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Chemo-Radiological Assessment of Groundwater Potability in the North-western Region of Maharashtra, India

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Abstract

Groundwater is essential for sustainable development, serving as a key element in environmental resilience and meeting human needs.This study assesses radiological and chemical risks associated with uranium concentrations in drinking water in Jalgaon district. The research explores various water quality parameters, including uranium concentrations, and calculates ECR, Lifetime Average Daily Dose (LADD), and Hazard Quotient (HQ) for different age groups and seasons. Pearson correlation analysis reveals significant associations between pH, TDS, EC, nitrate, and other constituents. Using Inverse Distance Weighting, spatial distribution mapping illustrates variations in water quality parameters across geographic areas. Results indicate notable correlations between uranium concentration and salinity, with higher concentrations in the western region during the pre-monsoon season. Conversely, post-monsoon values suggest lower concentrations, potentially due to groundwater dissolution. These findings contribute valuable insights for policymakers and environmental stakeholders in addressing potential health risks of uranium in the Jalgaon district's drinking water.

Keywords: Water quality, Uranium, Risk assessment, Radiotoxicity, Chemo-toxicity, Spatial distribution mapping.

Introduction

Uranium (U) is a natural lithophilicelement(Sasowsky and Mylroie, 2007; Smedley and Kinniburgh, 2023)that is presentin almost all components of nature,i.e., soil, rock, and water(U^{238}, U^{235}, and U^{234}) account for 49%, 2%, and 49% of the radioactivity of naturally occurring U.Water passing through the rocks and soil which dissolves many components and minerals, including U (Brugge et al., 2005). The dissolution concentration in groundwater depends on the region's lithology, geomorphology, and other geological conditions. Monitoring water quality helps assess the natural occurrence(Babu et al., 2008)of uranium in water. Consequently, the ingestion dose assessment of the members of the public residing around the study region may be useful to aid the establishment of regulation standards and management schemes(Herschy, 2012).The uranium concentrations(Underhill, 2020)in various environmental matrices, including soils, rocks, plants, water, etc., have been reported in the last few years. A similar study was reported in 2019, where uranium concentration was found to be 0.13 – 1340 ppb [7],higher than the guideline value of 30 ppb WHO and USEPA. Even if we consider the higher permissible limit of 60 ppb as suggested in India by the Atomic Energy Regulatory Board of the Department of Atomic Energy(Board, 2007). It reported that the uranium concentration ishigher than permissible limits in groundwater in certain parts of India[8]. An anthropogenic activity can also elevate its environmental levels, but they are unlikely to cause any significant change in its concentration in the groundwater(Read et al., 1993; Roy, 2018). It is normally present in the groundwater through the weathering of underground parent rocks(Crançon et al., 2010).The measurements of U concentration in drinking water are useful in assessing its dose incorporated into an average person through its pathway. Uranium is a hard, silvery-white, amphoteric, naturally occurring, radioactive and toxic heavy metal found in the earth's crust at an average concentration of about 3 mg/kg(Fawell, 2011; Okofo et al., 2022).The risk of uranium consumption to the public depends on various factors, including uranium concentration in the drinking water(Schnug and Lottermoser, 2013),water ingestion rate, duration of ingestion, andtheperson's general health. Drinking water contributes about 85% of the total ingestion of uranium(Fawell and Nieuwenhuijsen, 2003; Schnug and Lottermoser, 2013). Regular water monitoringcan reassure the public that drinking water quality is appropriate(Fawell and Nieuwenhuijsen, 2003; Yadav et al., 2014). Despite their toxic effects, groundwater naturally contains many chemical constituents that are not routinely tested as indicators of water quality.The amount of U in groundwater depends on its availability in bedrock, the proximity of U-rich rocks and soil, U's pH and oxidation state, and concentrations of other species in water that can form U complexes(Hassan, 1992).On the other hand, U occurs as UO_2^{2+} in toxic waters and forms highly mobile, stable and highly soluble ionic and neutralcomplexes that play the most important role in U transport during weathering(Lartigue et al., 2020). U has become a broadly studied heavy metal in environmental and health-related research in recent years. It is a natural constituent of the earth's crust and occurs in rocks, soils, and fluids(Tchounwou et al., 2012).Redox and complexation reactions of U are strongly affected by hydrolysis, as hydrolysis can limit solubility or affect sorption onto particles(McGowan et al., 2023).Large-scale U distribution is controlled by geology, mainly due to the heavy metal's incompatible behaviour in magmatic differentiation, which leads to elevated U contents in felsic migmatites like granites and pegmatites and associated sediment basins and, finally, groundwater(Aly, 2013). Intermediate U sinks and sources include organic-rich sediments like fen peats and gleyic soils, reflecting the element's affinity towards organic matter sorption. Inorganic phosphorus fertilizers, former uranium mining sites, depleted U ammunition, emissions from the nuclear industry, and combustion of coal and other fuels represent potential anthropogenic U

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sources(Balaram et al., 2022; Banning and Benfer, 2017).Uranium is a heavy metal with both radiotoxic and chemotoxic properties, potentially leading to adverse health effects in exposed populations whereby not only total concentration but also U speciation/complexation are decisive(De Kok, 2008; Liesch et al., 2015; Schnug and Haneklaus, 2015).The main U exposure pathway appears to be uptake via drinking water in most cases, indicating that the population supplied with drinking water from U-rich groundwater resources may exhibit elevated health risksassociated with the nephrotoxic potential of ingested U mainly as it damages the kidney tubular cells(Bjørklund et al., 2020; Services, 2002).In recent years, there has been increasing concern over uraniumin drinking water due to its chemical and radiological toxicity(Mathews et al., 2015). Uranium in natural groundwater systems depends on several factors, such as the region's lithology, geomorphology, and other geological attributes. Furthermore, the spatial variation of U mainly depends on geochemical factors (rock-water interaction) and its residence time in groundwater(Kumar et al., 2018). Nevertheless, anthropogenic sources also contribute to its enrichment, which includes agricultural activities in the form of excessive fertilizer application, leaching from natural deposits, mining activities, the nuclear industry, and fertilizer manufacturing(Balaram et al., 2022).Municipal discharges may release uranium from various sources, a factor that remains mostly unaddressed. The World Health Organization had earlier recommended a safe limit of 15 ppb foruranium in drinking water (Kale et al., 2018; Skeppström, 2007). Therefore, the purpose of this study is to analyse uranium in groundwater and use it as various criteria, with 30 ppb [32], 60 ppb [7], and 30 ppb [33] to be estimated. The main objective of this study is to estimate the risk assessment and dose based on the public U concentration by ingestingwater samples as a drinking water source.

Materials and Methods

About study region

Jalgaon district is in the northwest region of the state of Maharashtra. The study area, an important district of the Khandeshi region, is situated in the northwestern part of Maharashtra. It has a total population of 42,29,917 individuals as per 2011census(GOI, 2012). It has a total geographical area of 117670 Km^2. It falls in parts of Survey of India toposheet number 46K, 46 L, 46 P, 55 C, 55 D, and 56 O. The district lies between north latitudes 20°15' and 21°25' and east longitudes 74°55' and 76°28 in the northern part of the state abutting district is bounded on the north by Madhya Pradesh, on the east by Buldhana district, on the west by Nashik and Dhule districts and on the south by Chhatrapati Sambhajinagar(Aurangabad)(CGWB, 2015) (Fig. 1).

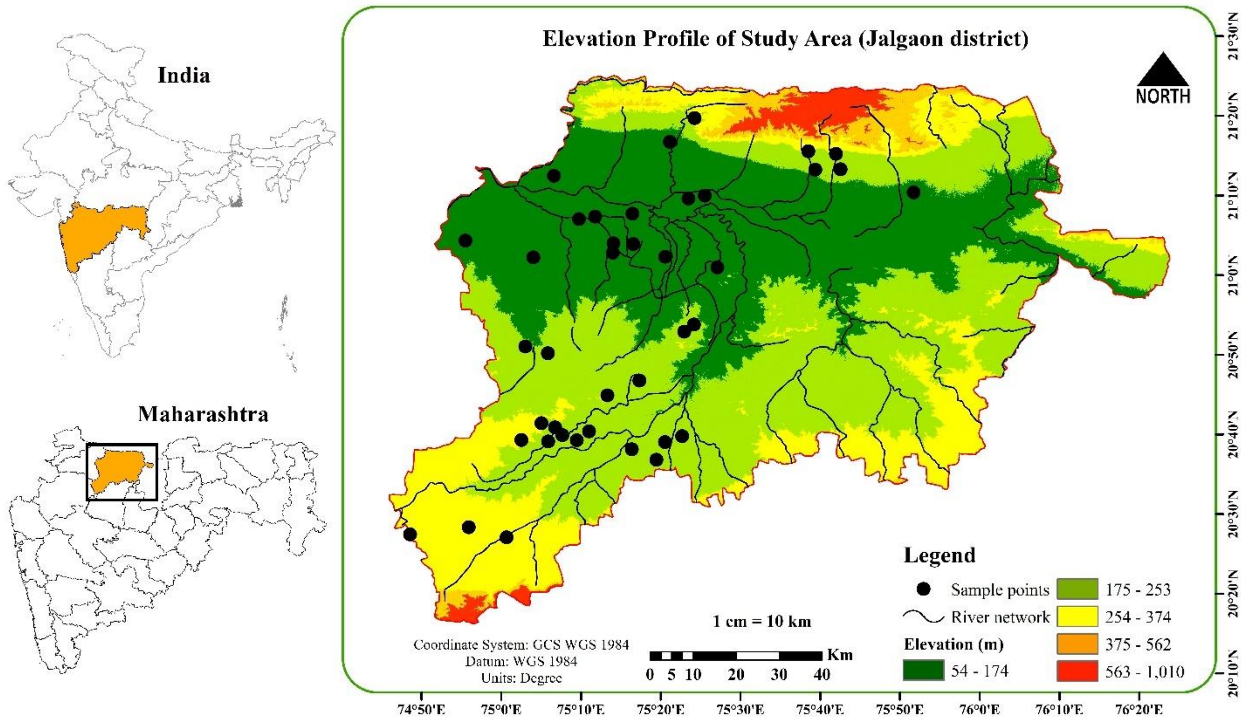

Fig. 1 Digital Elevation Model (DEM) of Jalgaon district as study region.

Geology, Geomorphology, Soil, and Climate

Basalt lava flows are the major rock formations along with alluvium/Bazada. The Deccan Trap basaltic lava flows from the upper Cretaceous to the lower Eocene. The alluvium flows from the Quaternary to recent (Ghope et al., 2019) (Fig. 2).The Tapi Alluvial Basin soil is a black alluvial clay found in the southern part of the Yawal, Raver, Chopda, Jalgaon, Bhusawal, Chalisgaon, Amalner, and Badgaon blocks. The area also has an alluvial land cover on either side of major rivers and streams (Fig.3). The Deccan Trap lava sequences were classified into the Satupda and Sahyadri groups north and south of the Tapi River. The lava flow lies just north of Tapi, and within the alluvium are the Lower Pahoehoe and Upper Aa Flows grouped under the Chahardi Formation(CGWB, 2018, 2015). Soils in the Jalgaon area are mainly derived from basaltic lava flows and are classified as a) jet black soils, b) medium black soils, c) loamy and sandy soils, and d) forest soils. Loamy soils are found at the southernmost ends of the Amalner, Erandol, Jalgaon and Bhusawal blocks.

Sandy soils are located near the foothills and southern hills of the Satpuda Mountains (Patil et al., 2012). The district can be divided into three main geographic divisions. The Tapi Valley consists of an alluvial plain in the central part of the district and the Ajanta Mountains of hills flanked by ridges and small valleys in the southern part of the district. A significant portion of the district comes under the Tapi basin. The Tapi Valley includes the vast central alluvial plains of Burhanpur to the east and Duree to the west. However, the riverbanks have eroded, creating canyons and wastelands that inhabit vast farmland areas. The Tapi River alluvial plain is bounded north by the steep southern bluffs of Satupda, a chain of high hills running east-west and southwest. The district's northern boundary is characterized by the valleys of the Anel River and, to its east, the valley of the Mamat River, a tributary of the Saki River. These two longitudinal valleys separate the southern extent of Satpuda from its northern members.

The Tapi River Valleyarea has a varied topography, including hilly plains, small ridges, and broad valleys. The Hatti Hills and the Purna Valley to the east stretch from the northwest to the southeast and cut through the southeast corner of the Jalgaon district for about 32 km. Satmala, also known as Chandur or Ajanta, divides sharply northwest of Nashik from Sahyadri's and runs about 80 km to the east on a series of ridges and basalt hills. The district's climate has been characterisedby hot summers and general drought year-round, except for the southwest monsoon season from June to September. The average low temperature is 10.8 °C, and the average high temperature is 42.2 °C ("मध्यक्षेत्र , नागपुर Central Region, Nagpur," n.d.). The average precipitation in 2017 for the Jalgaon district was about 521 mm. Over the past ten years, the average annual rainfall for the years 2008 to 2017 ranges from 550 (Jamuna) to 751 mm (Chopda) (Fig. 1)(Bhagat et al., 2021).

Principal cropsin the study region are banana, wheat, millet, lime, groundnut, cotton, and sugarcane.The Bazada Formation consists primarily of large deposits of pebbles, gravels, sand, residue, and clay mixed in loose form. This formation occurs at the foot of the Satupda Hills, which stretches 80 km from east to west and borders the western part of Jargon near the Anel River. The Bazada zone is covered with brown to black sandy soils. These deposits form by depositing rock fragments carried from the hills of the Satupda Mountains by local streams. The maximum thickness of these deposits is unknown. However, it is over 100 mbgl thick around Naygaon(CGWB, 2013; Ghope et al., 2019).

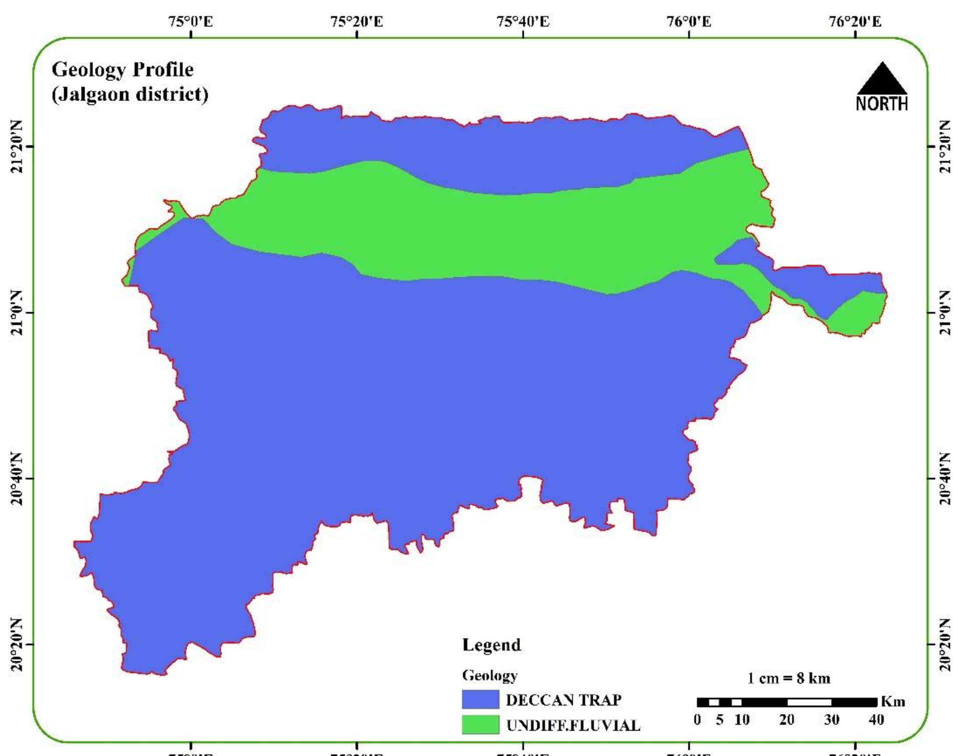

Fig. 2 Geological profile of Jalgaon district as study region

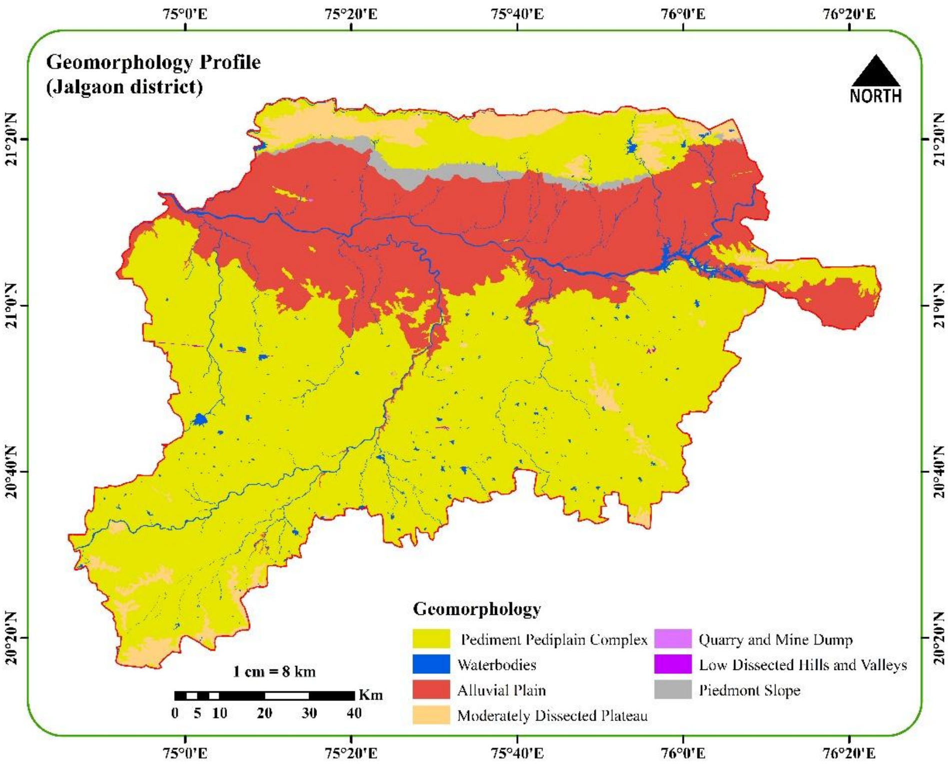

Fig. 3 Geomorphological profile of Jalgaon district as study region

Hydrogeology

Hydrogeology is primarily concerned with underground water's occurrence, distribution, movement and chemical propertiesin the geological environment. Geological conditions largely determine the occurrence and movement of water in the subsoil. H. Rock formation properties, including porosity (primary and secondary) and permeability. The principal aquifers in this region are Bazada, alluvium and basalt, and groundwater generation and movement in these rocks is controlled by factors such as Bazada particle size and clay content. Aquifer accumulation in alluvial aquifers, that is, aquifer accumulation, is higher in coarser strata, and the strata lack clay mixtures and intercalations. On the other hand, for basalts, groundwater generation and migration mainly depend on the degree of interconnection of secondary pores/voids created by fracturing and weathering. The cysts of the Deccan basalt layer are always filled with secondary minerals, leading to near-zero primary porosity(CGWB, 2018, 2015, 2013).

Sample Collection

A systematic grid(6×6 km) sampling method was adoptedto collectrepresentative water samples. A total of 144 water samples weregathered around the Jalgaon district area. To ensure freshwater was sampled from the aquifer, samples were taken by running bored wells for minutes before collection. The standard protocols are followed to minimize contamination during water sampling, filtration, storage, and handling. Water samples were collected in polythene bottles (1000 and 250 ml separately) pre-treated with 10% nitric acid to remove impurities.The U concentrations were analysed by Fluorometer (Quantalase India Pvt. Ltd) Model No. LF-2aand other water quality parameters were measured per the standard protocol APHA gave(Walter, 1961).Thephysicochemical parameters, i.e., Temperature (temp.), potential of hydrogen (pH), Electrical Conductivity (EC), Total Dissolved Solids (TDS), Dissolved Oxygen (DO), Oxidation

Reduction Potential (ORP), and salinity were analysed at sampling points using a portable multi-parameter meter kit (Orion Star A329).

Uranium analysis

In this investigation, uranium, along with other associated water quality parameters (pH, TDS, temperature, ORP, DO, fluoride, chloride, nitrate, sulfate, phosphate, hardness, and alkalinity, etc), underwent analysis following protocols outlined in national and international standards. The examination of ultra-trace levels of uranium in water samples employed a fluorimetry technique based on LEDs. A set of seven LEDs with a wavelength of 410 nm served as the excitation source to stimulate the uranium complex in the solution. The resulting uranium complex exhibited fluorescence, yielding four emission peaks (494, 516, 540, and 565 nm, with a maximum of around 510 nm), measured using a photomultiplier tube (PMT). Approximately 5 ml of the collected water sample was placed in a clean and dry suprasil quartz cuvette for analysis. Subsequently, 0.5 ml of a 5% sodium pyrophosphate solution (pH seven adjusted with phosphoric acid) was added. This sodium pyrophosphate solution acted as a fluorescence-enhancing buffer, converting the uranium species in the sample to a single and stable phosphate complex serving as a masking reagent. The fluorescence intensity, proportional to the uranium content in the aqueous solution, was determined. The impact of fluorescence from natural organic components ($\tau \sim 100$ ns and $\lambda = 400$ nm) present in the water sample was mitigated using the time-gating technology of the PMT and optical filters in the fluorimeter. Calibration of the LED fluorimeter involved using a standard uranium solution (certified Fluka standard) to assess linearity, sensitivity, and detection limit. Detailed information on fluorimetry and analytical techniques is available elsewhere. Due to the anticipated variations in the chemical composition of water samples, positive or negative interferences were accounted for using the standard addition method. This involved measuring the fluorescence intensity of the water sample, adding uranium standard to the cuvette, and measuring fluorescence intensity again. This process was repeated with additional uranium standards. A minimum three-point graph was plotted against uranium content, and a linear fit was applied for extrapolation to estimate uranium content in the water sample. The remaining water quality parameters in all samples were measured following the IS 3025 protocol.

The impact of these parameters on uranium geochemistry in drinking water sources was considered. The hardness and alkalinity of the water samples were measured by titrimetry, fluoride and chloride by ion-selective electrodes, and nitrate by a spectrophotometer. A subset of samples underwent analysis by ion chromatography. Table 2 provides a list of the parameters analyzed in this study, the instruments and standards used, and their respective detection limits.

The sample bottles are well-labelled for uranium analysis, representing the time, place, and sampling date. The uranium concentration was analysed in the departmental laboratory atthe university by using an LED fluorimeter LF-2a.The wavelength, pulse duration and peak power of the LED Fluorimeter output can be set to match the excitation requirements of the sample. A pulsed photomultiplier detects the fluorescence. The filters can be broad-band coloured glass filters or multilayer narrow-band filters. The microcontroller controlsthe instrument, which pulses the LEDs and photomultiplier tube. The microcontroller also controls the ADC, which converts the fluorescence signal from photomultiplier to digital form for further processing. A single-board computer averages the photomultiplier output over 2000 pulses and performs any necessary calculations. A touchscreen display permits the operator to set the required parameters and display the fluorescence measurement. The detector used in this operation is a Photomultiplier tube with an excitation source as alight-emitting diode (LED). A set of seven light-emitting diodes (LEDs) at a wavelength of 410 nm is utilized as the excitation source to activate the uranium complex within the solution. The uranium complex generates fluorescence, manifesting four distinct emission peaks at 494, 516, 540, and 565 nm, with the highest intensity observed approximately at 510 nm. A photomultiplier tube (PMT) is employed to detect and measure these emissions with bandwidth emission of 10-20 nm. Pulse duration was manually arranged with a pulse repetition rate of 1 kHz. The water samples were analysed using the standard addition methodto avoid the matrix effect. Sodium pyrophosphate ($Na_4P_2O_7 \cdot 10H_2O$) was used as a fluorescence enhancement reagent and a complexing agent (Sahoo et al., 2021, 2010, 2009)

Results and discussion

Descriptive statistics

In the pre-monsoon season, an in-depth analysis of uranium concentration levels, along with water quality parameters of drinking water samples from the Jalgaon District, Maharashtra, was conducted.The descriptive statistics of all water quality parameters for the seasons are presented in Table 4. All parameters were compared with standard permissible limits suggested by the World Health Organization (WHO) and the Bureau of Indian Standards (BIS) for drinking purposes. The pH is a critical parameter in assessing water quality, influencing the solubility of minerals and the biological availability of nutrients. It is a crucial determinant for various water uses, including drinking water (Hamid et al., 2019). In the pre-monsoon season, they exhibited a pH range of 7.1 to 8.8, with an average value of 8.16 ± 0.39. This range falls within the World Health Organization's (WHO) recommended range of 6.5 to 8.5, indicating generally acceptable pH levels. During the post-monsoon season, pH values ranged from 5.4 to 9.8, averaging 8.34 ± 0.68. While the average remains within WHO limits, the broader range suggests increased variability. Notably, the lower end of the spectrum approaches the lower limit of the recommended pH range. These variations highlight the dynamic nature of water quality, influenced by seasonal changes and local conditions (Saalidong et al., 2022). Monitoring pH levels is crucial to ensure water safety and adherence to established standards, especially considering the 30% increase in samples exceeding WHO pH limits in the pre-monsoon season and a further rise to 40% post-monsoon season. The Total Dissolved Solids (TDS) indicate the concentration of dissolved ions in water and can affect its taste and safety. In the pre-monsoon season, TDS ranged from 220 to 2270 ppm, averaging 803 ± 553 ppm. During the post-monsoon season, the range was 200 to 2348 ppm, with an average of 931 ± 380 ppm. In both seasons, they exceeded WHO (WHO, 2021) and Bureau of Indian Standards (BIS, 2012) limits, with 62% of post-monsoon samples surpassing BIS limits. Elevated TDS levels could impact water usability and indicate contaminants' presence. The significant percentage of samples exceeding permissible limits underscores the need for continued monitoring and appropriate water treatment measures. Electrical Conductivity (EC) measures water's ability to conduct an electric current, reflecting its ion concentration (Marandi et al., 2013). Pre-monsoon EC ranged from 505 to 9010 µS/cm, averaging 1774 ± 1503 µS/cm. Post-monsoon EC varied from 420 to 4770 µS/cm, averaging 1851 ± 762 µS/cm. While both seasons exceed WHO's recommended limit of 1500 µS/cm, the post-monsoon season exhibits a higher percentage (64%) of samples surpassing the limit. The elevated EC values suggest a higher ion concentration, indicating potential contamination. Continuous monitoring and targeted interventions are crucial to mitigate any adverse effects on water quality. Salinity measures the concentration of dissolved salts in water and can impact its suitability for various uses. Pre-monsoon salinity ranged from 157 to 519 ppm, averaging 366 ± 94.1 ppm. Post-monsoon salinity varied from 76 to 1250 ppm, averaging 506 ± 313 ppm. While WHO does not specify salinity limits, the considerable post-monsoon variation raises concerns. The notable increase in salinity during the post-monsoon season may affect water usability, particularly for agricultural purposes (Marandi et al., 2013; Rawat et al., 2018; Sharma et al., 2017). Regular monitoring and assessment are essential to understand the implications of these variations on local water resources. Oxidation-reduction potential (ORP) provides insights into the water's oxidative and reductive characteristics (Wang et al., 2022). In the pre-monsoon season, ORP ranged from -52.3 to -1.2 mV, averaging -2.8 ± 15.6 mV. Post-monsoon ORP varied from -74 to -0.33 mV, averaging -28.6 ± 17.03 mV. No specific standards are mentioned for ORP, but the fluctuations suggest changes in water chemistry. The negative ORP values indicate reducing conditions, potentially influencing the water's ability to support specific aquatic life. Regular monitoring is essential to understand the seasonal dynamics and implications for water ecosystems. The Temperature of water bodies affects various water properties and influences aquatic ecosystems. Pre-monsoon temperatures ranged from 22.2 to 30°C, averaging 26.8 ± 2.27°C. Post-monsoon temperatures varied from 18 to 26.8°C, averaging 21.2 ± 4.42°C. While no specific limits are provided, the data illustrates seasonal temperature variations. Temperature changes can impact aquatic life and biological processes. Understanding these variations is crucial for assessing water quality and potential ecological consequences. Continuous monitoring helps evaluate the broader environmental implications (Doney et al., 2012). Dissolved Oxygen is vital for aquatic life, and its levels indicate water's ability to support organisms. In the pre-monsoon season, DO ranged from 4.1 to 9.6 ppm, averaging 6.43 ± 1.65 ppm. Post-monsoon DO varies from 1.45 to 9.65 ppm, with an average of 6.01 ± 1.79 ppm. The decline in samples meeting DO standards during the post-monsoon season suggests potential challenges for aquatic life. Continuous monitoring and interventions are crucial to maintaining a healthy marine environment (Mishra et al., 2021). Fluoride (F^-) levels in water can impact dental and skeletal health (Das et al., 2020; Tiwari et al., 2023). Pre-monsoon fluoride levels ranged from 0.1 to 5.37 ppm, with an average of 0.96 ± 1.07 ppm. Post-monsoon fluoride varied from 0.106 to 0.17 ppm, averaging 0.36 ± 0.2 ppm. Both seasons fall within WHO and BIS limits (BIS, 2012; WHO, 2021), with no post-monsoon samples exceeding the standards. The consistent adherence to fluoride standards is positive for public health. Regular monitoring remains essential to ensure continued compliance and prevent potential health issues associated with fluoride exposure (Aoun et al., 2018). Chloride (Cl^-) levels in water can affect taste and corrosion. Pre-monsoon chloride levels ranged from 13.1 to 730 ppm, averaging 196 ± 179 ppm. Post-monsoon chloride varied from 2 to 910 ppm, averaging 303 ± 195 ppm. In both seasons, they have exceeded WHO and BIS limits, with an increase in post-monsoon samples exceeding the standards. Elevated chloride levels can impact water quality and infrastructure. Continuous monitoring and appropriate interventions are necessary to address potential taste issues and prevent corrosion in water distribution systems (Pieper et al., 2018; Stets et al., 2018). Nitrate levels in water can indicate contamination and affect human health. In the pre-monsoon season, nitrate levels ranged from 1.47 to 42.3 ppm, averaging 19.3 ± 11.6 ppm. Post-monsoon nitrate varied from 0.22 to 1.65 ppm, averaging 0.94 ± 0.43 ppm. Both seasons fall within WHO and BIS limits, with no samples exceeding the standards. Consistent adherence to nitrate standards is favourable for water safety (Perveen and Amar-Ul-Haque, 2023). Regular monitoring is crucial to detect any potential sources of contamination and maintain water quality. Sulfate levels in water can influence taste and odour and indicate contamination sources. Pre-monsoon sulfate levels ranged from 1.17 to 290 ppm, averaging 51.9 ± 61.9 ppm. Post-monsoon sulfate varied from 3.17 to 100 ppm, averaging 0.36 ± 29.2 ppm. Both seasons fall within WHO and BIS limits, with only one pre-monsoon sample exceeding WHO limits. The variations highlight potential changes in contamination sources. Continued monitoring is essential to understand these variations and address emerging water quality concerns (Altenburger et al., 2019). Phosphate levels in water can impact aquatic ecosystems. In the pre-monsoon season, phosphate levels ranged from 0.01 to 0.36 ppm, with an average of 0.04 ± 0.049 ppm. Post-monsoon phosphate varied from 0.007 to 0.45 ppm, averaging 0.47 ± 0.01 ppm. No specific limits are given, but the data illustrates variations between seasons. Phosphate levels can influence nutrient dynamics in aquatic systems. Understanding these variations is crucial for assessing potential ecological impacts and ensuring the overall health of water ecosystems (Altenburger et al., 2019; Robson, 2014). Total Hardness (TH) in water can affect its suitability for various uses. In the pre-monsoon season, TH ranged from 218 to 2010 ppm, averaging 721 ± 489 ppm. Post-monsoon TH varied from 120 to 22.02 ppm, averaging 893 ± 373 ppm. While no specific limits are provided, the considerable variations between seasons are noteworthy. High TH levels can impact water hardness and may require appropriate treatment for particular uses (Diggs and Parker, 2009). Monitoring these variations helps identify potential challenges and ensures the proper management of water resources. Calcium Hardness (Ca H) is a specific measure of calcium content in water. Pre-monsoon calcium hardness ranged from 100 to 5015 ppm, averaging 465 ± 702 ppm. Post-monsoon calcium hardness varied from 105 to 920 ppm, averaging 442 ± 180 ppm. No specific limits are suggested, but the data illustrates variations between seasons. Calcium hardness affects water's ability to form lather and can influence industrial processes. Understanding these variations is crucial for addressing specific water quality concerns and ensuring suitability for various applications. Magnesium Hardness (Mg H) is a particular measure of magnesium content in water. In the pre-monsoon season, magnesium hardness ranged from 98 to 910 ppm, averaging 323 ± 233 ppm. Post-monsoon magnesium hardness varied from 110 to 1050 ppm, averaging 388 ± 152 ppm. No specific limits are given, but the data illustrates variations between seasons. Magnesium hardness, along with calcium hardness, contributes to overall water hardness. Monitoring these variations helps assess water quality for specific uses and ensures appropriate management. Total Alkalinity (TA) in water measures its buffering capacity. Pre-monsoon TA ranged from 128 to 938 ppm, averaging 458 ± 167 ppm. Post-monsoon TA varied from 75 to 744 ppm, averaging 449 ± 141 ppm. While no specific limits are suggested, the variations between seasons are evident. Alkalinity influences water's ability to resist pH changes. Understanding these variations is crucial for managing water quality and ensuring its suitability for various applications (Ameen, 2019; Diggs and Parker, 2009; Menon et al., 2023; Millard et al., 2021; Nguyen et al., 2023). Uranium (U) levels in water can impact human health due to its chemo-radiotoxic properties (Banning and Benfer, 2017; Kale et al., 2021a, 2020a, 2018; Kumari et al., 2021; Kurttio et al., 2002; Magdo et al., 2007; Sharma and Singh, 2016). In pre-monsoon and post-monsoon seasons, uranium levels ranged from 1.2 to 26.8 ppb, with average values of 15.2 ± 6.87 ppb and 7.63 ± 4.59 ppb, respectively. Both seasons meet WHO and Atomic Energy Regulatory Board (AERB) standards, with no samples exceeding the limits. The consistent adherence to uranium standards is favourable for water safety. Regular monitoring is essential to detect any potential sources of contamination and maintain water quality within acceptable limits.

Table 1. Summary of the parameters studied and comparison with prescribed limits.

Parameter	Pre-monsoon	Post-monsoon	Permissible Limits	Number of samples (%) exceeding permissible limits	
				Pre-monsoon	**Post-monsoon**
pH	7.1-8.8 (8.16 ± 0.39)	5.4-9.8 (8.34 ± 0.68)	WHO: 6.5-8.5	5 (12)	12 (27)
TDS ppm	220-2270 (803 ± 553)	200-2348 (931 ± 380)	WHO: 1000 & BIS: 500	14 (33), 26 (62)	18 (41), 35 (80)
EC (µS/cm)	505-9010 (1774 ± 1503)	420-4770 (1851 ± 762)	WHO: 1500	16 (38)	28 (64)
Salinity (ppm)	157-519 (366 ± 94.1)	76-1250 (506 ± 313)	Not specified	-	-
ORP (mV)	-52.3 to -1.2 (-2.8 ± 15.6)	-74 to -0.33 (-28.6 ± 17.03)	Not specified	-	-
Temp (^{0}C)	22.2-30 (26.8 ± 2.27)	18-26.8 (21.2 ± 4.42)	Not specified	-	-
DO (ppm)	4.1-9.6 (6.43 ± 1.65)	1.45-9.65 (6.01 ± 1.79)	Not specified	-	-
F^- (ppm)	0.1-5.37 (0.96 ± 1.07)	0.106-0.17 (0.36 ± 0.2)	WHO: 1.5, BIS: 1.0	8 (19), 11 (26)	(0), (0)
Cl^- (ppm)	13.1-730 (196 ± 179)	2-910 (303 ± 195)	WHO: 250, BIS: 250	15 (35)	19 (43), 19 (43)
NO^{3-} (ppm)	1.47-42.3 (19.3 ± 11.6)	0.22-1.65 (0.94 ± 0.43)	WHO: 50, BIS: 45	(0), (0)	(0), (0)
SO42- (ppm)	1.17-290 (51.9 ± 61.9)	3.17-100 (0.36 ± 29.2)	WHO: 250, BIS: 200	1 (2)	(0), (0)
PO_4^{3-} (ppm)	0.01-0.36 (0.04 ± 0.049)	0.007-0.45 (0.47 ± 0.01)	Not specified	-	-
TH (ppm)	218-2010 (721 ± 489)	120-22.02 (893 ± 373)	Not specified	-	-
Ca H (ppm)	100-5015 (465 ± 702)	105-920 (442 ± 180)	Not specified	-	-
Mg H (ppm)	98-910 (323 ± 233)	110-1050 (388 ± 152)	Not specified	-	-
TA (ppm)	128-938 (458 ± 167)	75-744 (449 ± 141)	Not specified	-	-
U (ppb)	1.2-26.8 (15.2 ± 6.87)	1.2-26.8 (7.63 ± 4.59)	WHO: 30, AERB: 60	(0), (0)	(0), (0)

Risk Assessment

This study assessed the radiological risk, called Excess cancer risk (ECR) and chemical risks associated with the uranium concentration in drinking water (Table 2). Most important is the natural radiation hazard due to the ionizing radiation of the radioactive element uranium. Another is a chemical risk (Table 3). The prominent radiation uptake of uranium complexes is inhaled from the human body. Due toits carcinogenicnature, it is harmful to health. Many essential chemical effects are associated with exposure to uranium(Kale et al., 2021b, 2020a, 2018).

Radiological risk (ECR)

An ECR value was assessed using the following equation.

$$\textbf{Radiological risk } (\textbf{ECR}) = \text{Conc. of U in groundwater } (\text{Bq/L})^{*} \times \text{ risk factor (per Bq/L)}^{**}$$

$$* \textbf{ Conc. of U } (\text{Bq/L}) = \text{Analysed value of U (ppb) x conversion factor } (0.025 \text{ Bq/L}) \ldots.1$$

$$** \textbf{ Risk Factor} = \text{Risk Coefficient (Bq/L)} \times \text{Water injection rate (L/day)} \times \text{total exposure duration day} \ldots.2$$

Average daily dose (LADD) was assessed by using the following equation(Kale et al., 2021b, 2020a, 2018)

$$\textbf{Lifetime Average Daily Dose } [\textbf{LADD } (\boldsymbol{\mu}\textbf{g/kg/day})] = \frac{[\text{Cd } \times \text{ IR } \times \text{ EF } \times \text{ LE}]}{[\text{BW } \times \text{ AT}]} \ldots..3$$

$$\boldsymbol{HQ} = \frac{(LADD)}{RfD} \ldots.4$$

Table 2. Chemo-radiological risk of uranium in Jalgaon district.

Entity	Pre-monsoon				Post-monsoon			
	Min	**Max**	**Average**	**SD**	**Min**	**Max**	**Average**	**SD**
Uranium (ppb)	1.2	26.8	11.5	6.9	1.2	26.3	7.7	4.5
Conc. Of U in (Bq/L)	0.03	0.68	0.29	0.18	0.03	0.66	0.19	0.11
ECR (Mortality)	3.5E-06	7.9E-05	3.4E-05	2.1E-05	3.5E-06	7.8E-05	2.3E-05	1.3E-05
ECR (Morbidity)	5.8E-06	1.3E-04	5.5E-05	3.3E-05	5.8E-06	1.3E-04	3.7E-05	2.2E-05
LADD	6.9E-02	1.6E+00	6.6E-01	4.0E-01	6.9E-02	1.5E+00	4.4E-01	2.6E-01
HQ	1.5E-02	3.4E-01	1.5E-01	8.9E-02	1.5E-02	3.4E-01	9.8E-02	5.7E-02

Table 3. Age-dependent annual effective doses at Jalgaon district.

Entity	Age group (in years)	DWI (L/day)	Pre-monsoon				Post-monsoon			
			Min	Max	Average	SD	Min	Max	Average	SD
Infants	0-0.5	0.7	3.4E-07	7.6E-06	3.3E-06	2.0E-06	3.4E-07	7.5E-06	2.2E-06	1.3E-06
	0.6-1	0.8	3.9E-07	8.7E-06	3.7E-06	2.3E-06	3.9E-07	8.5E-06	2.5E-06	1.5E-06
Children	1 to 3	1.3	6.3E-07	1.4E-05	6.1E-06	3.7E-06	6.3E-07	1.4E-05	4.0E-06	2.4E-06
	4 to 8	1.7	8.3E-07	1.8E-05	7.9E-06	4.8E-06	8.3E-07	1.8E-05	5.3E-06	3.1E-06
Males	9 to 13	2.4	1.2E-06	2.6E-05	1.1E-05	6.8E-06	1.2E-06	2.6E-05	7.5E-06	4.4E-06
	14 to 18	3.3	1.6E-06	3.6E-05	1.5E-05	9.3E-06	1.6E-06	3.5E-05	1.0E-05	6.0E-06
adult	>71	3.7	1.8E-06	4.0E-05	1.7E-05	1.0E-05	1.8E-06	3.9E-05	1.2E-05	6.7E-06
Female	9 to 13	2.1	1.0E-06	2.3E-05	9.8E-06	5.9E-06	1.0E-06	2.2E-05	6.5E-06	3.8E-06
	14 to 18	2.3	1.1E-06	2.5E-05	1.1E-05	6.5E-06	1.1E-06	2.5E-05	7.2E-06	4.2E-06
adult	>71	2.7	1.3E-06	2.9E-05	1.3E-05	7.6E-06	1.3E-06	2.9E-05	8.4E-06	4.9E-06
Pregnancy	14 to 18	3.0	1.5E-06	3.3E-05	1.4E-05	8.5E-06	1.5E-06	3.2E-05	9.3E-06	5.5E-06
	19 to 50	3.0	1.5E-06	3.3E-05	1.4E-05	8.5E-06	1.5E-06	3.2E-05	9.3E-06	5.5E-06
Lactation	14 to 18	3.8	1.9E-06	4.1E-05	1.8E-05	1.1E-05	1.9E-06	4.1E-05	1.2E-05	6.9E-06
	19 to 50	3.8	1.9E-06	4.1E-05	1.8E-05	1.1E-05	1.9E-06	4.1E-05	1.2E-05	6.9E-06

Correlation analysis

Correlation analysis is the most commonly and widely used statistical data analysis tool to interpret the association between two or more variables. Many scientists and researchers in different fields, viz., economic, agricultural science, engineering, data sciences, environmental, social sciences, and so on, frequently use this test due to its simple, reliable, and confirmatory statistical significance(Bioresita et al., 2018; Drašković et al., 1987; Kale et al., 2020b; Kozak et al., 2012; Singaraja et al., 2014; Wilkie, 1985). Several correlation analysis methods (Pearson correlation, Kendall rank correlation, Spearman correlation, and the Point-Biserial correlation) are formulated as per their applicability and significance(Rousseau et al., 2018). In the present study, the Pearson correlation was adopted due to its applicability and suitability for non-normal distributions of the data set (here water quality dataset) at two significant levels viz., 0.05 and 0.01, which are denoting into correlations graphs single asterisk and double asterisk (* & **) respectively for both seasons viz., post-monsoon and pre-monsoon (from here onwards POM & PRM). In the PRM season, the pH is strongly negatively correlated with TDS, EC, and nitrate with -0.40, -0.52, and -0.40 at the significant level $p<=0.01$) and in the case of pH vs. $PO_4^{3-}$is moderately positively correlated with coefficient 0.37 and values with $p<=0.05$. Vice versa, in the POM, the pH is only moderately positively correlated (coefficient 0.34 at a significant level $p<=0.05$). The TDS itself denoted the aggregation of all dissolved organic as well as inorganic content of constituents. Based on the chemistry of water in PRM as well as POM seasons were performed, and significant to moderate correlations were found. In the PRM, the TDS is strongly positively correlated with EC, NO_3^-, TH, CaH, and MgH with correlation coefficient values 0.58, 0.41, 0.99, 0.45, and 0.93 at significant levels p<=0.01, respectively. The correlation between TDS vs. salinity is significantly negative (-0.43) recorded in PRM, and vice versa; it is found to be significantly positively correlated (0.51) at the significant level p<=0.01 in POM,respectively. It may be due to the accumulation of cations and anions in the groundwater chemistry or may be due to a significant concentration of salt-forming constituents in PRM. The ORP negatively correlated with NO_3^-(-0.42 with 0.01 significance) in the PRM season only, which was missed in the POM season. The significant negative values of ORP result in the liberation of anoxic or anaerobic conditions in groundwater, resulting in more nitrification/denitrification processes in the study region's groundwater chemistry(Peng et al., 2005; Weißbach et al., 2018). In the PRM, a moderate positive correlation between salinity and uranium was observed (correlation coefficient 0.36 at 0.01 significance level);conversely, no such correlation was found in POM.In the rest cases, the significant correlations in PRM are found as Cl^- with SO_4^{2-} (correlation coefficient 0.62), NO_3^- with TH, and MgH (correlation coefficient 0.41 & 0.41). The CaH and MgHare the parts of total hardness meant to be highly correlated with each other. In the POM, SO_4^{2-} is significantly negatively correlated with CaH and MgH (correlation coefficient -0.43 & -0.56). The same results were found in the hardness (TH, CaH, and MgH) like PRM into POM season. In the end, we conclude that the correlation test helps analyze the water chemistry and its association with the water quality parameters.

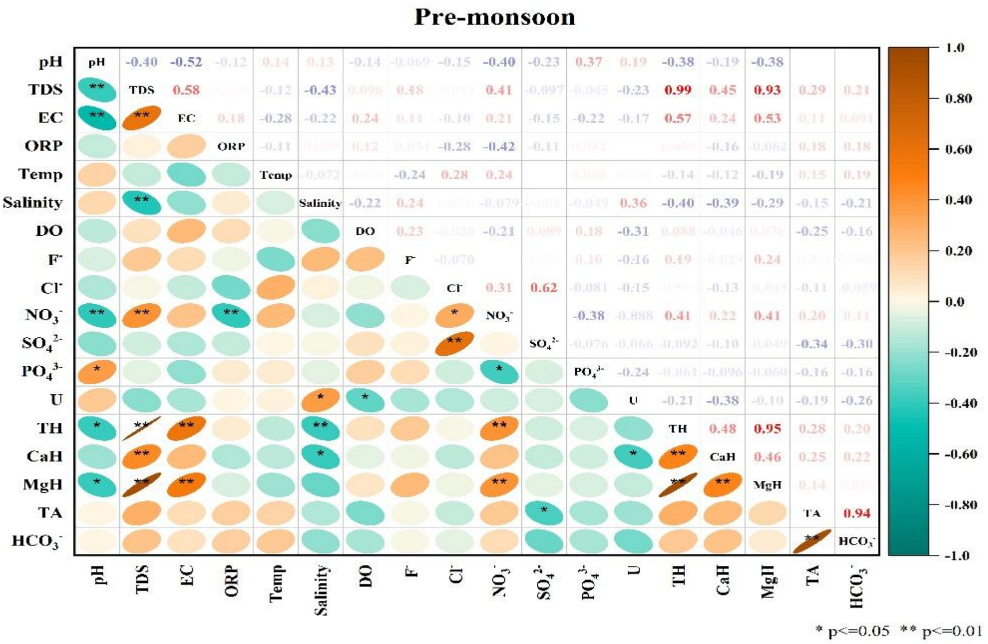

Fig. 4 Pearson correlation output of water quality data from Jalgaon district (PRM).

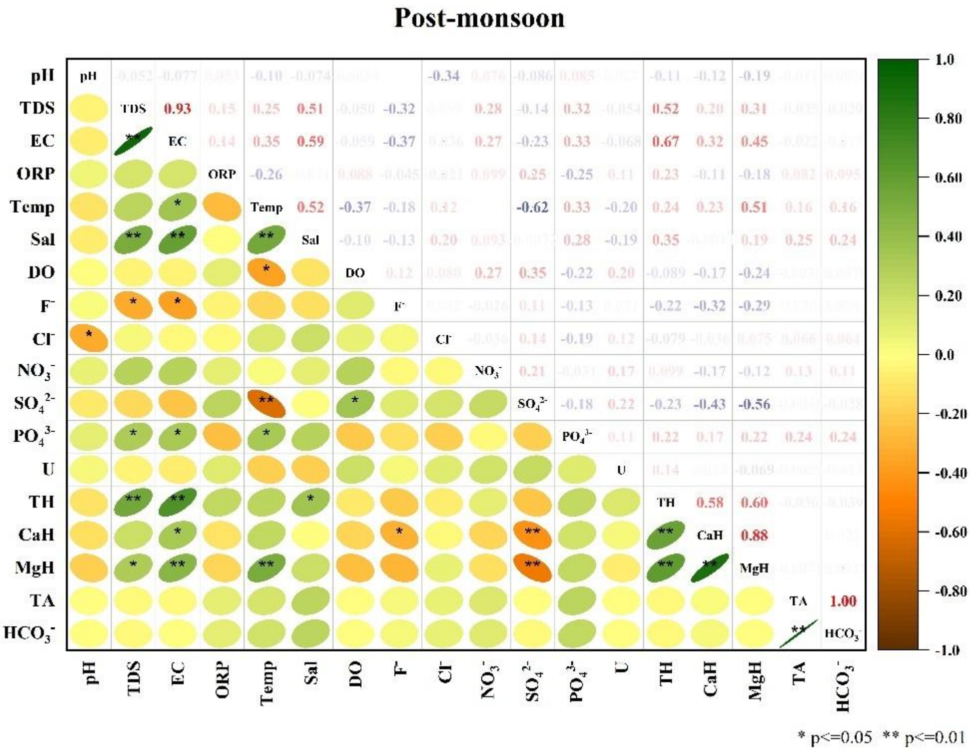

Fig. 4 Pearson correlation output of water quality data from Jalgaon district (POM).

Spatial distribution mapping

Spatial distribution mapping of water quality data is a part of data visualization over the space. It helps us understand how water quality parameters vary across geographic areas. Inverse distance weighting (IDW) is a technique for interpolating data and creating maps showing these parameters' distribution. The IDW is a technique used to estimate location values by considering the values at sampled areas. The basic idea behind IDW is that sites near sampled points impact the interpolated value compared to those farther away. This method assumes that deals tend to change across space. IDW is a valuable tool for spatially interpolating water quality parameters, visually representing the distribution patterns across a given area. Proper interpretation of these maps can aid in understanding the spatial dynamics of water quality, assisting in effective environmental management and decision-making. The spatial distribution map of U concentration (as the main parameter here) is represented in Fig. 5; all the remaining maps of water quality parameters were submitted in a supplementary file. In the PRM season, uranium concentration is found in the range of 17 – 27 ppb in the western region of study (Fig. 5: PRM). It may be due to the high salinity, and a moderate positive correlation (Fig. 4: PRM) was noted between these parameters. In the POM season, it may vary from 2 to 23 ppb,and the values are lower than the PRM, which may be due to groundwater dissolution by rainfall orother factors.

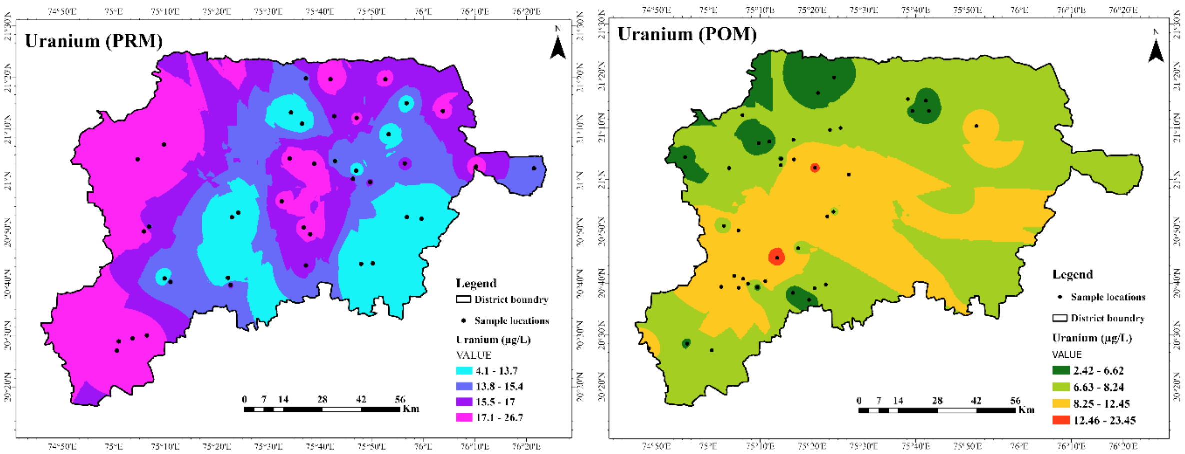

Fig. 5 Spatial distribution mapping of uranium concentration in study region from PRM and POM seasons.

Conclusion

In conclusion, the study on uranium concentrations in drinking water in Jalgaon district underscores the critical importance of addressing potential health risks associated with both radiological and chemical factors. The calculated Excess Cancer Risk (ECR) values for mortality and morbidity provide a nuanced understanding of the health hazards posed by uranium exposure. These risk assessments are pivotal for guiding regulatory measures and interventions to safeguard public health. Radiological risk evaluations, including Lifetime Average Daily Dose (LADD) and Hazard Quotient (HQ), reveal age-dependent variations in health effects. Considering different age groups enhances the study's relevance, as it recognizes varying vulnerabilities across demographics. The Hazard Quotient values, indicative of non-carcinogenic health risks, offer valuable insights for risk management strategies and regulatory decision-making. Correlation analysis, employing the Pearson correlation, elucidates complex associations between water quality parameters. The negative correlation between pH and Total Dissolved Solids (TDS), Electrical Conductivity (EC), and nitrate in the pre-monsoon season and the positive correlation between pH and phosphate ion highlights the intricate interplay of factors shaping water quality dynamics.

Spatial distribution mapping, facilitated by Inverse Distance Weighting (IDW), visually represents variations in water quality parameters across geographical areas. The maps, particularly those depicting uranium concentration, reveal spatial disparities, emphasizing the need for localized interventions and monitoring strategies. The correlation between uranium and salinity, especially during the pre-monsoon season, suggests influencing factors linked to geological and hydrological characteristics. The study's implications for policymakers and environmental stakeholders are significant. Elevated uranium concentrations in specific regions necessitate targeted interventions to ensure safe drinking water. Incorporating these findings into water quality management frameworks can enhance the efficacy of regulatory measures. The study also underscores the importance of considering seasonal variations and advocating for dynamic and context-specific approaches to water quality management. This research contributes substantially to understanding uranium-related risks in Jalgaon district's drinking water. The combination of risk assessments, correlation analyses, and spatial mapping provides a multifaceted view of the challenges of uranium exposure. As global concerns about water quality and environmental health persist, the insights gained from this study can inform strategies in the context of Jalgaon and serve as a valuable reference for regions facing similar challenges. Addressing uranium contamination complexities requires collaborative efforts from policymakers, scientists, and local communities to safeguard public health and ensure water resource sustainability.

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Author Contributions

Author 1: Conceived and designed the study, conducted a literature review, collected and analysed data, and drafted the manuscript.

Author2: Contributed to study design, performed statistical analysis, and provided critical revisions to the manuscript.

Author3: Conducted experiments, gathered field data, and contributed to interpreting results.

Author 4*: Provided expertise in data analysis, critically revised the manuscript, and coordinatedthe final approval among all authors.

Author 5: Finalizing and validating data processing methods and guidance into the manuscript revision.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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