dose reconstruction provides a critical foundation for evaluating the long-term health risks—such as cancer and kidney disease—faced by nuclear fuel cycle workers in the Stepnogorsk region.

2. Study Area and Methodology

Study Area

For the present study, the post-capital city of India, Delhi has been selected as shown in Fig. 2. Delhi, with latitude and longitude as 28.7041° N, 77.1025° E respectively, is located in the northern part of the country, situated between the Himalayan range to the north and the Aravalli range to the southwest. It lies on the banks of the Yamuna River, spanning a total area of 1,483 km². Delhi is bordered by Haryana on three sides (north, west, south) and Uttar Pradesh to the east. The geology of Delhi is dominated by the Delhi Supergroup of rocks (part of the ~1,500-million-year-old Proterozoic Aravalli-Delhi orogen), which form the prominent rocky ridge in the city. This ancient, poly-deformed ridge consists mainly of quartzite, schist, and marble, surrounded by Quaternary alluvium. It lies in a tectonically active region, vulnerable to seismic activity despite being an intraplate zone, due to proximity to the Delhi-Haridwar Ridge fault line.The total agricultural area of Delhi, largely situated in its rural pockets and along the Yamuna floodplains, covers roughly 45,000 hectares, though this is actively shrinking due to urbanization. The primary crops cultivated in Delhi are wheat (Rabi) and paddy/rice (Kharif), along with significant production of vegetable.

Fig. 2. Location map of Study Area, Delhi



Methodology

For the present study, the water quality data from the website of Central Ground Water Board had been collected and studied for the year 2023 and 2025. From the data, all sites of Delhi where Uranium contamination in groundwater exceeded the permissible limit of WHO were plotted through the help of Google Earth explorer in QGIS software. For the comparative study of

Uranium contamination in groundwater, the dataof year 2023 and 2025 was assessed statistically using the following parameters:

i. **Mean**

Mean ($\bar{x}$) is the sum of a collection of numbers divided by the count of numbers in that collection. It represents the "central" value of a discrete set of numbers and is used to describe the average characteristics of a dataset.The current study uses the mean to determine the average concentration of Uranium across the study area. It is calculated with the help of formula stated in Equation 2.

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} (2)$$

Where, x_i represents each individual value in the data set, and n is the total number of values (sample size).

ii. **Median**

The Median is the middle value of a data set when the values are arranged in ascending or descending order. If the number of observations (n) is odd, it is the middle value; if n is even, it is the average of the two middle values and is calculated using Equation 3.

$$M = x_{\frac{n+1}{2}} (3)$$

Where, M is median, X is the value at position when arranged in ascending order and n is the number of observations.

Similarly, is the size of the sample is even, Equation 4 can be employes for the calculation of median.

$$M = \frac{x_{\left(\frac{n}{2}\right)} + x_{\left(\frac{n+1}{2}\right)}}{2} (4)$$

Where, al the notations are same as Equation 3

.

iii. **Standard deviation (SD)**

Measures the amount of variation or dispersion of a set of values.This tells how spread out the data is. A low SD value means the data points are close to the mean (consistent), while a high SD indicates high variability. It is represented by and is calculated with the help of formula given in Equation 5.

$$\sigma = \frac{\sqrt{\sum (x_i - \mu)^2}}{n} (5)$$

Where, σ is the standard deviation,μ is the mean value, 'i' is the respective year, n is the number of years taken for the study and x_i is the average value of contamination in that respective year.

iv. **Coefficient of Variation**

Coefficient of Variation is the ratio of the standard deviation to the mean, expressed as a percentage.This is crucial when there is need to compare the dispersion of two different datasets that have different units or widely different means. It can be calculated by the formula given in Equation 6.

$$CV = \frac{\sigma}{\bar{x}} \times 100 \quad (6)$$

Maximum and Minimum Value

These are the smallest and largestThese define the boundary of the study. They show the full scope of the observation in the dataset.

Increase in the concentration of Uranium from 2023 to 2025 was calculated and the Pollution Indexi.e., how many times the contamination exceeded the permissible limit was also calculated by dividing the increased concentration of Uranium with the permissible limit. The value of this factor revolves around 1. If the value is exactly 1, the contamination is at the threshold state; if the value is less than 1, then there is no contamination; but if the value goes more than 1, then higher goes the value, the higher will be the contamination level. With the help of Google Earth Explorer and QGIS software the LULC map of Delhi was prepared in order to access the land utilization of the area where Uranium contamination is higher than the permissible limit.Also, the land use land cover data was taken from Google Earth Explorer to understand the possible reasons for high Uranium contamination in the area. A summarization of the methodology opted for the present study is represented in Fig. 3.

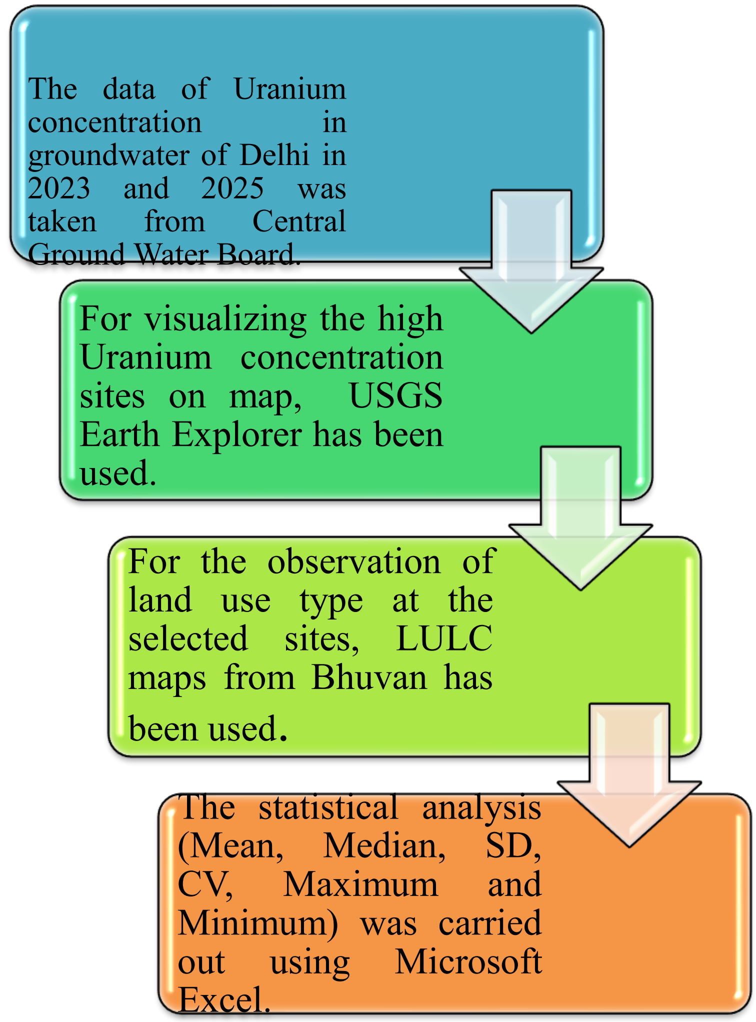


Fig. 3. Summary of the methodology opted for the study

Results and Discussion

From the water quality data provided by the Central Ground Water Board, it was evident that there were 12 sites in Delhi whereUranium contamination was higher than the permissible limit of WHO and in which some sites had extremely high levels of Uranium in groundwater as shown by Fig. 4. With the help of QGIS and Google Earth Explorer, all these 12 sites of Delhiwere plotted and represented in Fig. 5. Also, by the statistical analysis of the comparative study of Uranium contamination in 2023 and 2025, it was observed that then is an increase in the level of Uranium contamination in the groundwater. Fig.6 showsthe increase in the level of Uranium contamination in groundwater from 2023 to 2025. It is clearly visible in the figure that the maximum increase in Uranium contamination level was in the 12[th]site with the value reaching to 29 ppb, followed by 4[th] site with 22 ppb, 9[th] site with 21.1 ppb and 11[th]site with 16.5 ppb.The minimum increase in the level of Uranium contamination was observed in the 6[th]site with 6.2 ppb. Along with this, the pollution factor calculated for the study area,represented by Fig.7, reveals that the increase in the pollution is as high as twice the permissible limit in the 12[th] site. Even the minimum times increase in the level of Uranium contamination and groundwater depicted by the 6th site is reaching to a level of 1.2, that is, the contamination in the 6[th]site is reaching 1.2 times the permissible limit from year 2023 to year 2025.

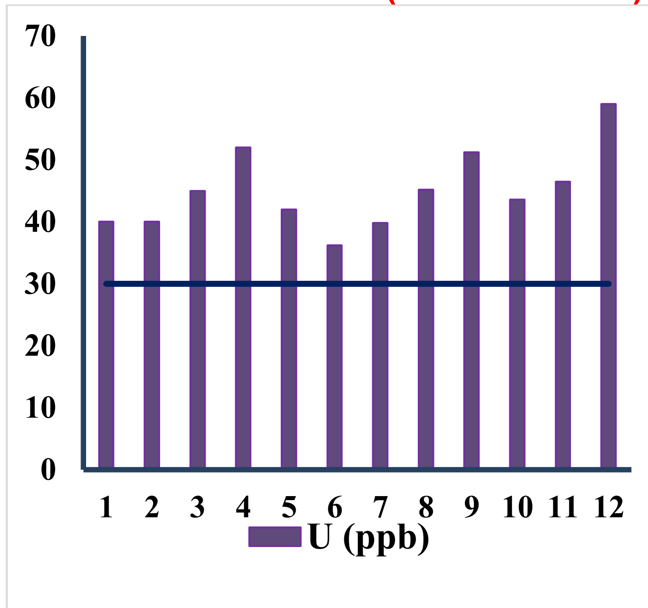


Fig. 4. UraniumConcentration in Groundwater in Delhi in 2025

Fig. 5. Geographic location of contaminated sites in Delhi

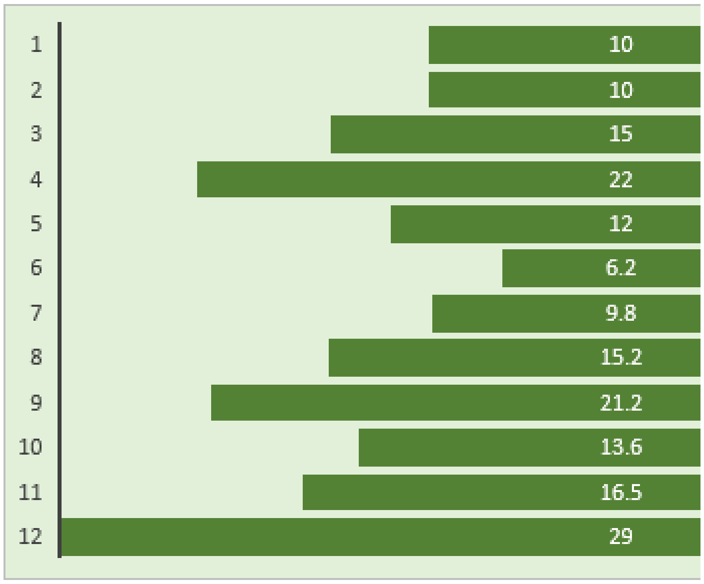


Fig. 6. Increase in UraniumConcentration in Groundwater in Delhi from 2023 to 2025

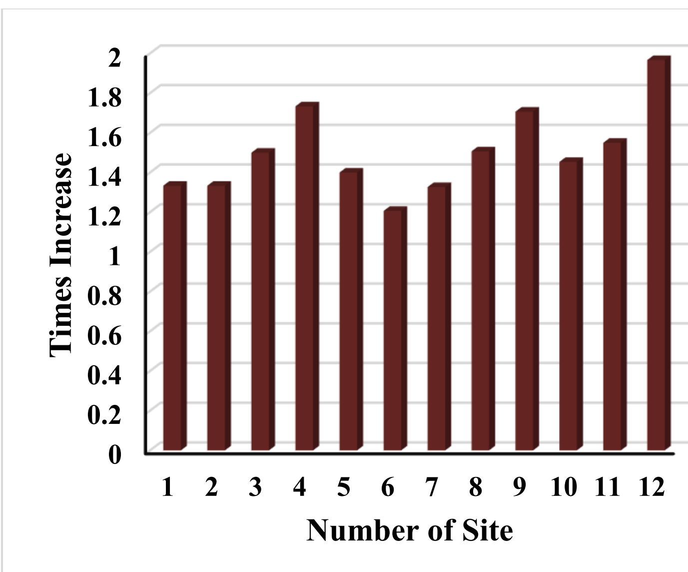


Fig. 7. Pollution factor of UraniumConcentration in Groundwater in Delhi

The comparative statistical analysis of Uranium contamination in the groundwater of the 12 contaminated sites of Delhi from 2023 to 2025 is shown in Fig. 8. It is evident from the figure that the median value as well as the minimum value of contamination level peaked in the year 2025 while standard deviation, maximum value and variation in the spread of contamination in the area lower in 2025 as compared to 2023. From Fig. 5, it is clear that all the 12 sides were located in the western region of Delhi. When the LULC map of the study area was prepared using Bhuvan software, it was observed that most of the sites were falling under the agriculture region of Delhi while some of them were falling in the urban sector of Delhi as shown in Fig. 9. Fig, 10 represents the overall land use of the Delhi state of India along with the areal extent to give a clear picture of Fig. 9.

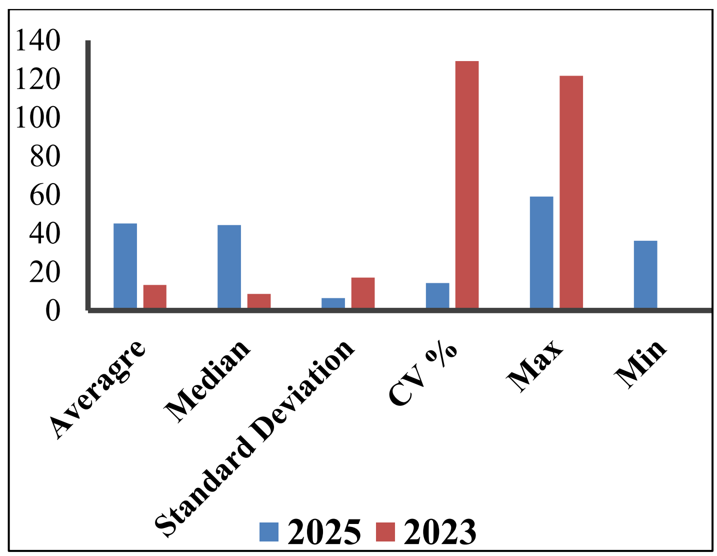


Fig. 8. Comparative statistical analysis of Uranium concentration in study area

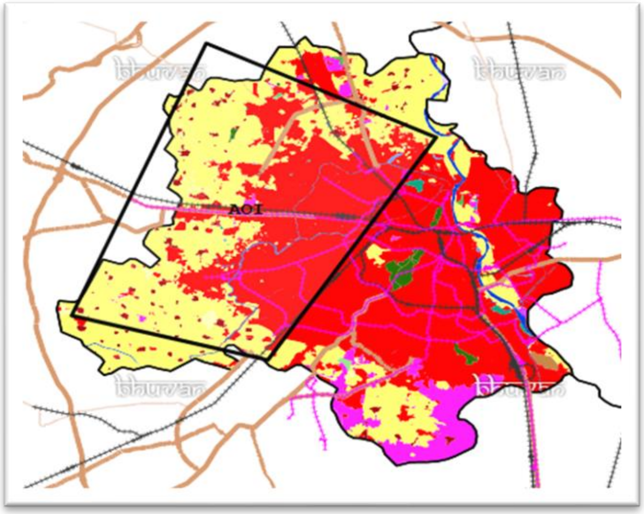
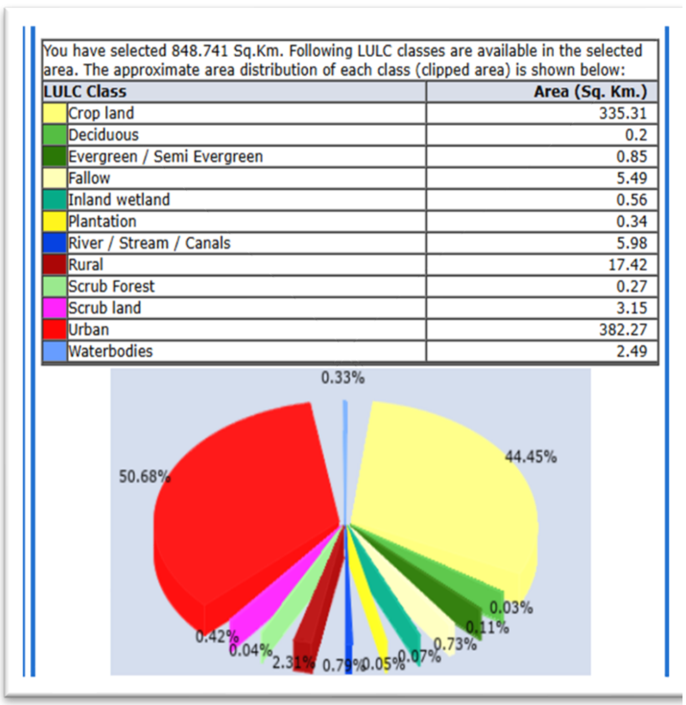


Fig. 9. LULC of the study area



You have selected 848.741 Sq.Km. Following LULC classes are available in the selected area. The approximate area distribution of each class (clipped area) is shown below:

LULC Class	Area (Sq. Km.)
Crop land	335.31
Deciduous	0.2
Evergreen / Semi Evergreen	0.85
Fallow	5.49
Inland wetland	0.56
Plantation	0.34
River / Stream / Canals	5.98
Rural	17.42
Scrub Forest	0.27
Scrub land	3.15
Urban	382.27
Waterbodies	2.49

Fig. 10. Areal extent under each land use typein the study area

Conclusion

The study confirms that Uranium contamination in the shallow aquifers of the Delhi NCR is a significant environmental concern, with concentrations at multiple sites exceeding the 30 μg/L safety limit set by the WHO and BIS. The mobilization of Uranium is driven by a transition from the insoluble "Stuck State" (U(IV)) to the soluble "Mobile State" (U(VI)), a process triggered by oxygen entering the aquifer due to factors like over-pumping or shallow water tables. In these alkaline conditions, the formation of negatively charged uranyl carbonate complexes causes electrostatic repulsion from similarly charged soil particles, allowing the Uranium to migrate unhindered into the human supply chain. Spatial analysis reveals that high-concentration hotspots are notably prevalent in areas with significant crop land and urban land use, suggesting that intensive groundwater withdrawal and anthropogenic activities play a critical role in this hydrogeochemical cycle. Consequently, urgent mitigation strategies are required to regulate groundwater extraction and manage the chemical drivers that pose long-term risks of nephrotoxicity and osteotoxicity to the local population.

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