Ethiopian Journal of Environmental Studies & Management 18(4): 496 – 524, 2025
ISSN:1998-0507 doi: https://ejesm.org/doi/v18i4.6
Submitted: October 13, 2025 Accepted: December 3, 2025

GROUNDWATER ARSENIC HEALTH RISK IN CHANDRAPUR DISTRICT, CENTRAL INDIA

KAMBLE, R. K.
Institution of Higher Learning, Research and Specialized Studies in Environmental Science
Sardar Patel College, Ganj Ward, Chandrapur 442 402, India
Email: rahulkk41279@yahoo.com

Abstract

Purposive random sampling at 36 sampling locations was carried out in the post-monsoon season, including 34 (94.44%) from hand pumps and two (5.56%) from dug wells, in order to determine the health risk of groundwater arsenic in Chandrapur district, India. The acid digestion method by using Inductively Coupled Plasma-Optical Emission Spectroscopy was adopted to determine the groundwater arsenic concentration. Arsenic concentration ranged from 0.015 to 0.041 mg/L, with an average of 0.031 mg/L (±0.005). The average non-carcinogenic risk from ingestion (HQ_{Oral}) and dermal contact (HQ_{Dermal}) from the study area in males, females, and children were 3.2023, 3.7845, 6.6531 and 0.0111, 0.0117, 0.0182, respectively. The average HQ_{Total} were 3.2134, 3.7962, and 6.6713 for male, female and children, respectively. In case of average carcinogenic risk from ingestion (CR_{Oral}) and dermal contact (CR_{Dermal}) from the study area in males, females, and children were 0.0014, 0.0017, 0.0030, and $5.01x10^{-6}$, $5.26x10^{-6}$, $8.18x10^{-6}$, respectively. The average CR_{Total} for males, females, and children were 0.0014, 0.0017, and, 0.0030 respectively. Of the residents in the study area, children are more vulnerable to both non-carcinogenic and carcinogenic risks than males and females. The maximum health risk for non-carcinogenic and carcinogenic was through oral ingestion rather than dermal pathway. As both non-carcinogenic and carcinogenic risks are beyond the acceptance level at all sampling locations residents are vulnerable to health risks associated with groundwater arsenic.

Keywords: *Arsenic exposure, Groundwater contamination, Hazard index, Health risk, Hydrogeochemistry, Central India*

Introduction

Without water, human existence is impracticable. The "quality of life" that locals experience is determined by the "quality of water" in that place. The two most easily available sources of water are surface water and groundwater. Aquifers and groundwater are difficult to pollute since they are often impermeable. Nevertheless, during penetration, groundwater does naturally filter a little bit. These qualities have led to a significant increase in the use of groundwater for drinking over surface water (UNEP, 2002). The primary source of drinking water for almost 50% of the population of the world is groundwater (Fry, 2005). The main source of drinking water for almost 2.5 billion people worldwide is groundwater (WWAP, 2015). For small and rural communities, groundwater may occasionally be their only source of drinking water (Hani, 1990). Groundwater mining is the only workable way to meet the dispersed rural water demand, claim MacDonald *et al.* (2005). This is because it is accessible from any location and needs less funding to develop and maintain (Bresline, 2007; Habila, 2005).

Roughly 90% of Indian rural residents directly rely on groundwater for irrigation and drinking, according to Narsimha *et al.* (2022). The 2011 Census of India indicates that 63% of India's drinking water comes from sources considered untreated or less safe, highlighting significant concerns regarding water safety and quality across the nation. In India's rural areas, 76.6% are accounted for by hand pumps (43.63%), untreated sources (12.95%), uncovered wells (11.76%), and tubewells/borewells (8.72%). These figures demonstrate that in rural India, groundwater - which is usually untreated - serves as the main source of drinking water. In addition, compared to the 17.3% of individuals in urban areas, 20.5% of persons in rural regions are between the ages of 5 and 14. The statistics indicate that children residing in rural areas are vulnerable to contaminants found in groundwater.

Drinking water contamination has become a significant worldwide issue, mostly due to the discharge of hazardous chemicals and heavy metals associated with human activity (Rapant and Krcmova, 2007). Both the environment and human health are significantly impacted by water resource pollution (Emmanuel *et al.,* 2009; Muhammad *et al.,* 2011). In 1997, the United Nations reported that 2.3 billion people globally suffer from illnesses associated with water. Mexico (Armienta and Segovia, 2008; Bundschuh *et al.,* 2012), the United States (Amasa *et al.,* 2008; Haque and Johannesson, 2006), China (Guo and Wang, 2005; Yang *et al.,* 2012), India (Kumar *et al.,* 2010a; Kumar *et al.,* 2010b; Shah, 2012), Bangladesh (Halim *et al.,* 2009; Kamal and Parkpian, 2002), Vietnam (Berg *et al.,* 2007; Winkel *et al.,* 2011), and Pakistan (Farooqi *et al.,* 2007a; Farooqi *et al.,* 2007b; Muhammad *et al.,* 2010) have documented to have elevated groundwater arsenic contents. It has been discovered that arsenic contamination has also been identified in groundwater in Korea (Ahn, 2012) and Japan (Yoshizuka *et al.,* 2010).

Numerous severe health issues, such as skin lesions, cardiovascular diseases, type II diabetes, and cancers of the bladder, lungs, and skin, have been connected to extended exposure to arsenic-contaminated waters (Cubadda *et al.,* 2015; Karim, 2000; Rossman *et al.,* 2004; Tchounwou *et al.,* 2004; Yoshida *et al.,* 2004). Arsenic levels in drinking water above World Health Organization (WHO) recommendations are harmful to an estimated 200 million people globally (George *et al.,* 2014).

The possible health hazards of groundwater arsenic for local adults and children in the Chandrapur district, central India, have not been investigated, according to a review of the literature. As a result, this is the subject domain's identified knowledge gap. It was recommended that this study be carried out with the aim of assessing the health risks related to adults and children's use of arsenic-contaminated groundwater in order to fill this knowledge gap with fresh data. The study's conclusions will advance new knowledge of the health hazards that adults and children pose from groundwater arsenic. Additionally, in order to lower the health risk for the residents of the study area, regional actions must be implemented along with the establishment of appropriate policies and mechanisms for their implementation.

Study Area

Chandrapur district, positioned between latitudes 19°25' to 20°45' N and longitudes 78°50' to 80°10' E, lies in the Vidarbha region of Maharashtra, a central Indian state (Fig. 1). The district is 11,364 km^2 in size and ranges from 106 to 589 meters above mean sea level (amsl). The district has 15 administrative blocks rich in coal, limestone, iron, copper, and other minerals. Numerous thermal power plants, sizable coal mines, cement factories, and a pulp and paper industry have all been established in the area due to its abundance of natural resources and minerals. Additionally, Tadoba Andhari Tiger Reserve is home to some of the greatest concentrations of tigers in the world (CGWB, 2009).

Alongside constant dryness throughout the year, the area has experienced severe weather events, such as a scorching summer with temperatures soaring to 46 °C in May, and a frigid winter where December temperatures drop to 7 °C. The climate of the study area can be categorized as hot and tropical. During the monsoon season, humidity levels reached 70%, while in the summer, they dropped to 20%. The southwest monsoon marks the onset of the rainy season, occurring from June to September. Annually, there are about 60 to 65 days of rain, with total precipitation ranging from 1200 mm to 1450 mm. The district experiences erratic rainfall patterns. In the Worora administrative block, rainfall is minimal, gradually increasing until it reaches a peak in the Bramhapuri administrative block (CGWB, 2009). From a geological perspective, Chandrapur district lies within the sedimentary basin of Gondwana. The lithology of Chandrapur comprises both Archean rocks and more recent alluvium and laterites. Figure 2 illustrates the regional geomorphology of the study area.

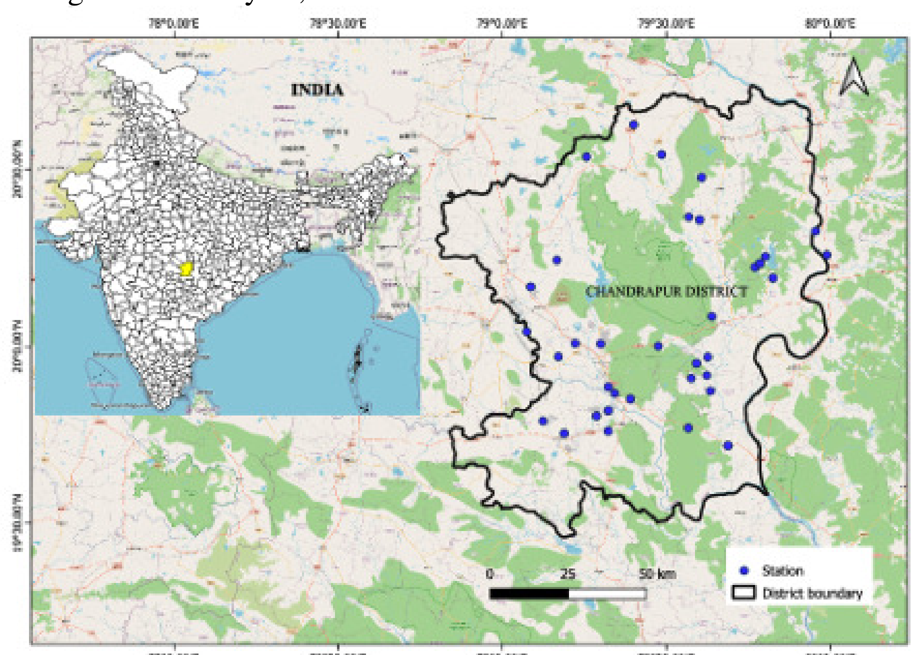

Fig. 1: Spatial distribution of groundwater sampling locations

The district has 21,94,262 inhabitants, with 10,73,946 females and 11,20,316 males, according to the 2011 Census of India. With a decadal growth rate of 6.0% from 2001 to 2011, the population density was 192 people per square kilometre, and 35.1% of people lived in urban areas. Further analysis of Census data indicates that in the rural regions of the Chandrapur district, hand pumps account for 36% of the population's primary source of drinking water, followed by uncovered wells (24.2%). According to these statistical findings, groundwater serves as the study region's main supply of drinking water for its residents (Census of India, 2011).

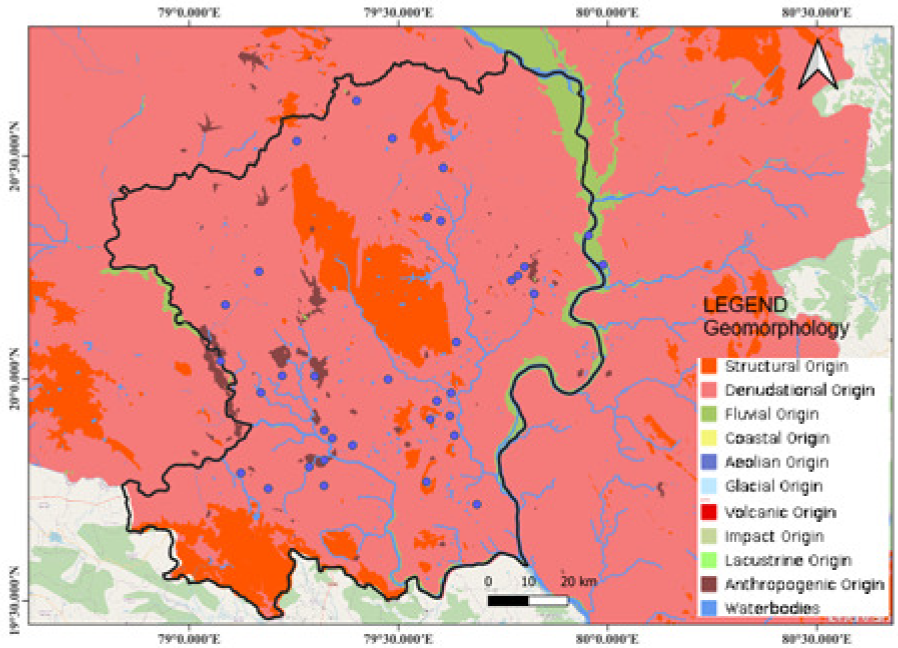

Fig. 2: Regional geomorphology of the study area

Methodology

Groundwater Sampling Strategy

The groundwater sample site selection criteria gave priority to the rural portion of the study region due to its heavy reliance on hand pumps and/or dug wells for domestic requirements such as cooking and drinking. Groundwater samples were also obtained from a number of administrative blocks in the district, which include a range of geological formations, precipitation classes, and altitudes, to better understand the distribution of groundwater arsenic. In the post-monsoon season, in October, the groundwater samples were collected.

For this study from the Chandrapur district, a total of 36 groundwater sampling locations were selected. The sampling locations on different elevations from the study area are depicted in Fig. 3. There were hand pumps and dug wells at these places. Stratified and deliberate random sampling was employed for the groundwater sample from the study area. Two sampling sites (5.55%) were from dug wells, whereas 34 (94.44%) were from hand pumps. Groundwater samples were collected using the grab sampling method. Sampling occurred once per season during the post-monsoon period.

The groundwater sample was extracted up to the edge of a 1000 mL capacity container (Poly lab, India) to prevent headroom that can change the sample's physicochemical characteristics.

This was done to determine the general properties of the groundwater sample. To keep contaminants out, the sampling containers were closed with packing tape after being secured with a screw cover. The details about sampling locations were recorded in the field journal and on the sampling container. With the use of a handheld GPS, the geographic information related to latitude, longitude, and altitude was gathered.

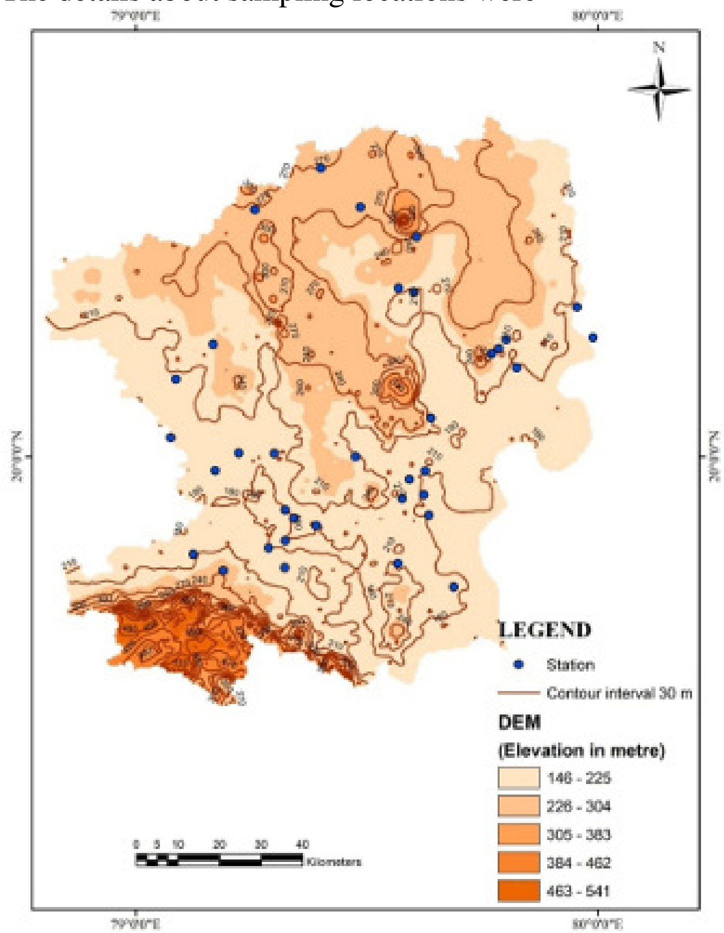

Fig. 3: Digital elevation model of groundwater sampling locations

Groundwater Analysis Methods

The temperature of groundwater fluctuates when it is exposed to the atmosphere, so the data it gives in the field is accurate. A mercury thermometer (Gera, GTI, India) with a 0.5°C division was used to measure it on the spot. The different physicochemical properties were checked for in the laboratory on the groundwater samples, with the exception of the field analysis parameter. For the physicochemical analysis, borosilicate glassware was used, and all of the reagents were AR grade (Merck). The reagents were prepared using double-distilled water. According to APHA recommendations, all reagents were produced (APHA, 2017). These reagents underwent a standardization process before being utilized for analysis.

The heavy metal (in this case, arsenic) present in the groundwater samples was preserved by adding concentrated nitric acid (HNO_3, 16 N, Merck, 1 mL per 100 mL of sample) on-site to another polyethylene container (Poly lab, India).

The entry of contaminants in the sampling container was arrested by closing the container with a screw cap followed by an adhesive tape. The groundwater samples were promptly taken to the laboratory to analyze the levels of arsenic concentration.

Groundwater samples were digested to determine total arsenic content using concentrated nitric acid (HNO_3). Approximately 50 mL of each sample was placed in pre-leached glass beakers, covered with clean watch glasses, and heated on a hot plate at 95 °C until reduced to ~5 mL without boiling. After cooling, 1:1 nitric acid (16 N, Merck) was added, and the samples were refluxed for 15 minutes to dissolve any precipitates. The digests were cooled, diluted to 25 mL with double-distilled water in volumetric flasks, and used for analysis. Arsenic concentrations were measured using Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES; PerkinElmer Optima Dv 7000, Shelton, CT, USA) with WinLab 32 for ICP software (version 4.0). Analysis was performed at 193.61 nm using axial plasma view. A low-flow GenCone nebulizer and cyclonic spray chamber were used for sample introduction. Calibration was performed using working standards prepared from a NIST traceable PerkinElmer stock standard. All solutions were prepared with double-distilled water and matrix-matched to ensure analytical accuracy.

Quality Control / Quality Assurance

The ensure quality control, the glassware used in reagent preparation and analysis was cleansed with nitric acid (HNO_3, 15%, Merck) and then washed three times with ultra-pure water. The reagents used in the analysis were all of ultra-pure quality. Furthermore, the various instruments used in groundwater analysis were calibrated as per standard procedure and maintained to provide accurate and precise measurements. The standard methods as described in APHA (2017) were followed to ensure consistency and compatibility of results. The certified reference materials were used for accuracy and to detect potential biases. A groundwater sample was analysed three times for a particular parameter for precision and reproducibility of the results. The blank analysis was carried out—wherever required—to assess the presence of contaminants in the analytical process itself. The sample injection system of the ICP consists of a spray chamber with a temperature-controlled nebulizer connected to an auto-sampler. Throughout the measurement period, consistent operating conditions were maintained which resulted in maintained ICP responsiveness. The reporting was carried out with a 95% level of confidence to ensure repeatability for all samples prepared, analysed, and results.

Human Health Risk Assessment

The foundation for lowering groundwater pollution and guaranteeing a safe supply of drinking water is the human health risk assessment (Chen *et al.,* 2019; Li *et al.,* 2016; Zhang *et al.,* 2018; Zhu *et al.,* 2019). Humans can be exposed to groundwater in a variety of ways, but the most common ones are drinking water and skin contact (Wu and Sun, 2016). Models created by the US Environmental Protection Agency (USEPA, 1989) served as the basis for this investigation. The study area is home to several industrial and agricultural production activities. Thus, the parameters of risk assessment are chosen to include typical contaminants viz. fluoride, arsenic, iron, manganese, hardness, and total dissolved solids. Because males, women, and children have different physiologies, the health hazards of oral and dermal ingestion were evaluated separately in this study.

Non-carcinogenic Health Risk

Ingestion, inhalation, and skin contact are the three major pathways human beings are exposed to heavy metal (Khan *et al.,* 2016). The following equations [Eqs. (1) and (2)] are used to determine the non-carcinogenic risk associated with water consumption (Li *et al.,* 2016, Wu and Sun, 2016).

$$\text{Intake}_{\text{Oral}} = \frac{\text{C x IR x EF x ED}}{\text{BW x AT}} \quad (1)$$

$$\text{HQ}_{\text{Oral}} = \frac{\text{Intake}_{\text{Oral}}}{\text{RfD}_{\text{Oral}}} \quad (2)$$

The dermal contact-induced non-carcinogenic risk is expressed as follows [Eqs. (3) - (7)] (Li *et al.,* 2017)

$$\text{Intake}_{\text{Dermal}} = \frac{\text{DA x EV x SA x EF x ED}}{\text{BW x AT}} \quad (3)$$

$$\text{DA} = \text{K x C x t x CF} \quad (4)$$

$$\text{SA} = 239 \text{ x } \text{H}^{0.417} \text{ x } \text{BW}^{0.517} \quad (5)$$

$$\text{HQ}_{\text{Dermal}} = \frac{\text{Intake}_{\text{Dermal}}}{\text{RfD}_{\text{Dermal}}} \quad (6)$$

$$\text{RfD}_{\text{Dermal}} = \text{RfD}_{\text{Oral}} \text{ x } \text{ABS}_{\text{gi}} \quad (7)$$

Where, $\text{Intake}_{\text{Oral}}$, $\text{Intake}_{\text{Dermal}}$, HQ_{Oral}, $\text{HQ}_{\text{Dermal}}$, RfD_{Oral}, and $\text{RfD}_{\text{Dermal}}$ refer to the long-term daily dosage through ingestion and skin contact (mg/kg/day), the hazard quotient for oral and dermal exposure routes, and the reference doses for both ingestion and dermal contact pathways (mg/kg/day). The variables C, DA, SA, and ABSgi denote the concentration of pollutants in groundwater (mg/L), the exposure dose (mg/cm^2), the area of skin surface (cm^2), and the gastrointestinal absorption factor, respectively. Additional details and values for the other parameters are presented in Tables 1 and 2.

Table 1: Definition and value of key parameters for human health risk assessment

Parameters	Unit	Values		
		Male	Female	Children
Daily water ingestion rate (IR)	L/day	2	2	1
Annual exposure frequency (EF)	day/a	350	350	350
Exposure duration (ED)	a	24	24	6
Body weight (BW)	kg	65	55	15
Average time (AT)	day	8400	8400	8400
Skin permeability coefficient (K)	cm/h	0.001	0.001	0.001
Daily dermal contact duration (t)	h/day	0.4	0.4	0.4
Conversion factor (CF)	-	0.001	0.001	0.001
Average body height (H)	cm	165	153	108
Daily exposure frequency (EV)	-	1	1	1

Table 2: The value of RfD, ABS_{gi}, and SF for arsenic

Parameter	Non-Carcinogenic		Carcinogenic		ABS_{gi}
	RfD_{Oral}	RfD_{Dermal}	SF_{Oral}	SF_{Dermal}	
Arsenic	0.0003	0.0003	1.5	1.5	1

The following formula is used to determine the overall non-carcinogenic risks [Eq. (11)] (Ji *et al.,* 2020; Wang and Li, 2022; Zhou *et al.,* 2021)

$$\text{HQ}_{\text{i}} = \text{HQ}_{\text{Oral}} + \text{HQ}_{\text{Dermal}} \quad (11)$$

The hazard quotient, denoted as HQ, reflects non-carcinogenic risks, while the letter 'i' signifies the parameters used in risk assessment. The hazard index (HI) is a measure of the overall non-carcinogenic risk. If the hazard index is less than 1, the non-carcinogenic risk is considered acceptable; if it is greater than 1, the risk is considered unacceptable. It is safe for human health when HQ and HI are less than 1. Residents are exposed to non-carcinogenic dangers, and HQ and HI > 1 imply unacceptable risk.

Carcinogenic Health Risk

In addition to non-carcinogenic risk, arsenic can also create carcinogenic risks for humans. The carcinogenic risk through drinking water intake [(Eq. (12)] and dermal contact [Eqs. (13) and (14)] is calculated as follows

$$CR_{Oral} = Intake_{Oral} + SF_{Oral} \quad (12)$$

$$CR_{Dermal} = Intake_{Dermal} \times SF_{Dermal} \quad (13)$$

$$SF_{Dermal} = \frac{SF_{Oral}}{ABS_{gi}} \quad (14)$$

$$CR_{Total} = CR_{Oral} + CR_{Dermal} \quad (15)$$

Where CR represents the carcinogenic risk. Using Eq. (15), the overall carcinogenic risk was determined. For carcinogenic substances, SF stands for the slope factor (mg/kg/day). The SF_{oral} values for As are displayed in Table 3. Because arsenic's negative effects on human health are permanent, the average period (AT) for carcinogenic risk is 27,740 days for both adults and children. For CR, a maximum of 1 x 10^{-6} is permitted. The chronic risk assessment and the characterisation scale are shown in Table 3 (USEPA, 1999).

Table 3: Scales for chronic and carcinogenic risk assessment (Bortey-Sam *et al.,* 2015; USEPA, 1999)

Risk level	HQ or HI	Chronic risk	Calculated cases of cancer occurrence	Cancer risk
1	< 0.1	Negligible	< 1 per 1000,000 inhabitants (10^{-6})	Very low
2	≥ 0.1< 1	Low	> 1 per 1000,000 inhabitants (10^{-6}) < 1 per 100,000 inhabitants (10^{-5})	Low
3	≥ 1 < 4	Medium	> 1 per 100,000 inhabitants (10^{-5}) < 1 per 10,000 inhabitants (10^{-4})	Medium
4	≥ 4	High	> 1 per 10,000 inhabitants (10^{-4}) < 1 per 1000 inhabitants (10^{-3})	High
5			> 1 per 1000 inhabitants (10^{-3})	Very high

HQ – Hazard Quotient, HI – Hazard Index

Statistical Analysis

IBM SPSS 20 (SPSS Inc., IL) was used for statistical analysis after the data had been normalized using log transformation. The spatial distribution of groundwater quality characteristics has been extensively studied using the inverse distance weighting (IDW) interpolation method. Instead of calculating the unknown value based on distant points, IDW uses the deterministic model method. For real-world parameters, this interpolation technique works well (Ram *et al.,* 2021; Kawo and Karuppannan, 2018; Sener *et al.,* 2017). The findings of laboratory analysis and field survey data overlapped to validate the IDW interpolation results. The IDW interpolation map's pixel values closely correspond to the field verification data.

Results and Discussion

Hydro-chemical Characteristics of Groundwater

The groundwater quality statistical analysis for a number of physicochemical characteristics from the study area is displayed in Table 4. The physicochemical characteristics of temperature, pH, electrical conductivity, total dissolved solids, chloride, total alkalinity, total hardness, calcium hardness, and magnesium hardness were evaluated about the groundwater quality parameters. The inorganic non-metallic components, including fluoride, and chloride, were measured. Manganese, iron, and arsenic were also analyzed as part of the heavy metal examination. The findings were evaluated against the Indian drinking water standards (IS 10500:2012).

One of the most crucial factors in determining if drinking water is suitable is pH (Li *et al.,* 2016). According to the Indian drinking water standard, groundwater should have a pH range of 6.5 to 8.5 (IS 10500:2012). The average pH of groundwater in the study area is 6.86 (±0.33), with a range of 5.74 to 7.42. This shows that the study area's groundwater is mildly acidic and falls within the standard limit, except for samples that have a pH of < 6.5 (n = 4, 11.11%), which are unfit for human consumption.

One of the key indicators of water quality is TDS, which primarily represents the different minerals found in the water (Varol and Davraz, 2015). The mean total dissolved solids (TDS) in the study area is 1157 mg/L (±695), with values varying from 200 to 3060 mg/L. According to Liu *et al.,* (2014), water quality can be categorized as freshwater if TDS is below 1000 mg/L, and as brackish when TDS exceeds 1000 mg/L. TDS values > 1000 mg/L were found in 50% (n = 18) of the 36 groundwater samples from the study region, indicating that the water was brackish. Higher TDS is caused by fertilizer application, irrigation return flow, residential wastewater, and a stronger water-rock interaction (Karakus, 2019; Wang and Li, 2022). In healthy individuals, high TDS in groundwater is usually innocuous and may result in constipation or a laxative effect; but, in those with heart and kidney issues, it may have a more significant effect (Li *et al.,* 2010; Ramakrishnaiah *et al.,* 2009; Varol and Davraz, 2015).

Anthropogenic sources and local lithological factors are the primary determinants of groundwater chloride levels (Mohamed *et al.,* 2019). The chloride concentration exceeded the 250 mg/L Indian drinking water standard and ranged from 9.0 to 678 mg/L, with an average of 149 mg/L (±140). Six samples (16.66%) have chloride levels above the acceptable limit of the drinking water standard.

The existence of dissolved carbonates, bicarbonates, and hydroxides - which result from geological processes and the interaction of water with rocks and soil - is the main cause of groundwater's alkalinity. The concentration of these alkaline compounds in the water increases as a result of this interaction, which causes carbonate minerals to dissolve. The average total alkalinity in the study area is 361 mg/L as $CaCO_3$ (±110), with a range of 108-636 mg/L as $CaCO_3$. Only one sample (2.77%) (Durgapur, HP, 636 mg/L as $CaCO_3$) had an alkalinity concentration beyond the permissible limit (600 mg/L), while 33 (91.66%) of the 36 samples from the study region had an alkalinity concentration above the acceptable level (200 mg/L as $CaCO_3$) of the Indian standard. The study area's southwest and southeast directions exhibit the highest and lowest concentrations of the limestone mineral, respectively. Alkalinity increases as groundwater passes through or is replenished by regions with carbonate rocks, such as limestone, which dissolve to release Ca^{++} and Mg^{++} ions in addition to carbonate and bicarbonate ions. It's also possible that dissolved materials like carbonates and bicarbonates were discharged into groundwater in the study area due to the natural weathering of the alkaline soil. Overly high alkalinity can change the flavour, induce gastrointestinal issues, and perhaps result in disorders like hyperkalemia in people with kidney ailments.

Groundwater's dissolved Ca^{++} and Mg^{++} are represented by total hardness

(TH). Elevated groundwater total hardness can impact drinking water quality and decrease detergent effectiveness (Wu *et al.,* 2020). According to Mohammed *et al.,* (2019), prolonged exposure to excessively hard water (> 180 mg/L as $CaCO_3$) may also increase the risk of kidney stones, anencephaly, perinatal mortality, and several cardiovascular disorders linked to cancer. The average TH value in this investigation was 406 mg/L as $CaCO_3$ (±320), with values ranging from 60 to 1448 mg/L as $CaCO_3$. Twenty-seven (75%) samples had TH concentrations over the acceptable range (200 mg/L as $CaCO_3$) by the Indian drinking water standard, while five samples (13.88%) had concentrations above the allowed limit (600 mg/L as $CaCO_3$). Both anthropogenic activities and the dissolution of soluble salts and minerals could be the cause of TH enrichment in groundwater (Wegahita *et al.,* 2020).

At low concentrations, fluoride in drinking water is vital for human health, including protecting teeth from cavities (Wegahita *et al.,* 2020). On the other hand, adults who intake excess fluoride may develop thyroid disorders, skeletal fluorosis, and dental fluorosis (Korner *et al.,* 2021; Zhang *et al.,* 2020). According to the Indian standard, the acceptable limit for fluoride concentration in drinking water is < 1.0 mg/L. Fluoride levels in this study vary from 0.5 to 2.32 mg/L, with an average of 1.18 mg/L (±0.42). A total of 24 samples (66.66%) exhibited groundwater levels over the acceptable limit (1.0 mg/L) of the Indian standard and five (13.88%) beyond the permissible level (> 1.5 mg/L). The region's lithology, particularly the dissolution of fluoride-bearing minerals, may be the primary cause of the high fluoride content in groundwater (Su *et al.,* 2018; Xiao *et al.,* 2015).

Groundwater typically has a low concentration of potentially toxic elements. They can, however, cause biological toxicity and represent a major risk to human health and aquatic ecology even at low concentrations (Papazotos, 2021; Pourret & Hursthouse, 2019; Yang *et al.,* 2015). The concentrations of Fe, Mn, and As varied from 0.055 to 4.022, 0.002-0.761, and 0.015-0.041 mg/L, respectively, as indicated in Table 4. The following is the order of average metal concentrations: Fe > Mn > As. The concentrations of all metals are higher than those allowed in drinking water. The central region of the study area is primarily home to samples with high concentrations of Fe, and As (Visapur, HP and Naleshwar, HP, respectively) and north direction for Mn concentration (Bhisi, HP). Manganese and iron behave geochemically similarly. Reduced circumstances, residency period, well depth, and salinity all have an impact on their dissolution and migration to growth (Zhang *et al.,* 2020).

The study area's groundwater arsenic concentration is shown in Fig. 4. It is evident that none of the study area's sampling locations had groundwater arsenic concentrations that were within the permissible range of the Indian guidelines for arsenic (0.01 mg/L). The concentration of groundwater arsenic at all sampling sites was below the allowable limit (0.05 mg/L) but beyond the acceptable limit. Naleshwar had the highest concentration of groundwater arsenic (0.041 mg/L, HP), whereas Arvi had the lowest (0.015 mg/L, HP). The research area's average groundwater arsenic concentration was 0.031 mg/L (±0.005). In comparison to the allowable limits set by Indian standards, Naleshwar (HP) recorded the greatest excess percentage at 310% with a concentration of 0.0314 mg/L, while Dongar Haldi (HP) followed closely with a level of 0.0296 mg/L, resulting in a 290% excess. Arvi (HP) had the lowest excess concentration (0.0058 mg/L, 50%). The research area's center contains the highest concentration of groundwater arsenic, with the west direction coming in second.

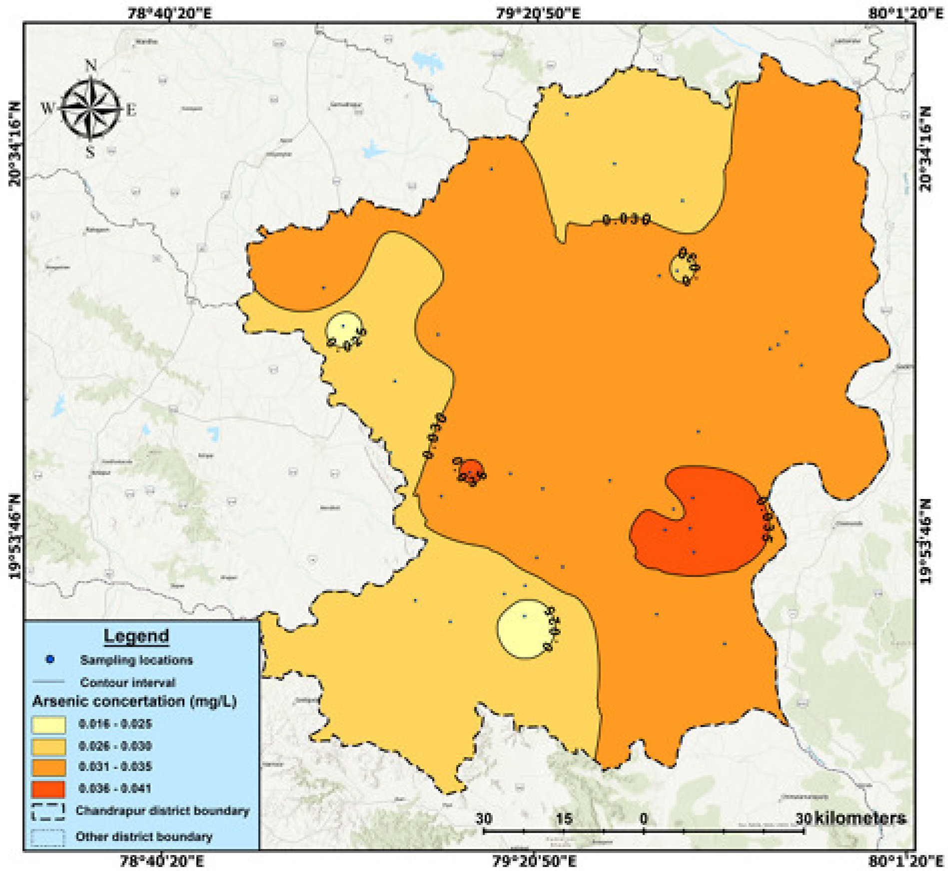

Fig. 4: Groundwater arsenic concentration from the study area

Table 4: Groundwater quality statistical analysis

Parameter	Min.	Max.	Average	SD (±)	Cumulative percentiles 25th	50th	75th	95th	98th	Standard limits for drinking water	P*
Temperature, °C	27.5	31.5	29.8	0.81	29	30	30	31	31	NS	-
pH	5.74	7.42	6.86	0.33	6.82	6.91	7.02	7.24	7.32	6.5-8.5	11
EC, µS/cm (10^3)	330	4710	1788	1052	950	1600	2307	4085	4598	NS	-
TDS, mg/L	200	3060	1157	695	595	1025	1505	2692	3018	500	89
Chloride, mg/L	9	678	149	140	49	123	210	383	534	250	17
Total Alkalinity, mg/L as $CaCO_3$	108	636	361	110	313	374	413	550	596	200	92
Total Hardness, mg/L as $CaCO_3$	60	1448	406	320	202	320	542	1168	1386	200	75
Calcium Hardness, mg/L as $CaCO_3$	32	852	274	171	151	266	340	582	734	NS	-
Magnesium Hardness, mg/L as $CaCO_3$	4	900	132	182	25	78	117	469	625	NS	-
F^-, mg/L	0.50	2.32	1.18	0.42	0.92	1.1	1.31	2.04	2.20	1.0	67
As, mg/L	0.015	0.041	0.031	0.004	0.029	0.032	0.034	0.037	0.04	0.01	100
Fe, mg/L	0.055	4.022	0.582	0.92	0.14	0.19	0.53	2.19	3.80	0.3	36
Mn, mg/L	0.002	0.761	0.058	0.13	0.004	0.011	0.03	0.177	0.44	0.1	17

P* refers to the percentage of samples that exceed permissible limits according to Indian standards.

Risk Assessment for Human Health

Non-carcinogenic Health Risk

The study area's groundwater is contaminated with arsenic and other pollutants, making it unsuitable for drinking and posing a high risk to human health. The non-carcinogenic health risk of groundwater arsenic for males, females, and children is shown in Table 5. For adult males, the oral (HQOral) values vary between 1.5385 (Arvi, HP) and 4.2051 (Naleshwar, HP), resulting in an average of 3.2023. For adult females and children, HQOral values range from 1.8182 (Arvi, HP) to 4.9697 (Naleshwar, HP) and from 3.1963 (Arvi, HP) to 8.7367 (Naleshwar, HP), with averages of 3.7845 and 6.6531, respectively. Regarding HQDermal values, males show a range of 0.0054 (Arvi, HP) to 0.0146 (Naleshwar, HP), while females range from 0.0056 (Arvi, HP) to 0.0153 (Naleshwar, HP). Children's values range from 0.0087 (Arvi, HP) to 0.0239 (Naleshwar, HP), with average values of 0.0111 for males, 0.0117 for females, and 0.0182 for children. The highest risk associated with oral ingestion (HQOral) is 4.2051 for males, 4.9697 for females, and 8.7367 for children. In terms of dermal contact (HQDermal), the greatest risks are 0.0146 for males, 0.0153 for females, and 0.0239 for children. In the study area, all HQTotal values for males, females, and children exceed 1, suggesting that residents are exposed to significant non-carcinogenic risks.

Carcinogenic Health Risk

The carcinogenic risk of drinking water and dermal contact exposure to groundwater arsenic is shown in Table 6. The CR_{Oral} ranges for males, females, and children are from 0.0007 (Arvi, HP) to 0.0019 (Naleshwar, HP); 0.0008 (Arvi, HP)-0.0022 (Naleshwar, HP) and 0.0014 (Arvi, HP)-0.0039 (Naleshwar, HP) with an average 0.0014, 0.0017, and 0.0030, respectively. The CR_{Dermal} results are comparatively smaller than CR_{Oral}, ranging from 2.41×10^{-6} (Arvi, HP) to 6.58×10^{-6} (Naleshwar, HP) for males, 2.53×10^{-6} (Arvi, HP)-6.91×10^{-6} (Naleshwar, HP) for females, and 3.93×10^{-6} (Arvi, HP)-1.07×10^{-5} (Naleshwar, HP) for children, with an average 5.01×10^{-6}, 5.26×10^{-6}, and 8.2×10^{-6}, respectively. The CR_{Total} values for males and females range from 0.0007 (Arvi, HP) to 0.0019 (Naleswar, HP) and 0.0008 (Arvi, HP)-0.0022 (Naleshwar, HP), with an average of 0.0014, and 0.0017, respectively. About children, the CR_{Total} values range from 0.0014 (Arvi, HP) to 0.0039 (Naleshwar, HP) with an average of 0.0030. All of the samples' carcinogenic risk estimates are higher than the permissible threshold (1×10^{-6}) for both adults and children. Furthermore, children are at a higher risk of developing cancer than adults, especially females. Li *et al.,* (2016) and Zhang *et al.,* (2018) also discovered similar outcomes in Weining Plain and Guanzhong Plain, respectively.

The inter-comparison among males, females, and children for HQOral, HQDermal, HQTotal, CROral, CRDermal, and CRTotal indicates that children are more vulnerable to groundwater arsenic contamination than adult males and females. The risk hierarchy is as follows: children > female > male. Due to their lower body weight, children and females are exposed to higher levels of pollutants on average each day than males. Oral exposure, as opposed to dermal contact, is the primary cause of the non-carcinogenic risk.

The maximum HQ_{Oral} and HQ_{Dermal} were observed in Naleshwar (HP) and it has emerged as a major non-carcinogenic risk location from the study area based on HQ classification with HQ_{Total} for male (4.2198), female (4.9850), and children (8.7605) (Fig. 5). Similar observations were also recorded for carcinogenic risk with CR_{Total} for male (0.0019), female (0.0022), and, children (0.0039) (Fig. 6). This sampling location is situated in a primary school premises and it was informed that the students use this water for drinking purpose. Therefore, prompt and appropriate corrective actions must be implemented to mitigate the health risks faced by children.

The Chandrapur district is bestowed with deposits of various minerals including coal. The coal-bearing formation in the Chandrapur district is the Wardha Valley Coalfield which is a part of the larger Gondwana sequence and distributed predominately at Ghuggus, Ballarpur, Rajura, and Warora. In 2012, there were 27 coal mines in the district. The findings imply a strong correlation between the local geological environment and the carcinogenic risk. The pollutants, like arsenic in this instance, enter into the groundwater. Under the appropriate favorable geochemical conditions, the use of N- and phosphorus-bearing fertilizers in agricultural activities will increase the concentration of As in groundwater (Papazotos *et al.,* 2019; Papazotos *et al.,* 2020). Residents who ingest such groundwater over an extended period run the risk of developing visceral cancers, including those of the kidney, liver, skin, and lungs (Qasemi *et al.,* 2019). According to Liu *et al.,* (2002), coal in China's Guizhou region has mineralized and created a significant concentration of arsenic. According to Guo *et al.,* (2017), arsenic levels in global coals averaged 5 mg/kg. Arsenic levels of up to 14.53 mg/kg were found in coal from West Bengal, India, while the Singrauli Industrial Region, India, recorded a concentration of 3.14 mg/kg (Dubey *et al.,* 2022). According to Patowary (2016), most of the water sources (ponds and groundwater, except rivers) were found to be polluted by arsenic and it was exceeding the permissibility level (50 µg/L). The high arsenic content may be due to the entry of acid mine drainage into the water that contains arsenic, dissolved in coal. Dubey *et al.,* (2012) reported water samples along the Yamuna Flood Plain, New Delhi, India showed > 55% had arsenic contamination beyond the WHO limit of 10 ppb. At the Rajghat coal-based thermal power plant in India, the highest levels of arsenic in coal and fly ash were 200 and 3,200 parts per billion, respectively. The maximum concentration of arsenic contamination was found within a 5-km radius of power plants. In Chandrapur district, six thermal power plants (5240 MW) and 11 captive power plants are operating and they utilize coal as a source of fuel. The health implications perhaps due to the emission of arsenic from the flue gas need to be ascertained along with the correlation with groundwater arsenic and associated health risks for residents.

The Naleshwar village is known for barite ($BaSO_4$) and is also rich in coal reserves. As per the Geology and Mineral Resources of Maharashtra 2000 (2000) two major barite zones measuring 1050 m and 800 m respectively have been located near Naleshwar and Uthalpeath villages of the Chandrapur district. The total estimated reserves of barite in this area are 14,800 tonnes with good grade of barite (90-94% $BaSO_4$). The barite and arsenic can be found together in specific geological contexts, particularly around barite mining areas and arsenic can be incorporated into the barite mineral structure itself. The presence and form of arsenic in barite can have implications for both environmental geochemistry and human health risk assessments. Necula *et al.,* (2021) reported arsenic (0.68 g/kg) in an abandoned barite mining area. According to Yang *et al.,* (2023), arsenate is mainly incorporated into the top monolayer of barite with a sorption coverage of 100%.

Table 5: The non-carcinogenic risk from ingestion of groundwater and dermal contact

Sampling location (Groundwater source)	HQ_{Oral}			HQ_{Dermal}			HI_{Total}		
	Male	Female	Child	Male	Female	Child	Male	Female	Child
Sonegaon (HP)	3.0769	3.6364	6.3927	0.0107	0.0112	0.0175	3.0876	3.6476	6.4102
Telwasa (HP)	2.6667	3.1515	5.5403	0.0093	0.0097	0.0151	2.6759	3.1612	5.5555
Belora (HP)	2.6667	3.1515	5.5403	0.0093	0.0097	0.0151	2.6759	3.1612	5.5555
Sagra (DW)	3.1795	3.7576	6.6058	0.0111	0.0116	0.0180	3.1905	3.7692	6.6238
Pethbhansouli (HP)	3.3846	4.0000	7.0320	0.0118	0.0124	0.0192	3.3964	4.0124	7.0512
Bhisi (HP)	2.5641	3.0303	5.3272	0.0089	0.0094	0.0145	2.5730	3.0397	5.3418
Pimpalgaon (HP)	2.9744	3.5152	6.1796	0.0103	0.0109	0.0169	2.9847	3.5260	6.1965
Mowada (HP)	2.3590	2.7879	4.9011	0.0082	0.0086	0.0134	2.3672	2.7965	4.9144
Dongargaon (HP)	3.4872	4.1212	7.2451	0.0121	0.0127	0.0198	3.4993	4.1339	7.2648
Lohara (HP)	3.3846	4.0000	7.0320	0.0118	0.0124	0.0192	3.3964	4.0124	7.0512
Chichpalli (HP)	3.1795	3.7576	6.6058	0.0111	0.0116	0.0180	3.1905	3.7692	6.6238
Dabgaon (Tukum) (HP)	3.1795	3.7576	6.6058	0.0111	0.0116	0.0180	3.1905	3.7692	6.6238
Naleshwar (HP)	4.2051	4.9697	8.7367	0.0146	0.0153	0.0239	4.2198	4.9850	8.7605
Karwan (HP)	3.0769	3.6364	6.3927	0.0107	0.0112	0.0175	3.0876	3.6476	6.4102
Chikmara (HP)	3.3846	4.0000	7.0320	0.0118	0.0124	0.0192	3.3964	4.0124	7.0512
Pathri (HP)	3.1795	3.7576	6.6058	0.0111	0.0116	0.0180	3.1905	3.7692	6.6238
Gunjewahi (DW)	3.5897	4.2424	7.4581	0.0125	0.0131	0.0204	3.6022	4.2555	7.4785
Mangali Chak (HP)	3.3846	4.0000	7.0320	0.0118	0.0124	0.0192	3.3964	4.0124	7.0512
Govindpur (HP)	2.9744	3.5152	6.1796	0.0103	0.0109	0.0169	2.9847	3.5260	6.1965
Ratnapur (HP)	3.3846	4.0000	7.0320	0.0118	0.0124	0.0192	3.3964	4.0124	7.0512
Antargaon (HP)	2.9744	3.5152	6.1796	0.0103	0.0109	0.0169	2.9847	3.5260	6.1965
Visapur (HP)	3.6923	4.3636	7.6712	0.0128	0.0135	0.0209	3.7051	4.3771	7.6922
Ballarpur (HP)	3.3846	4.0000	7.0320	0.0118	0.0124	0.0192	3.3964	4.0124	7.0512
Sasti (HP)	2.9744	3.5152	6.1796	0.0103	0.0109	0.0169	2.9847	3.5260	6.1965
Gowari (HP)	2.9744	3.5152	6.1796	0.0103	0.0109	0.0169	2.9847	3.5260	6.1965
Arvi (HP)	1.5385	1.8182	3.1963	0.0054	0.0056	0.0087	1.5438	1.8238	3.2051
Awarpur (HP)	2.6667	3.1515	5.5403	0.0093	0.0097	0.0151	2.6759	3.1612	5.5555
Lakhmapur (HP)	3.0769	3.6364	6.3927	0.0107	0.0112	0.0175	3.0876	3.6476	6.4102
Kem (Tukum) (HP)	3.3846	4.0000	7.0320	0.0118	0.0124	0.0192	3.3964	4.0124	7.0512
Ganpur (HP)	3.3846	4.0000	7.0320	0.0118	0.0124	0.0192	3.3964	4.0124	7.0512
Gondpipari (HP)	3.3846	4.0000	7.0320	0.0118	0.0124	0.0192	3.3964	4.0124	7.0512

Pombhurna (HP)	3.5897	4.2424	7.4581	0.0125	0.0131	0.0204	3.6022	4.2555	7.4785
Jam Tukum (HP)	3.6923	4.3636	7.6712	0.0128	0.0135	0.0209	3.7051	4.3771	7.6922
Dongar Haldi (HP)	4.0000	4.7273	8.3105	0.0139	0.0146	0.0227	4.0139	4.7419	8.3332
Durgapur (HP)	3.5897	4.2424	7.4581	0.0125	0.0131	0.0204	3.6022	4.2555	7.4785
Morwa (HP)	3.6923	4.3636	7.6712	0.0128	0.0135	0.0209	3.7051	4.3771	7.6922
Minimum	1.5385	1.8182	3.1963	0.0054	0.0056	0.0087	1.5438	1.8238	3.2051
Maximum	4.2051	4.9697	8.7367	0.0146	0.0153	0.0239	4.2198	4.9850	8.7605
Average	3.2023	3.7845	6.6531	0.0111	0.0117	0.0182	3.2134	3.7962	6.6713
SD (±)	0.4855	0.5738	1.0087	0.0017	0.0018	0.0028	0.4872	0.5755	1.0114

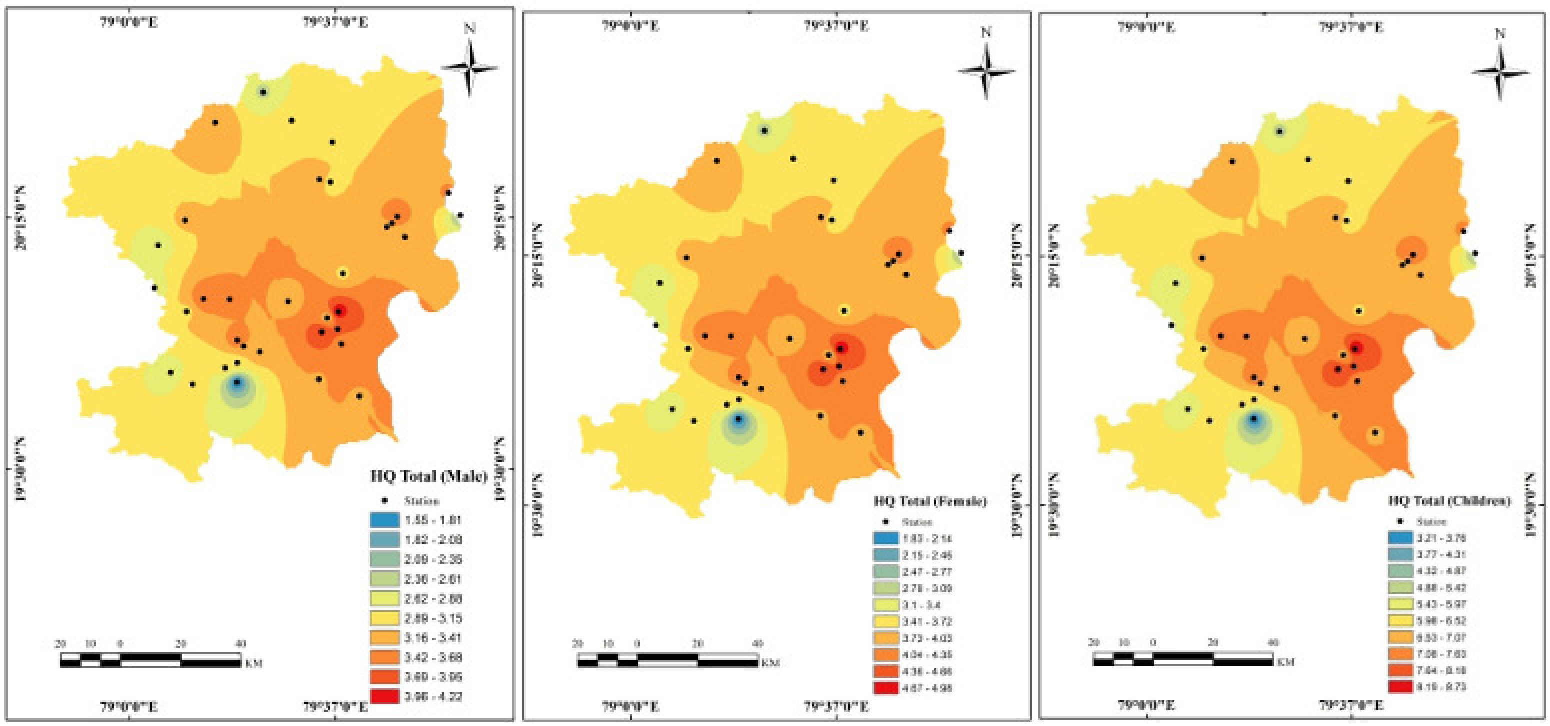

Fig. 5: Geographic distribution of non-carcinogenic health risks for men, women, and children

Table 6: The carcinogenic risk from ingestion of groundwater and dermal contact

Sampling location (Groundwater source)	CR_{Oral}			CR_{Dermal}			CR_{Total}		
	Male	Female	Child	Male	Female	Child	Male	Female	Child
Sonegaon (HP)	0.0014	0.0016	0.0029	4.82×10^{-6}	5.05×10^{-6}	7.86×10^{-6}	0.0014	0.0016	0.0029
Telwasa (HP)	0.0012	0.0014	0.0025	4.17×10^{-6}	4.38×10^{-6}	6.81×10^{-6}	0.0012	0.0014	0.0025
Belora (HP)	0.0012	0.0014	0.0025	4.17×10^{-6}	4.38×10^{-6}	6.81×10^{-6}	0.0012	0.0014	0.0025
Sagra (DW)	0.0014	0.0017	0.0030	4.98×10^{-6}	5.22×10^{-6}	8.12×10^{-6}	0.0014	0.0017	0.0030
Pethbhansouli (HP)	0.0015	0.0018	0.0032	5.3×10^{-6}	5.56×10^{-6}	8.64×10^{-6}	0.0015	0.0018	0.0032
Bhisi (HP)	0.0012	0.0014	0.0024	4.01×10^{-6}	4.21×10^{-6}	6.55×10^{-6}	0.0012	0.0014	0.0024
Pimpalgaon (HP)	0.0013	0.0016	0.0028	4.66×10^{-6}	4.88×10^{-6}	7.59×10^{-6}	0.0013	0.0016	0.0028
Mowada (HP)	0.0011	0.0013	0.0022	3.69×10^{-6}	3.87×10^{-6}	6.02×10^{-6}	0.0011	0.0013	0.0022
Dongargaon (HP)	0.0016	0.0019	0.0033	5.46×10^{-6}	5.73×10^{-6}	8.9×10^{-6}	0.0016	0.0019	0.0033
Lohara (HP)	0.0015	0.0018	0.0032	5.3×10^{-6}	5.56×10^{-6}	8.64×10^{-6}	0.0015	0.0018	0.0032
Chichpalli (HP)	0.0014	0.0017	0.0030	4.98×10^{-6}	5.22×10^{-6}	8.12×10^{-6}	0.0014	0.0017	0.0030
Dabgaon (Tukum) (HP)	0.0014	0.0017	0.0030	4.98×10^{-6}	5.22×10^{-6}	8.12×10^{-6}	0.0014	0.0017	0.0030
Naleshwar (HP)	0.0019	0.0022	0.0039	6.58×10^{-6}	6.91×10^{-6}	1.07×10^{-5}	0.0019	0.0022	0.0039
Karwan (HP)	0.0014	0.0016	0.0029	4.82×10^{-6}	5.05×10^{-6}	7.86×10^{-6}	0.0014	0.0016	0.0029
Chikmara (HP)	0.0015	0.0018	0.0032	5.3×10^{-6}	5.56×10^{-6}	8.64×10^{-6}	0.0015	0.0018	0.0032
Pathri (HP)	0.0014	0.0017	0.0030	4.98×10^{-6}	5.22×10^{-6}	8.12×10^{-6}	0.0014	0.0017	0.0030
Gunjewahi (DW)	0.0016	0.0019	0.0034	5.62×10^{-6}	5.9×10^{-6}	9.17×10^{-6}	0.0016	0.0019	0.0034
Mangali Chak (HP)	0.0015	0.0018	0.0032	5.3×10^{-6}	5.56×10^{-6}	8.64×10^{-6}	0.0015	0.0018	0.0032
Govindpur (HP)	0.0013	0.0016	0.0028	4.66×10^{-6}	4.88×10^{-6}	7.59×10^{-6}	0.0013	0.0016	0.0028
Ratnapur (HP)	0.0015	0.0018	0.0032	5.3×10^{-6}	5.56×10^{-6}	8.64×10^{-6}	0.0015	0.0018	0.0032
Antargaon (HP)	0.0013	0.0016	0.0028	4.66×10^{-6}	4.88×10^{-6}	7.59×10^{-6}	0.0013	0.0016	0.0028
Visapur (HP)	0.0017	0.0020	0.0035	5.78×10^{-6}	6.06×10^{-6}	9.43×10^{-6}	0.0017	0.0020	0.0035
Ballarpur (HP)	0.0015	0.0018	0.0032	5.3×10^{-6}	5.56×10^{-6}	8.64×10^{-6}	0.0015	0.0018	0.0032
Sasti (HP)	0.0013	0.0016	0.0028	4.66×10^{-6}	4.88×10^{-6}	7.59×10^{-6}	0.0013	0.0016	0.0028
Gowari (HP)	0.0013	0.0016	0.0028	4.66×10^{-6}	4.88×10^{-6}	7.59×10^{-6}	0.0013	0.0016	0.0028
Arvi (HP)	0.0007	0.0008	0.0014	2.41×10^{-6}	2.53×10^{-6}	3.93×10^{-6}	0.0007	0.0008	0.0014
Awarpur (HP)	0.0012	0.0014	0.0025	4.17×10^{-6}	4.38×10^{-6}	6.81×10^{-6}	0.0012	0.0014	0.0025
Lakhmapur (HP)	0.0014	0.0016	0.0029	4.82×10^{-6}	5.05×10^{-6}	7.86×10^{-6}	0.0014	0.0016	0.0029
Kem (Tukum) (HP)	0.0015	0.0018	0.0032	5.3×10^{-6}	5.56×10^{-6}	8.64×10^{-6}	0.0015	0.0018	0.0032
Ganpur (HP)	0.0015	0.0018	0.0032	5.3×10^{-6}	5.56×10^{-6}	8.64×10^{-6}	0.0015	0.0018	0.0032
Gondpipari (HP)	0.0015	0.0018	0.0032	5.3×10^{-6}	5.56×10^{-6}	8.64×10^{-6}	0.0015	0.0018	0.0032

Pombhurna (HP)	0.0016	0.0019	0.0034	5.62 x10^{-6}	5.9 x10^{-6}	9.17 x10^{-6}	0.0016	0.0019	0.0034
Jam Tukum (HP)	0.0017	0.0020	0.0035	5.78 x10^{-6}	6.06 x10^{-6}	9.43 x10^{-6}	0.0017	0.0020	0.0035
Dongar Haldi (HP)	0.0018	0.0021	0.0037	6.26 x10^{-6}	6.57 x10^{-6}	1.02 x10^{-5}	0.0018	0.0021	0.0037
Durgapur (HP)	0.0016	0.0019	0.0034	5.62 x10^{-6}	5.9 x10^{-6}	9.17 x10^{-6}	0.0016	0.0019	0.0034
Morwa (HP)	0.0017	0.0020	0.0035	5.78 x10^{-6}	6.06 x10^{-6}	9.43 x10^{-6}	0.0017	0.0020	0.0035
Minimum	0.0007	0.0008	0.0014	2.41 x10^{-6}	2.53 x10^{-6}	3.93 x10^{-6}	0.0007	0.0008	0.0014
Maximum	0.0019	0.0022	0.0039	6.58 x10^{-6}	6.91 x10^{-6}	1.07 x10^{-5}	0.0019	0.0022	0.0039
Average	0.0014	0.0017	0.0030	5.01 x10^{-6}	5.26 x10^{-6}	8.18 x10^{-6}	0.0014	0.0017	0.0030
SD (±)	0.0002	0.0003	0.0005	7.6 x10^{-7}	7.97 x10^{-7}	1.24 x10^{-6}	0.0002	0.0003	0.0005

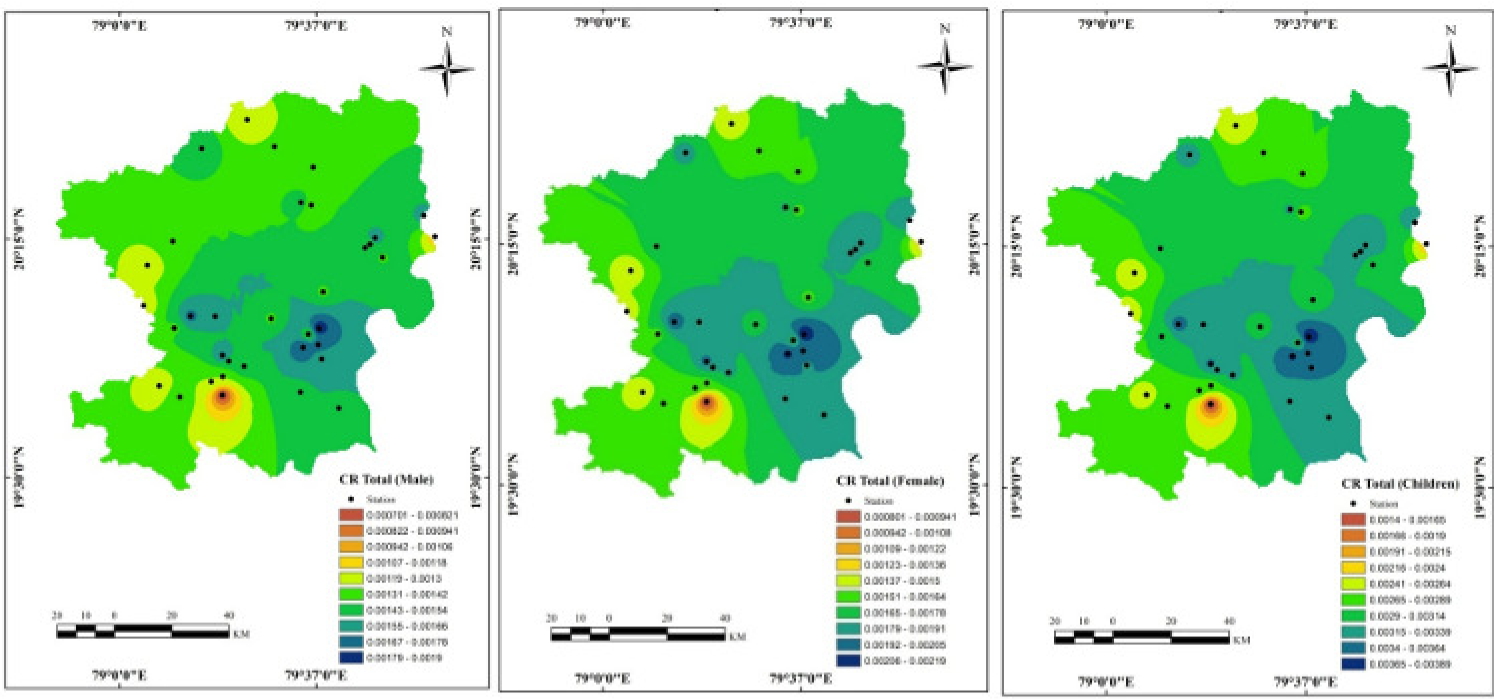

Fig. 6: Geographic distribution of carcinogenic health risks for men, women, and children

Table 7: The non-carcinogenic and carcinogenic health risks result from drinking water and dermal contact

As conc.		Non-carcinogenic health risk				
		$Intake_{Oral}$	HQ_{Oral}	$Intake_{Dermal}$	HQ_{Dermal}	HQ_{Total}
Min. 0.015, Max. 0.041, Avg. 0.031	Male	0.0005, 0.0013, 0.0010	1.5385, 4.2051, 3.2023	1.60 x10^{-6}, 4.38 x10^{-6}, 3.34 x10^{-6}	0.0054, 0.0146, 0.0111	1.5438, 4.2198, 3.2134
	Female	0.0005, 0.0015, 0.0011	1.8182, 4.9697, 3.7845	1.68 x10^{-6}, 4.60 x10^{-6}, 3.51 x10^{-6}	0.0056, 0.0153, 0.0117	1.8238, 4.9850, 3.7962
	Child	0.0010, 0.0026, 0.0020	3.1963, 8.7367, 6.6511	2.62 x10^{-6}, 7.16 x10^{-6}, 5.45 x10^{-6}	0.0087, 0.0239, 0.0182	3.2051, 8.7605, 6.6713
	Carcinogenic health risk					
		CR_{Oral}	CR_{Dermal}	CR_{Total}		
	Male	0.0007, 0.0019, 0.0014	2.41 x10^{-6}, 6.58 x10^{-6}, 5.01 x10^{-6}	0.0007, 0.0019, 0.0014		
	Female	0.0008, 0.0022, 0.0017	2.53 x10^{-6}, 6.91 x10^{-6}, 5.26 x10^{-6}	0.0008, 0.0022, 0.0017		
	Child	0.0014, 0.0039, 0.0030	3.93 x10^{-6}, 1.07 x10^{-5}, 8.18 x10^{-6}	0.0014, 0.0039, 0.0030		

As conc. in mg/L, Min. - Minimum, Max. - Maximum, Avg. - Average, HQ - Hazard Quotient, CR - Carcinogenic Risk

The non-carcinogenic and carcinogenic health hazards for men, women, and children at the minimum, maximum, and average concentrations of groundwater arsenic are shown in Table 7. From the table, it can be seen that non-carcinogenic health risk due to $Intake_{Oral}$ in men, women, and children was in the range from 0.0005 to 0.0013, 0.0005-0.0015, and 0.0010-0.0026 respectively. In the case of $Intake_{Dermal}$, it was in the range of 1.60 x 10^{-6}-4.38 x 10^{-6}, 1.68 x 10^{-6}-4.60 x 10^{-6}, and, 2.62 x 10^{-6}-7.16 x 10^{-6} in men, women, and children, respectively. From these findings, it can be arrived that health risk exposure due to $Intake_{Oral}$ is comparatively higher than $Intake_{Dermal}$. These findings further translate into $HQ_{Oral} > HQ_{Dermal}$. The non-carcinogenic health risk is highest for children, followed by women, and lowest for men. This is due to the difference in weight and height of the children, women, and men. The same findings were obtained for HQ_{Total} with a range from 1.5438 to 4.2198, 1.8238-4.9850, and 3.2051-8.7605 in men, women, and children, respectively. The average HQ_{Total} for men, women, and children, was 3.2134, 3.7962, and, 6.6713, respectively.

In case of carcinogenic health risk findings are reported due to oral and dermal exposure. The oral exposure (CR_{Oral}) route range for men, women, and children was from 0.0007 to 0.0019, 0.0008-0.0022, and 0.0014-0.0039, respectively. The carcinogenic risk due to dermal exposure (CR_{Dermal}) was in the range of 2.41 x 10^{-6}-6.58 x 10^{-6}, 2.53 x 10^{-6}-6.91 x 10^{-6}, and, 3.93 x 10^{-6}-1.07 x 10^{-5} for men, women, and children, respectively. The results indicate that the overall carcinogenic risk (CR_{Total}) associated with oral and dermal exposure for males, females, and children ranges from 0.0007 to 0.0019, 0.0008 to 0.0022, and 0.0014 to 0.0039, respectively. The average total carcinogenic risk was 0.0014, 0.0017, and 0.0030 in male, female, and children, respectively. These two health risks are above the acceptable limit and thus residents from the study area are vulnerable to groundwater arsenic-associated health risks. Of these two health risks, non-carcinogenic risk was more. The prolonged ingestion of groundwater contaminated with arsenic may pose a significant risk and may perhaps lead to the formation of various types of cancers in children - who are most vulnerable to these health risks - when they become adults.

Table 8: The non-carcinogenic risk assessment classification based on HQ

HQ	Chronic and cancer risk	Risk level	Number (%) of sampling locations		
			Male	Female	Children
$\geq 1 < 4$	Medium	3	34 (94)	18 (50)	01 (3)
> 4	High	4	02 (6)	18 (50)	35 (97)

The non-carcinogenic risk assessment classification based on HQ in the study area is displayed in Table 8. From the table, it can be seen that males in 34 (94%) sampling locations are in medium chronic and cancer risk ($HQ \geq 1 < 4$) with a risk level of 3. In the case of females, an equal number i.e. 18 (50%) sampling locations are in medium ($HQ \geq 1 < 4$) and high chronic and cancer risk ($HQ > 4$) with risk levels of 3 and 4, respectively. Whereas, children from 35 (97%) sampling locations are in high chronic and cancer risk (HQ > 4) with risk level 4. As the non-carcinogenic risk is > 1 for the inhabitants of the study area this indicates that from all sampling locations the health risks are associated with groundwater arsenic with children being at high risk.

Conclusion

This study evaluated the health risk of groundwater arsenic from 36 sampling locations in the Chandrapur district, central India. The study area's groundwater arsenic levels ranged from 0.015 to 0.041 mg/L (0.031 mg/L average, ±0.005). All sampling sites showed groundwater arsenic levels exceeding the acceptable limit of 0.01 mg/L set by Indian drinking water standards, but they remained within the permissible threshold of 0.05 mg/L. Residents in the study region may be at risk for health problems due to drinking water and dermal contact, among other exposure pathways, from arsenic-contaminated groundwater. The overall risk of non-carcinogenic health (HQ_{Total}) for men, women, and children ranges from 1.5438 to 4.2198, 1.8238-4.9850, and 3.2051-8.7605, respectively. Since HQ is greater than 1, all study area residents are at non-carcinogenic health risk from groundwater arsenic, with children being at higher risk than both men and women. The total carcinogenic health risk (CR_{Total}) ranges for men, women, and children are 0.0007-0.0019, 0.0008-0.0022, and, 0.0014-0.0039, respectively. The carcinogenic risk exceeds the acceptable limit ($CR_{Total} > 1 \times 10^{-6}$) for both adults and children. The greatest health risk for children followed by women and men was found in Naleshwar (HP). The health risk posed through oral ingestion contributes a greater proportion to the total risk than the dermal exposure pathway.

Alternative drinking water should be arranged and made available to the public by the local government authorities by water tankers into sizable plastic tanks positioned at strategic points across the community in order to lessen the health hazards connected with groundwater arsenic exposure. The study's findings will be utilized to inform and control the danger to locals who often use groundwater and to avoid any negative health effects. The findings of the study can be used to preserve public health and drinking water safety as well as to scientifically manage the local groundwater environment.

References

Ahn, J.S. (2012). Geochemical occurrences of arsenic and fluoride in bedrock groundwater: a case study in Geumsan County, Korea. *Environmental Geochemistry and Health,* 34: 43-54. https://doi.org/10.1007/s10653-011-9411-5

Amasa, S.K., Nyarko, B.J.B., Adotey, D.K., Dampare, S.K. and Adomako, D. (1975). Arsenic pollution at Obuasi goldmine, town and surrounding countryside. *Environmental Health Perspective,* 12: 131-135. doi: 10.1289/ehp.7512131

APHA (American Public Health Association). 2017. Standard methods for the examination of water and wastewater (23rd ed.). Washington D.C.: APHA, AWWA, WPCF, 2017.

Armienta, M. and Segovia, N. (2008). Arsenic and fluoride in the groundwater of Mexico.

Environmental Geochemistry and Health, 30: 345e353. https://doi.org/10.1007/s10653-008-9167-8

Berg, M., Stengel, C., Pham, T.K.T., Pham, H.V., Sampson, M. L., Leng, M., Samreth, S. and Fredericks, D. (2007). Magnitude of arsenic pollution in the Mekong and Red River deltas-Cambodia and Vietnam. *Science of the Total Environment,* 372: 413-425. https://doi.org/10.1016/j.scitotenv.2006.09.010

Bortey-Sam, N., Nakayama, S.M.M., Ikenaka, Y., Akoto, O., Baidoo, E., Mizukawo, H. and Ishizuka, M. (2015). Health risk assessment of heavy metals and metalloid in drinking water from communities near gold mines in Tarkwa, Ghana. *Environmental Monitoring and Assessment*, 187: 4630. 10.1007/s10661-015-4630-3.

Bresline, E. (2007). Sustainable water supply in developing countries. Geological Society of America. Paper No. 194-1: 2007.

Bundschuh, J., Litter, M.I., Parvez, F., Roman-Ross, G., Nicolli, H.B., Jean, J. S., Liu, C. W., Lopez, D., Armienta, M., Guilherme, L.R.G., Cuevas, A.G., Cornejo, L., Cumbal, L. and Toujaguez, R. (2012). One century of arsenic exposure in Latin America: a review of history and occurrence from 14 countries. *Science of the Total Environment,* 429: 2-35. https://doi.org/10.1016/j.scitotenv.2011.06.024

Census of India (2011). Chandrapur district profile. Directorate of Census Operation, Maharashtra. Ministry of Home Affairs, Government of India, Mumbai, pp. 1-8.

CGWB (Central Ground Water Board) (2009). Ground Water Information Chandrapur district, Maharashtra. Ministry of Water Resources. Government of India, Central Ground Water Board, Central Region, Nagpur, pp. 1-10.

Chen, J., Wu, H., Qian, H. and Gao, Y. (2017). Assessing nitrate and fluoride contaminants in drinking water and their health risk of rural residents living in a semiarid region of Northwest China. *Exposure and Health,* 9: 183–195. https://doi.org/10.1007/s12403-016-0231-9

Cubadda, F., D'Amato, M., Mancini, F.R., Aureli, F., Raggi, A., Busani, L., and Mantovani, A. (2015). Assessing human exposure to inorganic arsenic in high-arsenic areas of Latium: A biomonitoring study integrated with indicators of dietary intake, *Annali Di Igiene,* 27: 39-51. doi: 10.7416/ai.2015.2021

Dubey, C.S., Mishra, B., Shukla, D., Singh, R. P., Tajbakhsh, M. and Sakhare, P. (2012). Anthropogenic arsenic menace in Delhi Yamuna flood plains. *Environmental Earth Sciences*, 65(1): 131-139. doi: 10.1007/s12665-011-1072-2.

Dubey, C.S., Usham, A.L., Mishra, B.K., Shukla, D.P., Singh, P.K., and Singh, A.K. (2022). Anthropogenic arsenic menace in contaminated water near thermal power plants and coal mining areas of India. *Environmental Geochemistry and Health*, 44(3): 1099-1127. doi: 10.1007/s10653-021-01010-0

Emmanuel, E., Pierre, M.G. and Perrodin, Y. (2009). Groundwater contamination by microbiological and chemical substances released from hospital wastewater and health risk assessment for drinking water consumers. *Environment International,* 35: 718-726. https://doi.org/10.1016/j.envint.2009.01.011

Farooqi, A.B.F., Asuda, H.A.M., Usakabe, M.I.K., Aseem, M.U.N. and Irdous, N.O.F. (2007a). Distribution of highly arsenic and fluoride contaminated groundwater from East Punjab, Pakistan, and the controlling role of anthropogenic pollutants in the natural hydrological cycle. *Geochemical Journal,* 41(4): 213-234. https://doi.org/10.2343/geochemj.41.213

Farooqi, A., Masuda, H., and Firdous, N. (2007b). Toxic fluoride and arsenic contaminated groundwater in the Lahore and Kasur districts, Punjab, Pakistan and possible contaminant sources. *Environmental Pollution,* 145(3): 839-849. https://doi.org/10.1016/j.envpol.2006.05.007

Fry, A. (2005). Water facts and trends. World Business Council for Sustainable Development. Geology and Mineral Resources of Maharashtra 2000 (2000). Directorate of Geology and Mining, Government of Maharashtra. Mumbai.

George, C.M., Sima, L., Arias, M.H.J., Mihalic, J., Cabrera, L.Z., Danz, D., Checkley, W. and Gilman, R.H. (2014). Arsenic exposure in drinking water: an unrecognized health threat in Peru. *Bulletin of World Health Organization,* 92: 565–572. https://doi.org/10.2471/blt.13.128496.

Guo, H. and Wang, Y. (2005). Geochemical characteristics of shallow groundwater in Datong basin, northwestern China. *Journal of Geochemical Explorer,* 87: 109-120. https://doi.org/10.1016/j.gexplo.2005.08.002

Guo, J., Yao, D., Chen, P., Chen, J.: and Shi, F. (2017). Distribution, enrichment and modes of occurrence of arsenic in Chinese coals. *Minerals*, 7(7): 114. https://doi.org/10.3390/min7070114

Habila, O. (2005). *Groundwater and the Millennium Development Goals*. Proceedings groundwater and poverty reduction in Africa. International Association of Hydrogeologist, London.

Halim, M.A., Majumder, R.K., Nessa, S.A., Hiroshiro, Y., Uddin, M.J. Shimada, J., and Jinno, K. (2009). Hydrogeochemistry and arsenic contamination of groundwater in the Ganges delta plain, Bangladesh. *Journal of Hazardous Material,* 16(2-3): 1335-1345. https://doi.org/10.1016/j.jhazmat.2008.09.046

Hani, H. (1990). The analysis of inorganic and organic pollutants in soil with special regard to their bioavailability. *International Journal of Environmental Analytical Chemistry,* 39: 197-208. https://doi.org/10.1080/03067319008027697

Haque, S. and Johannesson, K.H. (2006). Arsenic concentrations and speciation along a groundwater flow path: The Carrizo Sand aquifer, Texas, USA. *Chemical Geology,* 228(1-3): 57-71. https://doi.org/10.1016/j.chemgeo.2005.11.019

Ji, Y., Wu, J., Wang, Y., Elumalai, V. and Subramani, T. (2020). Seasonal variation of drinking water quality and human health risk assessment in Hancheng City of Guanzhong Plain, China. *Exposure and Health,* 12: 469–485. https://doi.org/10.1007/s12403-020-00357-6

Kamal, A.S. and Parkpian, P. (2002). Arsenic contamination in Hizla, Bangladesh: Sources, effects and remedies. *ScienceAsia,* 28: 181-189.

Karakus, C.B. (2019). Evaluation of groundwater quality in Sivas province (Turkey) using water quality index and GIS-based analytic hierarchy process. *International Journal of Environmental Health Research,* 29: 500–519. https://doi.org/10.1080/09603123.2018.1551521

Karim, M.M. (2000). Arsenic in groundwater and health problems in Bangladesh. *Water Research,* 34: 304-310. https://doi.org/10.1016/S0043-1354(99)00128-1

Kawo, N.S., and Karuppannan, S. (2018). Groundwater quality assessment using water quality index and GIS technique in Modjo River Basin, central Ethiopia. *Journal of African Earth Sciences,* 147: 300–311. https://doi.org/10.1016/j.jafrearsci.2018.06.034

Khan, S., Mack, R., Castillo, X., Kaiser, M. and Joergensen, R. G. (2016). Microbial biomass, fungal and bacterial residues, and their relationships to the soil organic matter C/N/P/S ratios. *Geoderma*, 271: 115–123. https://doi.org/10.1016/j.geoderma.2016.02.019

Korner, P., Georgis, L., Wiedemeier, D.B., Attin, T. and Wegehaupt, F.J. (2021). Potential of different fluoride gels to prevent erosive tooth wear caused by gastroesophageal reflux. *BMC Oral Health,* 21: 183. doi: 10.1186/s12903-021-01548-6

Kumar, M., Kumar, P., Ramanathan, L., Bhattacharya, P., Thunvik, R., Singh, U.K., Tsujimura, M. and Sracek, O. (2010a). Arsenic enrichment in groundwater in the middle Gangetic plain of Ghazipur district in Uttar Pradesh, India. *Journal of Geochemical Exploration, 105*, 83-94. https://doi.org/10.1016/j.gexplo.2010.04.008

Kumar, M., Furumai, H., Kurisu, F., and Kasuga, I. (2010b). A comparative evaluation of mobile heavy metal pool in the soakaway sediment, road dust and soil through sequential extraction and isotopic dilution techniques. *Water Science and Technology,* 62(4): 920-928. https://doi.org/10.2166/wst.2010.911

Li, P., Hui, Q. and Wu, J. (2010). Groundwater quality assessment based on improved water quality index in Pengyang County, Ningxia, Northwest China.

Journal of Chemistry, 7: S209–S216. https://doi.org/10.1155/2010/451304

Li, P., Li, X., Meng, X., Li, M. and Zhang, Y. (2016). Appraising groundwater quality and health risks from contamination in a semiarid region of northwest China. *Exposure and Health,* 8: 361–379. doi:10.1007/s12403-016-0205-y

Li, P., Feng,W., Xue, C., Tian, R., and Wang, S. (2017). Spatiotemporal variability of contaminants in lake water and their risks to human health: A case study of the Shahu Lake Tourist Area, Northwest China. *Exposure and Health*, 9: 213–225. https://doi.org/10.1007/s12403-016-0237-3

Liu, J., Zheng, B., Aposhian, H.V., Zhou, Y., Chen, M.L., Zhang, A. and Waalkes, M.P. (2002). Chronic arsenic poisoning from burning high-arsenic-containing coal in Guizhou, China. *Environmental Health Perspectives*, 110(2):119-22. doi: 10.1289/ehp.02110119

Liu, Y.L., Luo, K.L., Lin, X.X., Gao, X., Ni, R.X., Wang, S.B. and Tian, X.L. (2014). Regional distribution of longevity population and chemical characteristics of natural water in Xinjiang, China. *Science of the Total Environment,* 473–474: 54–62. https://doi.org/10.1016/j.scitotenv.2013.11.134

MacDonald, A., Davies, J., Calow, R. and Chilton, J. (2005). Developing groundwater: A guide to rural water supply. Rugby: Practical Action Publishing Ltd. pp. 358, http://dx.doi.org/10.3362/9781780441290

Mohamed, A.K., Dan, L., Kai, S., Mohamed, M.A.A., Aldaw, E., and Elubid, B.A. (2019). Hydrochemical analysis and fuzzy logic method for evaluation of groundwater quality in the North Chengdu Plain, China. *International Journal of Environmental Research and Public Health*, 16: 302. doi: 10.3390/ijerph16030302

Muhammad, S., Shah, M.T. and Khan, S. (2010). Arsenic health risk assessment in drinking water and source apportionment using multivariate statistical techniques in Kohistan region, northern Pakistan. *Food and Chemical Toxicology,* 48(10): 2855-2864. https://doi.org/10.1007/s12594-017-0705-9

Muhammad, S., Shah, M.T. and Khan, S. (2011). Health risk assessment of heavy metals and their source apportionment in drinking water of Kohistan region, northern Pakistan. *Microchemical Journal,* 98: 334-343. doi: 10.1016/j.microc.2011.03.003

Narsimha, A., Manne, R., Zhang, Y-H., Xu, P. and Qian, H. (2022). Evaluation of groundwater quality and its suitability for drinking purposes in semi-arid region of Southern India: An application of GIS. *Geocarto International,* 37(25): 1-13. doi: 10.1080/10106049.2022.2040603

Necula, R., Zaharia, M., Zaharia, M. M., Butnariu, A., Zamfirache, M., Surleva, A., Surleva, A., Ciobanu, C., Ionica Ciobanu, C., Pintilie, O., Iacoban, C. and Drochioiu, G. (2021). Heavy metals and arsenic in an abandoned barite mining area: ecological risk assessment using biomarkers. *Environmental Forensics*, 24(3–4): 164–175. https://doi.org/10.1080/15275922.2021.1976315

NEERI (National Environmental Engineering Research Institute) (1988). Manual on water and wastewater analysis. National Environmental Engineering Research Institute, Nagpur, India, pp. 1-223.

Papazotos, P. (2021). Potentially toxic elements in groundwater: A hotspot research topic in environmental science and pollution research. *Environmental Science and Pollution Research,* 28: 47825–47837. https://doi.org/10.1007/s11356-021-15533-7

Papazotos, P., Vasileiou, E. and Perraki, M. (2019). The synergistic role of agricultural activities in groundwater quality in ultramafic environments: The case of the Psachna basin, central Euboea, Greece. *Environmental Monitoring and Assessment*, 191: 1–32. https://doi.org/10.1007/s10661-019-7430-3

Papazotos, P., Vasileiou, E. and Perraki, M. (2020). Elevated groundwater concentrations of arsenic and chromium in ultramafic environments controlled by seawater intrusion, the nitrogen cycle, and anthropogenic activities: The case of the Gerania Mountains, NE Peloponnese, Greece. *Applied Geochemistry*, 121: 104697. https://doi.org/10.1016/j.apgeochem.2020.104697

Patowary, K. (2016). Determination of arsenic in the water of coal mining areas of Assam. *Journal of Applied and Fundamental Sciences*, 2(1): 50-55.

Pourret, O. and Hursthouse, A. (2019). It's time to replace the term "heavy metals" with "potentially toxic elements" when reporting environmental research. *International Journal of Environmental Research and Public Health*, 16: 4446. https://doi.org/10.3390/ijerph16224446

Qasemi, M., Shams, M., Sajjadi, S.A., Farhang, M., Erfanpoor, S., Yousefi, M., Zarei, A. and Afsharnia, M. (2019). Cadmium in groundwater consumed in the rural areas of Gonabad and Bajestan, Iran: Occurrence and health risk assessment. *Biological Trace Element Research*, 192: 106–115. doi: 10.1007/s12011-019-1660-7

Ram, A., Tiwari, S.K., Pandey, H.K., Chaurasia, A.K., Singh, S. and Singh, Y.V. (2021). Groundwater quality assessment using water quality index (WQI) under GIS framework. *Applied Water Science,* 11: 46. https://doi.org/10.1007/s13201-021-01376-7

Ramakrishnaiah, C.R., Sadashivaiah, C. and Ranganna, G. (2009). Assessment of water quality index for the groundwater in Tumkur Taluk, Karnataka State, India. *Journal of Chemistry,* 6: 523–530.

https://doi.org/10.1155/2009/757424

Rapant, S. and Krcmova, K. (2007). Health risk assessment maps for arsenic groundwater content, application of national geochemical databases. *Environmental Geochemistry and Health,* 29: 131-141. doi: 10.1007/s10653-006-9072-y

Rossman, T.G., Uddin, A.N. and Burns, F.J. (2004). Evidence that arsenite acts as a cocarcinogen in skin cancer. *Toxicology and Applied Pharmacology,* 198: 394-404. doi: 10.1016/j.taap.2003.10.016

Sahu, P. and Sikdar, P.K. (2008). Hydrochemical framework of the aquifer in and around East Kolkata Wetlands, West Bengal, India. *Environmental Geology,* 55: 823–835. https://doi.org/10.1007/s00254-007-1034-x

Sanchez, E., Colmenarejo, M.F., Vicente, J., Rubio, A., García, M.G., Travieso, L. and Borja, R. (2007). Use of the water quality index and dissolved oxygen deficit as simple indicators of watersheds pollution. *Ecological Indicators,* 7: 315-328. https://doi.org/10.1016/j.ecolind.2006.02.005

Sener, S., Sener, E. and Davraz, A. (2017). Evaluation of water quality using water quality index (WQI) method and GIS in Aksu River (SW-Turkey). *Science of the Total Environment,* 584–585: 131–144. https://doi.org/10.1016/j.scitotenv.2017.01.102

Shah, B.A. (2012). Role of quaternary stratigraphy on arsenic-contaminated groundwater from parts of Barak valley, Assam, north-east India. *Environmental Earth Sciences,* 66: 2491-2501. https://doi.org/10.1007/s12665-011-1472-3

Su, H., Kang, W., Xu, Y. and Wang, J. (2018). Assessing groundwater quality and health risks of nitrogen pollution in the shenfu mining area of Shaanxi Province, Northwest China. *Exposure and Health,* 10: 77–97. https://doi.org/10.1007/s12403-017-0247-9

Tchounwou, P.B., Centeno, J.A. and Patlolla, A.K. (2004). Arsenic toxicity, mutagenesis, and carcinogenesis—A health risk assessment and management approach. *Molecular and Cellular Biochemistry*, 255: 47-55. doi: 10.1023/b:mcbi.0000007260.32981.b9

UNEP (United Nations Environmental Programme) (2002). Vital Water Graphics (Nairobi, Kenya).

USEPA (US Environmental Protection Agency) (1989). Risk assessment guidance for superfund, Volume I: Human Health Evaluation Manual (Part A); EPA/540/1-89/002; USEPA: Washington, DC, USA, 1989.

USEPA (US Environmental Protection Agency) (1999). A risk assessment–multiway exposure spreadsheet calculation tool. United States Environmental Protection Agency. Washington, D.C.

Varol, S. and Davraz, A. (2015). Evaluation of the groundwater quality with WQI (Water Quality Index) and multivariate analysis: A case study of the Tefenni plain (Burdur/Turkey). *Environmental*

Earth Sciences, 73: 1725–1744. https://doi.org/10.1007/s12665-014-3531-z

Wang, Y. and Li, P. (2022). Appraisal of shallow groundwater quality with human health risk assessment in different seasons in rural areas of the Guanzhong Plain (China). *Environmental Research,* 207: 112210. https://doi.org/10.1016/j.envres.2021.112210

Wegahita, N.K., Ma, L., Liu, J., Huang, T., Luo, Q. and Qian, J. (2020). Spatial assessment of groundwater quality and health risk of nitrogen pollution for shallow groundwater aquifer around Fuyang City, China. *Water,* 12: 3341. https://doi.org/10.3390/w12123341

Winkel, L.H.E., Trang, P.T.K., Lan, V.M., Stengel, C., Amini, M., Ha, N.T., Viet, P.H., and Berg, M. (2011). Arsenic pollution of groundwater in Vietnam exacerbated by deep aquifer exploitation for more than a century. *Proceedings of the National Academy of Sciences United States of America*, 108: 1246-1251. https://doi.org/10.1073/pnas.1011915108

Wu, J. and Sun, Z. (2016). Evaluation of shallow groundwater contamination and associated human health risk in an alluvial plain impacted by agricultural and industrial activities, mid-west China. *Exposure and Health*, 8: 311–329. https://doi.org/10.1007/s12403-015-0170-x

Wu, J., Zhang, Y. and Zhou, H. (2020). Groundwater chemistry and groundwater quality index incorporating health risk weighting in Dingbian County, Ordos basin of northwest China. *Geochemistry*, 80: 125607. https://doi.org/10.1016/j.chemer.2020.125607

WWAP (United Nations World Water Assessment Programme) (2015). The United Nations World Water Development Report 2015: Water for a Sustainable World. Paris, UNESCO.

Xiao, J., Jin, Z. and Zhang, F. (2015). Geochemical controls on fluoride concentrations in natural waters from the middle Loess Plateau, China. *Journal of Geochemical Exploration,* 159: 252–261. https://doi.org/10.1016/j.gexplo.2015.09.018

Yang, X., Hou, Q., Yang, Z., Zhang, X., and Hou, Y. (2012). Solid-solution partitioning of arsenic (As) in the paddy soil profiles in Chengdu Plain, Southwest China. *Geoscience Frontiers, 3*, 901-909. https://doi.org/10.1016/j.gsf.2012.03.006

Yang, X., Duan, J., Wang, L., Li, W., Guan, J., Beecham, S. and Mulcahy, D. (2015). Heavy metal pollution and health risk assessment in the Wei River in China. *Environmental Monitoring and Assessment,* 187: 111. https://doi.org/10.1007/s10661-014-4202-y

Yang, P., Lee, S.S., Fenter, P., Jacquelyn N. Bracco, J.N., and Stack, A.G. (2023). Sorption of arsenate, selenate, and molybdate on the Barite (001) surface. *ACS Earth and Space Chemistry*, 7(8): 1545–1556.

https://doi.org/10.1021/acsearthspacechem.3c00096

Yidana, S.M. and Yidana, A. (2010). Assessing water quality using water quality index and multivariate analysis. *Environmental Earth Science,* 59: 1461-1473. https://doi.org/10.1007/s12665-009-0132-3.

Yoshida, T., Yamauchi, H. and Fan Sun, G. (2004). Chronic health effects in people exposed to arsenic via the drinking water: dose-response relationships in review. *Toxicology and Applied Pharmacology,* 198(3): 243-252. doi: 10.1016/j.taap.2003.10.022

Yoshizuka, K., Nishihama, S. and Sato, H. (2010). Analytical survey of arsenic in geothermal waters from sites in Kyushu, Japan, and a method for removing arsenic using magnetite. *Environmental Geochemistry and Health,* 32: 297-302. https://doi.org/10.1007/s10653-010-9300-3.

Zhang, Y., Wu, J. and Xu, B. (2018). Human health risk assessment of groundwater nitrogen pollution in Jinghui canal irrigation area of the loess region, northwest China. *Environmental Earth Sciences,* 77: 273. https://doi.org/10.1007/s12665-018-7456-9

Zhang, L., Zhao, L., Zeng, Q., Fu, G., Feng, B., Lin, X., Liu, Z., Wang, Y. and Hou, C. (2020). Spatial distribution of fluoride in drinking water and health risk assessment of children in typical fluorosis areas in north China. *Chemosphere,* 239: 124811. https://doi.org/10.1016/j.chemosphere.2019.124811

Zhou, Y., Li, P., Chen, M., Dong, Z., and Lu, C. (2021). Groundwater quality for potable and irrigation uses and associated health risk in southern part of Gu'an County, North China Plain. *Environmental Geochemistry and Health,* 43: 813–835. https://doi.org/10.1007/s10653-020-00553-y

Zhu, L., Yang, M., Chen, X. and Liu, J. (2019). Health risk assessment and risk control: Drinking groundwater in Yinchuan Plain, China. *Exposure and Health,* 11: 59–72. https://doi.org/10.1007/s12403-017-0266-6