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Water quality index and human health risk assessment for heavy metals in groundwater of Bedkot Municipality, Kanchanpur, Nepal: A cross-sectional study

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Abstract

This study assessed groundwater quality and associated human health risks in Bedkot Municipality, Nepal, where 68.6% of households rely on tube wells (TWs). Twenty-three shallow TWs water samples (urban:10, semi-urban:6, and rural:7) were analyzed for physiochemical parameters (pH, temperature, turbidity, electrical conductivity, total dissolved solids, total hardness, calcium, ammonium, nitrate, total iron (Fe), and total arsenic (As)), following standard methods and assessed using the water quality index (WQI) and USEPA's human health risk assessment (HHRA). Results revealed slightly acidic freshwater, with hardness varying (hard to very hard: urban/semi-urban, and moderately hard to very hard: rural). WQI classified 80% of urban, 90% of semi-urban, and 100% of rural samples as "excellent" for drinking, with none deemed unsuitable (WQI > 300). However, health risks emerged: children in all areas faced non-carcinogenic risks (Hazard Index, HI: 1.5–6.31). Some urban adults also showed risks (HI: 0.73–2.98), whereas no such risks were identified for adults in semi-urban and rural areas (HI: 0.73–0.95). Carcinogenic risks from As ingestion were significant for children (7E-04–2.5E-03) and adults (3.3E-04– 1.2E-03) in urban, as well as children (7E-04– 9E-04) and adults (3.3E-04– 4.2E-04) in semi-urban and rural areas, exceeding acceptable thresholds (1E-06–1E-04). Children were 2.12 times more susceptible to non-carcinogenic and carcinogenic health risks than adults. These findings can guide sustainable groundwater quality management strategies in the region.

Keywords: *tube wells, groundwater quality, public health risks, heavy metals, water quality indices*

Introduction

Safe drinking water access is universally recognized as both a fundamental human right and a critical determinant of public health (World Health Organization [WHO], 2017). Globally, approximately 2.5 billion people depend on groundwater as their primary drinking water source, particularly in regions with limited access to treated surface water (Adimalla and Qian, 2019). This dependence is especially pronounced in Nepal's Terai (plain) region, where nearly 90% of the population relies on groundwater resources (Kayastha, 2015), extracted through hand pumps/ tube wells, and dug wells (Thakur et al., 2010). However, growing contamination from both natural and anthropogenic sources poses significant threats to water quality and public health (WHO, 2022). The geological and climatic conditions of Nepal's plains region, combined with increasing human activities, significantly influence groundwater quality by altering its physicochemical properties and elevating heavy .

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metal concentrations (Aryal, 2024; Thivya et al., 2014). Heavy metals such as arsenic (As) and iron (Fe) contamination have elevated the WHO permissible drinking water limit in Nepal. For instance, a study by Kayastha (2015) indicated that As contamination was particularly prevalent in shallow tube wells (32–65 feet deep) across Nepal's plains regions. National-scale assessments conducted across 25 districts revealed alarming contamination levels. In 22 of these districts, inclduing Kanchanpur, 10.25% of the 737,009 groundwater samples exceeded the WHO permissible limit of 0.01 mg/L for As. In Kanchanpur specifically, 3.73% of the population relied on water that surpassed this guideline (Thakur et al., 2010). Similarly pervasive is Fe contamination, with studies reporting exceedances of permissible limits in 61.14% of groundwater samples in eastern Nepal (Mahato et al., 2018) and 84% in the central Terai (Shrestha and Zhihou, 2024), and 79.16% in the Far Western region (Gurung et al., 2015). Local studies in Bhimdatta Municipality, Kanchanpur had confirmed these trends, with 6% of samples exceeding safe levels for both As and Fe (Bohara, 2015). Groundwater contains various ions, metals, and metalloids, which can have beneficial or toxic effects depending on exposure levels (Varol and Davraz, 2016). Several key physicochemical parameters determine water quality and its health implications. For instance, pH affects metal solubility and bioavailability, with low pH linked to gastrointestinal disorders (Ogarekpe et al., 2023). Electrical conductivity (EC) reflects dissolved solids and mineral salts, indicating the ionic strength of water, and high EC levels indicate poor water quality (Ahmed et al., 2019). Elevated total dissolved solids (TDS) levels result in corrosiveness, undesirable taste, and gastro-intestinal inflammation (Safo-Adu, 2022). Turbidity, which measures particularte matter such as sediments, algae, and microorganisms, can signal contamination (Trivedy and Goel, 1984). High turbidity affects water aesthetics and complicates treatment by protecting pathogens from disinfectants and hindering filtration (Ibrahim, 2019). Calcium contributes to water hardness and is essential for bone and teeth health, but insufficient calcium intake increases the risks of osteoporosis, kidney stones, hypertension, and cardio-vascular diseases (Howladar et al., 2018). Conversely, prolonged consumption of hard water has been associated with urolithiasis, prenatal mortality, and cardiovascular problems (Aryal, 2024). High nitrate poses health risks, for infants and pregnant women, as it can cause methemoglobinemia or "blue baby syn-drome," and an elevated risk of gastric cancer, congenital disabilities of the central nervous system, and hypertension in adults (Raheja et al., 2024). Ammonium contributes to the formation of disinfection byproducts (DBPs) during water treatment processes. It can react with chlorine disinfecttants to form chloramines and trihalomethanes, which have been associated with various health risks, including cancer and reproductive disorders (Altahan et al, 2023). Although Fe is essential for oxygen transport in the blood, excessive intake can lead to acute and chronic health problems, including liver disease, cancer, and cardiovascular issues (Ogarekpe et al., 2023), while As, a Group 1 carcinogen, is one of the most toxic heavy metals, associated with cancers of the lung, liver, bladder, kidney, and skin (Shaibur et al., 2024; Smith et al., 1992). These risks highlight the strong correla-tion between groundwater quality and public health. Given these risks, extensive research has employed the Water Quality Index (WQI) and Human Health Risk Assessment (HHRA) to evaluate groundwater suitability and associated health hazards. The WQI, developed by Horton in the 1960s, is a globally reco-gnized tool for determining groundwater suitability for drinking purposes (Akter et al., 2016; Ghosh et al., 2023; Howladar et al., 2018; Shaibur et al., 2024). It integrates multiple physicochemical parameters into a single numerical value, where lower values indicate better water quality (Ghosh et al., 2023; Shaibur et al., 2024). Meanwhile, the HHRA models quantify potential health risks to heavy metals through ingestion (drinking) and dermal contact (US Environmental Protection Agency [USEPA], 2004). This method integrates both qualitative and quantita-tive assessment to distinguish between carcinogenic risks, which assess the probability of cancer develop-ment, and non-carcinogenic risks, which account for effects such as genetic damage and teratogenic impacts (Bodrud-Doza et al., 2016; USEPA, 1989). The complexity of health risks increases when multiple contaminants are present or when individuals have pre-existing health conditions (Ghosh et al., 2023; Shaibur et al., 2024). While extensive research has evaluated groundwater quality and health risks in South Asia—including studies in India (Adimalla and Qian, 2019), Bangladesh (Shaibur et al., 2024; Ghosh et al., 2023), China (Liu et al., 2020), and Pakistan (Nawaz et al., 2023)—similar assessments remain scarce in Bedkot Municipality, Nepal, where majority of households rely on tube wells for drinking water (National Statistics Office [NSO], 2021).To address this gap, the

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present study aims to: (i) evaluate groundwater quality using WQI to classify suitability for drinking, and (ii) assess carcinogenic and non-carcinogenic health risks for children and adults posed by As and Fe exposure in urban, semi-urban, and rural areas of Bedkot Municipality. The findings will provide critical insights for policymakers, researchers, and water management authorities to ensure safe drinking water access.

Materials and Methods

Study area and site description

Bedkot Municipality, established in 2015, is located in the Kanchanpur District of Sudurpaschim Province, Nepal (28.57° N, 80.1348° E). Spanning 158.5 km², it is administratively divided into 10 wards and bordered by Shuklaphata National Park to the east and south, Bhimdatta Municipality to the west, and the Chure/ Siwalik Range (Parshuram Municipality) to the north (Fig. 1). Land-use patterns are dominated by forests (53.95%, 86.01 km²) and agriculture (32.68%, 52.1 km²), with smaller areas allocated to riverine zones (5.23%, 8.34 km²) and built-up settlements (4.98%, 7.94 km²) (Dahal and Timalsina, 2020). The region experiences a Tropical Savannah climate (Köppen-Geiger classification), characterized by an average annual temperature >26°C, annual precipitation of 1,800 – 2,000 mm, and elevation gradients ranging from 192 to 1,401 meters above sea level (Environment and Public Health Organization [ENPHO], 2022). Geologically, the municipality lies within Nepal's Northern plain and Siwalik (Chure) ranges, part of the Indo-Gangetic Plain formed ~10 million years ago through monsoon-driven sediment deposition (Upreti, 2001). The Northern plain comprises permeable sandy loam soils with coarse sediments, rendering shallow aquifers vulnerable to contamination (ENPHO, 2022). Adjacent Siwalik formations consist of fluvial sedimentary rocks (sandstone, siltstone, mudstone, and conglomerate), deposited during the Himalayan uplift ~50 million years ago (Upreti, 2001). These young, erodible strata contribute heavy sediment loads to seasonal rivers and streams like Radha Nadi, Sukha Nadi, Pipalthala Nadi, Saj Khola, Chulu Khola, Tatapani Khola, Bachhela Khola, Chunapur Khola and Bauji Khola during monsoons (Dahal and Timalsina, 2020). Groundwater extracted from shallow tube wells (20–60 feet depth) (ENPHO, 2022) serves as the primary drinking source for 68.6% of households (NSO, 2021), reflecting the region's reliance on aquifers within the Northern plain and Siwalik zones. Alternative water sources include piped systems (30.3%), dug wells (0.5%), natural spouts (0.2%), bottled water (0.2%), and rivers (0.2%) (NSO,

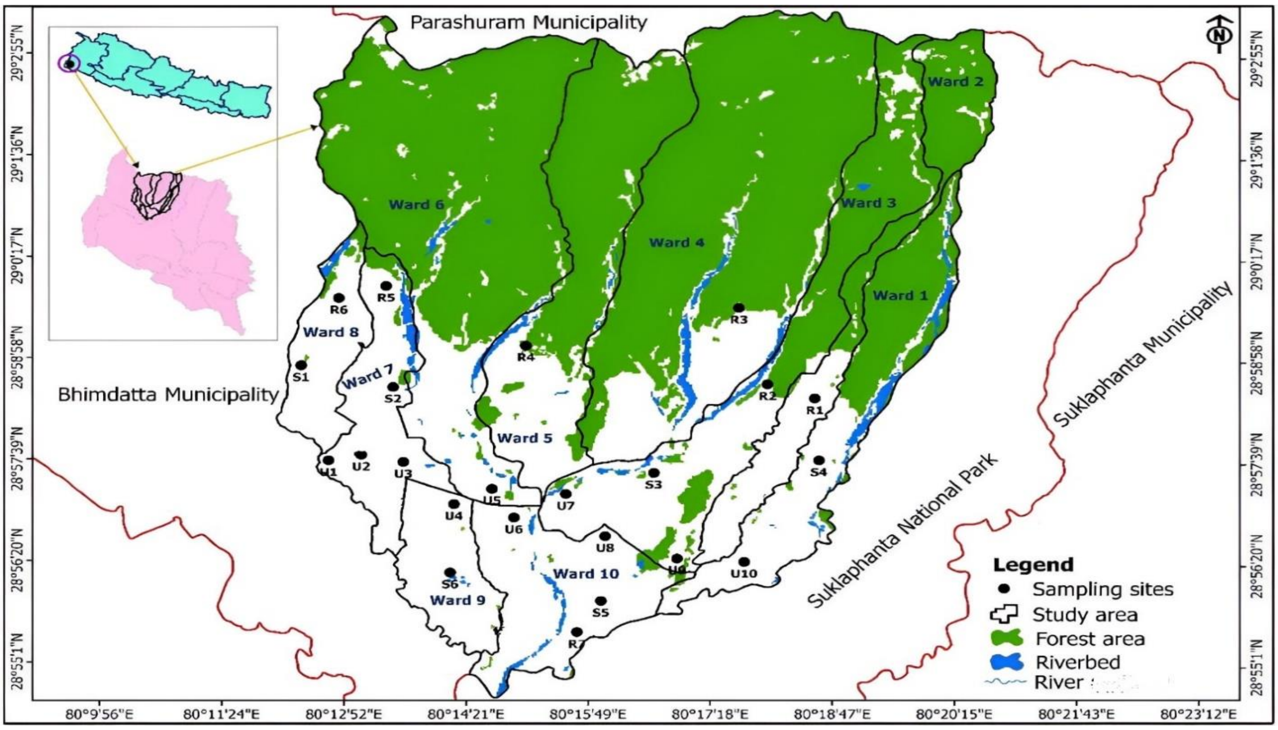

Figure 1. *Location Map showing: Nepal, Kanchanpur District, and the sampling sites within the study area (Bedkot Municipality)*

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2021), underscoring groundwater's critical role in municipal water security.

Study design and sampling technique

A cross-sectional study was conducted using stratified random sampling method (Krishna Kumar et al., 2015). The study area was stratified into urban, semi-urban, and rural areas based on population density and land-use patterns, as these factors critically influence groundwater quality (Ghosh et al., 2023; Nawaz et al., 2023; Ogarekpe et al., 2023). Urban areas, characterized by high-density settlements, extensive infrastructure, and industrial activities, were prioritized due to heightened risks of heavy metal contamination from anthropogenic sources (Bodrud-Doza et al., 2016; Nawaz et al., 2023). Rural zones, on the other hand, are typically low-density settlements where groundwater contamination often resultss from agricultural runoff, particularly nitrate and ammonium leaching (Adimalla and Qian, 2019; Bodrud-Doza et al., 2016). Semi-urban areas represent transitional zones with moderate population density and mixed land-use practices, including agriculture (Dahal and Timalsina, 2020). Shallow tube wells (≤ 60 feet in depth) were selected as sampling points, reflecting their dominance in the municipality's drinking water supply and documented susceptibility to arsenic and iron contamination in Nepal's plain region. Although statistical formulas could ideally be used to determine sample size, practical constraints—including limited time, budget, and accessibility—restricted the total number of samples to 23 (Fig. 1). This sample size is consistent with similar groundwater quality studies conducted across South Asia (Adimalla and Qian, 2019; Ghosh et al., 2023; Nawaz et al., 2023). Each tube well consisted of a long pipe drilled subsurface or deep aquifers, equipped with a hand pump for water extraction.

Sampling and analysis

The samples were collected from April 7 to 15, 2024, between 7:30 and 10:00 AM to ensure household members' availability, during the pre-monsoon (Kayastha, 2015). Water sampling utilized pre-cleaned high-density polyethylene (HDPE) bottles. Before collection, informed consent was obtained from household owners. To remove stale water, shallow TWs were pumped at full pressure for 2–3 minutes before sampling (Liu et al., 2020). Immediately after collection, in situ, measurements for pH, temperature (°C), electrical conductivity (EC, µS/cm), and total dissolved solids (TDS, mg/L) were conducted using a calibrated portable multi-parameter device (KC-600, China). To preserve water samples for As and Fe analysis, one bottle from each site was acidified with nitric acid (HNO_3) to achieve a pH < 2.0, while another bottle was left unacidified for additional analyses. All sample bottles were sealed airtight, labeled with unique identification codes, and geo-located using a GPS device, with data subsequently imported into ArcGIS to create a sampling location map (Fig 1). During transport, samples were stored in a cooler box at temperatures below 4°C and were refrigerated at 4°C upon arrival at the laboratory for further analysis. Unacidified samples were analyzed within 24 hours for turbidity (in NTU) using the Nephelometric method, nitrate (NO_3^-, in mg/L) and ammonium (NH_4^+, in mg/L), using UV-Vis Spectrophotometer (Peak In-struments C-7100, China), calcium (Ca^{2+}, in mg/L) and total hardness as $CaCO_3$ (TH, in mg/L) by EDTA titrimetric method. Subsequently, total iron (Fe, in mg/L) and total arsenic (As, in mg/L) were determined using an atomic absorption spectrophotometer (AAS) (Biobase BK-AA320N, China) were used. All sampling, preservation, and analytical procedures adhered to standard methodologies (American Public Health Association [APHA, 2012).

Quality control in the analysis

The portable multi-parameter device was calibrated for pH using three standard buffer solutions (pH 4.0, pH 7.0, and pH 10.0). The accuracy of the pH meter was verified after every three samples. For EC and TDS determination, the device was calibrated using standard solutions of 1,000 µS/cm for EC and 1,000 mg/L for TDS, with verification performed after every three measurements (Ghosh et al., 2023). Blank samples were analyzed to prevent contamination or interference during the analysis. For heavy metal analysis, blanks, internal standards, and spiked samples were used to ensure accuracy and precision. All chemicals and reagents used were of high analytical reagent grade. Water samples were diluted as needed to ensure concentrations fell within the instruments's detection range. Sampling bottles, laboratory equipment, and glassware were cleaned thoroughly with a 1+1 nitric acid (HNO_3) solution, rinsed with distilled water, and oven-dried before use (APHA, 2012). Fresh reagents were used to avoid chemical contamination. All samples were analyzed in triplicate, with the mean values of every sample reported (Aryal, 2024).

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Water Quality Index (WQI)

To compute the WQI, the previously mentioned 11 physicochemical parameters were used, and each parameter was assigned a weight (wi) according to its impact on primary health and its overall importance in drinking water quality. These weights range from 1 (least effect) to 5 (highest effect) (Ibrahim, 2019; Safo-Adu, 2022) as presented in Table 1. WQI can be calculated by the following Equations [1], [2] and [3] (Belew et al., 2024):

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \qquad [1]$$

$$q_i = \frac{C_i}{S_i} \times 100 \qquad [2]$$

$$WQI = \sum_{i=1}^{n} (W_i \times q_i) \qquad [3]$$

Where, n is the number of parameters, C_i is the concentration (mg/L) or value of each parameter in the groundwater sample, S_i is the World Health Organization standard (WHO, 2017) value for the respective parameter (Table 1). W_i is the relative weight of each parameter. q_i is the quality rating degree for a specific parameter (Belew et al., 2024). The computed WQI values were classified into five categories: excellent water (WQI < 50), good water (50 < WQI < 100), poor water (100.1 < WQI < 200), very poor water (200.1 < WQI < 300), and unsuitable for drinking water (WQI > 300) (Bodrud-Doza et al., 2016; Shaibur et al., 2024).

Human Health Risk Assessment (HHRA)

Risk assessment involves evaluating the likelihood of harmful health effects of a specific magnitude occurring over a defined period, based on the nature of the hazard and the level of exposure (USEPA, 2004). Previous studies, such as those by Adimalla and Qian (2019), Ghosh et al. (2023), and Nawaz et al. (2023), have investigated the health effects of exposure to pollutants through ingestion (drinking) of water. Similarly, this study assessed the ingestion of pollutants through water, focusing on chronic daily intake (CDI), hazard quotient (HQ), hazard index (HI), and carcinogenic risk (CR). The CDI (expressed in mg/kg/day) of heavy metals via ingestion of groundwater was calculated for both adults and children in the study area, following Equation [4] (Belew et al., 2024):

$$CDI_{ing} = \frac{C \times IR \times EF \times ED}{BW \times AT} \qquad [4]$$

where, 'C' represents the concentration of heavy metals in groundwater (mg/L), IR is the drinking water ingestion rate in L/day (2.2 L/day for adults and 1.0 L/day for children). The ED is the exposure duration (70 years for an adult and 10 years for a child), EF is the exposure frequency (365 days/year), BW is the average body weight (70 kg for an adult and 15 kg for children), and AT is the average time for non-carcinogenic expressed as AT (days) = 365 × ED) (Ghosh et al., 2023; Shaibur et al., 2024; USEPA, 2004). The HQ is computed as the ratio of CDI of heavy metal to the oral reference dose

Table 1
Weight (w_i), calculated relative weight (W_i), and WHO standards value for each physicochemical parameter

Parameters	Weight (w_i)	Relative weight (W_i)	WHO standard (WHO, 2017)
Temperature	1	0.025	20 - 30
pH	4	0.1	6.5 - 8.5
EC	4	0.1	1500
TDS	5	0.125	1000
Turbidity	2	0.05	5
Ca^{2+}	2	0.05	200
TH	3	0.075	500
NO_3^-	5	0.125	50
NH_4^+	5	0.125	1.5
Fe	4	0.1	0.3
As	5	0.125	0.01
	$\Sigma w_i = 40$	$\Sigma W_i = 1$	

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(RfD_{ing}) for the same heavy metal. The HQ of heavy metal through ingestion of water by the adults and children of the study area was calculated using Equation [5] (Belew et al., 2024):

$$HQ_{ing} = \frac{CDI_{ing}}{RfD_{ing}} \qquad [5]$$

Where, RfD_{ing} for Fe and As are 0.3 mg/kg/day and 0.0003 mg/kg/day, respectively (Shaibur et al., 2024). The HI is the total potential non-carcinogenic health risks caused by different heavy metals (As and Fe) present in water. It was computed for ingestion of water to adults and children of the study area using Equation [6] (Shaibur et al., 2024):

$$HI = \sum_{i=i}^{n} HQ_{ing} = HQ_{Fe} + HQ_{As} \qquad [6]$$

HQ value indicates no significant non-carcinogenic health impacts if HQ < 1, and considerable impacts if HQ > 1. HI < 1 denotes minimal or non-existent risk, while an HI > 1 indicates a high risk of adverse non-cancer health effects. Non-carcinogenic risk is classified into four categories based on HI values: negligible (< 0.1), low (≥ 0.1 < 1), medium (≥ 1 < 4), and high (≥ 4)(USEPA, 1999). The CR was anticipated as the incremental probability of individual cancer over a lifetime as the result of experiencing a prospective carcinogen and was computed by using Equation [7] (Bodrud-Doza et al., 2016; USEPA, 2004):

$$CR = CDI_{ing} \times CSF \qquad [7]$$

Where, CSF is the cancer slope factor (1.5 mg/kg/day for As) and As is a carcinogenic element (Shaibur et al., 2024). A risk value $< 10^{-6}$ represents no carcinogenic risk to health, while a risk value $> 1 \times 10^{-4}$ suggests a high risk of developing cancer. A risk value ranging from 1×10^{-6} to 1×10^{-4} signifies an acceptable risk to human health (Hu et al., 2012).

Data analysis

Descriptive statistics analysis, including maximum, minimum, mean, and standard deviations, was conducted. All data analyses were performed using Microsoft Excel 2013. Figure 2 illustrates a brief flowchart highlighting this study's conceptual framework.

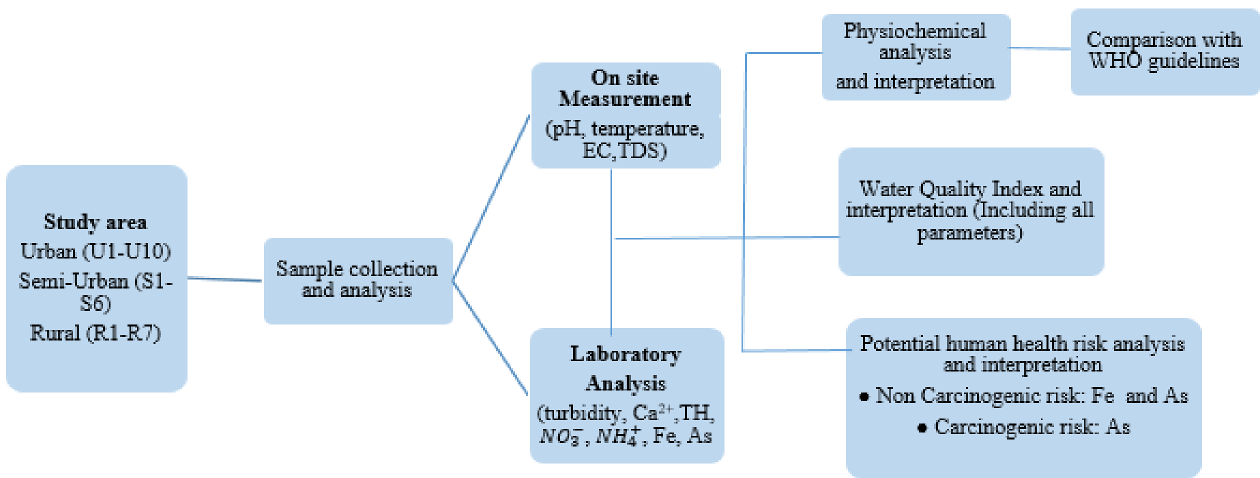

Figure 2. *A flow chart for the methodological design used in this study*

<u>Results and Discussion</u>

Physiochemical parameters

The analysis of physiochemical parameters provides insights into the nature, quality, and classification of shallow tube wells water (Howladar et al., 2018) across urban, semi-urban, and rural areas of Bedkot Municipality, Nepal. Table 2 presents the statistical summary (minimum, maximum, mean, and standard deviation) of these parameters, alongside a comparison with WHO drinking water standards. Water temperatures varied across urban (27.7–29.9°C; mean: 28.43 ± 0.64°C), semi-urban (29.4–33.5°C; mean: 31 ± 1.59°C), and rural areas (29–35.5°C; mean: 30.34 ± 2.29°C). Notably, 33.33% of semi-urban and 14.28% of rural samples exceeded the WHO permissible range (20–30°C), likely due to environmental conditions during sampling. The pH levels we-

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re slightly acidic, with urban (6.5–7.3; mean: 6.97 ± 0.23), semi-urban (6.68–7.2; mean: 6.92 ± 0.23), and rural (6.65–7.2; mean: 6.96 ± 0.18) samples falling within the WHO standard (6.5–8.5). This aligns with findings from Nepal's eastern plains (Mahato et al., 2018) and Bangladesh (Bodrud-Doza et al., 2016). Low pH may result from dissolved carbon dioxide (CO_2), organic acids, organic matter, or biogeochemical processes (Mahato et al., 2018). EC serves as a key indicator of water salinity, reflecting the concentration of dissolved ions, where higher EC values denote greater salinity and vice versa (Howladar et al., 2018). EC is classified into low (<1,500 µS/cm), medium (1,500–3,000 µS/cm), and high salt enrichment (>3,000 µS/cm) (Raheja et al., 2024). In the analyzed water samples, average EC values were 635 ± 147.8 µS/cm (urban), 606.17 ± 76.9 µS/cm (semi-urban), and 490 ± 114.65 µS/cm (rural), with respective ranges of 377–832, 478–677, and 372–717 µS/cm. These results, well below the WHO guideline of 1,500 µS/cm, confirm low salt enrichment across all areas. Similarly, TDS levels averaged 320 ± 72.79 mg/L (urban), 307.67 ± 38.1 mg/L (semi-urban), and 247 ± 55.03 mg/L (rural), with ranges of 187–416, 241–345, and 186–358 mg/L, respectively. All TDS values were within the WHO permissible limit of 1,000 mg/L, classifying the groundwater as freshwater (<1,500 mg/L) (WHO, 2011). The relatively low TDS concentrations suggest minimal dissolution of elements in the groundwater.

Both EC and TDS classifications confirm the freshwater nature of the samples. However, the high standard deviations in EC and TDS indicate variability in groundwater hydrochemistry, likely reflecting spatial differences in geological or anthropogenic influences (Ghosh et al., 2023). Urban areas exhibited the highest turbidity (8.45 ± 15.75 NTU, range: 0.01–44.7 NTU), followed by semi-urban zones (2.69 ± 5.69 NTU, range: 0.01–14.2 NTU), while rural areas showed the lowest values (0.12 ± 0.3 NTU, range: 0.01–0.8 NTU). Notably, 20% of urban samples (U2: 30.4 NTU, U8: 44.7 NTU) and 16.67% of semi-urban samples (S6: 14.2 NTU) exceeded the permissible limit of 5 NTU. Comparatively, this exceedance rate was lower than findings from previous studies in Nepal, such as Sudarshana et al. (2019) reporting 51.6% exceedance in Kathmandu and Mahato et al. (2018) documenting 44.57% in eastern plains, suggesting relatively better water quality in the current study area. However, urban and semi-urban regions still require mitigation efforts, as the milky appearance of groundwater in these areas likely stems from suspended solids, sewage, agricultural runoff, or organic matter, as identified by Mahato et al. (2018). TH in water, comprising temporary and permanent hardness, originates from dissolved calcium and magnesium salts, primarily bicarbonates (HCO_3^-), carbonates (CO_3^{2-}), sulfates (SO_4^{2-}), and chlorides (Cl^-) (APHA,

Table 2. *Comparison of physiochemical parameters of groundwater sample in four different areas with WHO drinking water standard*

Parameter	WHO (2017)	Urban area		Semi-urban area		Rural area	
		Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD
Temperature	20-30	27.7 - 29.9	28.43 ± 0.64	29.4-33.5	31 ± 1.59	29 - 35.5	30.34 ± 2.29
pH	6.5-8.5	6.5 - 7.3	6.97 ± 0.23	6.68-7.2	6.92 ± 0.23	6.65 - 7.2	6.96 ± 0.18
EC	1500	377- 832	635 ± 147.8	478 - 677	606.17 ± 76.9	372 - 717	490.4 ± 114.6
TDS	1000	187- 416	320 ± 72.79	241 - 345	307.67 ± 38.1	186 - 358	247.2 ± 55.02
Turbidity	5	0.01- 44.7	8.45 ± 15.75	0.01-14.2	2.69 ± 5.69	0.01 - 0.8	0.12 ± 0.29
Ca^{2+}	200	56-124	97.6 ± 23.66	58 -104	83 ± 19.95	40 - 118	62 ± 27.20
TH	500	150-336	272 ± 66.55	178-310	244.3 ± 59.46	94 - 300	157.4 ± 71.55
NO_3^-	50	0 - 11	1.7 ± 3.62	0-11	2.5 ± 4.32	0 - 1	0.14 ± 0.38
NH_4^+	1.5	0.4 -1.0	0.53 ± 0.18	0.26-1.2	0.73 ± 0.34	0.1-0.36	0.24 ± 0.11
Fe	0.3	0.01 - 3.4	0.541 ± 1.17	0.01-0.08	0.03 ± 0.03	0.01- 0.01	0.01 ± 0
As	0.01	0.01 – 0.03	0.013 ± 0.0	0.01- 0.01	0.01 ± 0	0.01- 0.01	0.01 ± 0

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2012; Ekawati and Widyaningrum, 2023). In this study, TH concentrations varied spatially, with urban areas exhibiting the highest levels (150–336 mg/L; mean: 272 ± 66.55 mg/L), followed by semi-urban (178–310 mg/L; mean: 244.3 ± 59.5 mg/L) and rural areas (94–300 mg/L; mean: 157 ± 71.55 mg/L). All values remained within the permissible limit of 500 mg/L (Table 2). Groundwater hardness is categorized as soft (<75 mg/L), moderately hard (75–150 mg/L), hard (150–300 mg/L), or very hard (>300 mg/L) (Ibrahim, 2019), suggesting urban and semi-urban samples predominantly fell into the "hard" and "very hard," categories, while rural areas showed "moderately hard" to "very hard“. All the parameters have mg/L unit, except pH, Temperature (°C), Turbidity (NTU), and EC (µS/cm); WHO: World Health Organization; SD: Standard Deviation. Comparative studies across Nepal's plains consistently highlight prevalent groundwater hardness issues. Bohara (2015) identified that 4% of drinking water samples in the Far Western plains exceeded permissible TH limits, highlighting hard to very hard. Similarly, Shrestha and Zhizhou (2024) noted that 4% of samples in the central plains surpassed TH standards, pointing hard. In the eastern plains, Mahato et al. (2018) found more severe conditions, with samples classified as moderately hard to very hard. Collectively, these studies underscore that groundwater in Nepal's plains is predominantly hard to very hard. Elevated TH levels (>80 mg/L), as noted by Ibrahim (2019), impair domestic use by causing soap coagulation and scale buildup in pipes, reducing water suitability. Ghimire et al. (2023) attribute this hardness to geological factors, particularly the dissolution of carbonate rocks (e.g., limestone, chalk) and calcium/magnesium-rich minerals, which release bicarbonates into groundwater. Ca^{2+} concentrations ranged from 56–124 mg/L, with urban areas showing the highest mean (97.6 ± 23.66 mg/L), followed by semi-urban (58– 104 mg/L, mean: 83 ± 19.95 mg/L) and rural (40– 118 mg/L, mean: 62 ± 27.20 mg/L) regions, all within the permissible limit (200 mg/L), indicating no calcium related hardness concerns. NO_3^- levels were low across urban, semi-urban, and rural areas ranging from 0–11 mg/L, 0–11 mg/L, and 0–1 mg/L, with a mean of 1.7 ± 3.62 mg/L, 2.5 ± 4.32 mg/L, and 0.14 ± 0.38 mg/L, respectively; NH_4^+ levels with ranged from 0.4–1 mg/L, 0.26– 1.2 mg/L, and 0.1– 0.36 mg/L, with mean of 0.53 ± 0.18 mg/L, 0.73 ± 0.34 mg/L, and 0.24 ± 0.11 mg/L, respectively. All values were within the permissible limits of 50 mg/L for NO_3^- and 1.5 mg/L for NH_4^+. These low NO_3^- and NH_4^+ values suggest minimal contamination from fertilizers, waste, animal waste, domestic effluent, or septic tank leakages, likely due to limited industrial activity and anthropogenic inputs (Adimalla and Qian, 2019, Shaibur et al., 2024). Urban water samples showed the highest Fe concentrations (0.01–3.4 mg/L; mean: 0.54 ± 1.17 mg/L), with 20% of samples exceeding the WHO limit of 0.3 mg/L. Semi-urban (0.01–0.08 mg/L; mean: 0.035 ± 0.03 mg/L) and rural areas (0.01–0.03 mg/L; mean: 0.01 ± 0.0 mg/L) exhibited much lower values. Notably, Fe levels here were far lower than those reported in Nepal (0.1 to 12.4 mg/L) (Sudarshana et al., 2019) and Ethiopia (0.7 to 29.13 mg/L) (Belew et al., 2024), indicating less severe contamination in the studied regions. Fe in groundwater primarily originates from natural weathering of iron-bearing minerals such as magnetite, hematite, pyrite, and limonite, which release Fe into aquifers over time (Shaibur et al., 2024). This process is accelerated by environmental factors like organic matter, dissolved oxygen (O_2), carbon dioxide (CO_2), and nitrate or sulfate under specific pH conditions (Islam and Mostafa, 2023). Anthropogenic activities, including urban waste disposal, agricultural runoff, and the use of iron-rich laundry and hygiene products, further contribute to Fe contamination (Belew et al., 2024). As were mostly within the permissible limit (0.01 mg/L), except in 20% of urban samples (U2 and U8: 0.03 mg/L). Urban areas showed As levels ranging from 0.01 to 0.03 mg/L (mean: 0.013 mg/L), while semi-urban and rural areas consistently recorded 0.01 mg/L. These values are notably lower than previous findings; for instance, studies in central Bangladesh reported 88.89% of urban and 71% of peri-urban groundwater samples exceeding safe As limits (Ghosh et al., 2023).

Water Quality Index

In this study, WQI for each sampling site was determined using the physiochemical parameters of the groundwater samples (Ghosh et al., 2023; Krishna Kumar et al., 2015), including pH, temperature, turbidity, EC, TDS, Ca^{2+}, TH, NO_3^-, NH_4^+, Fe, and As. In the WQI classification, water is defined as suitable for drinking if WQI < 300, while values exceeding this threshold are deemed unsuitable. The WQI results revealed notable variations in groundwater quality across urban, semi-urban, and rural areas, with urban areas being the most affected (Table 3). Urban areas exhibited the highest pollution levels, with 10% of samples classified as "poor" or "very poor" due to elevated turbidity, Fe, and As concentra-

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tions. Despite this, no samples exceeded the WQI unsuitability threshold (WQI > 300). Overall, 80% of urban, 90% of semi-urban, and 100% of rural samples fell within the "excellent" category (WQI < 50). These findings are consistent with Islam et al. (2017) in Sylhet, Bangladesh, who reported a similarly wide spectrum of groundwater quality, ranging from excellent to very poor, and Liu et al. (2020) in Yulin City, China, where the majority of samples were rated as excellent or good. Similarly, Shaibur et al. (2024) in Gopalganj, Bangladesh, reported 63% of samples as "excellent", though their study identified higher proportions of poor-quality water compared to this study. Moreover, studies in Bangladesh (Ghosh et al., 2023) and Ethiopia (Belew et al., 2024), reported that urban centers consi-stently showed degraded water quality compared to peri-urban and rural zones. A notable distinction in this study is the absence of "unsuitable" samples (WQI > 300), which contrasts sharply with findings from other regions. For instance, Nawaz et al. (2023) in Lahore, Pakistan, reported 89% of urban groundwater samples as undrinkable, while Bodrud-Doza et al. (2016) in central Bangladesh documented 1.67% of samples as unsuitable, alongside higher proportions of poor-quality water. The observed variations in WQI across urban, semi-urban, and rural zones likely stem from differences in aquifer depth, geological characteristics, and anthropogenic activities. Rural areas showed superior water quality, likely due to minimal industrial activity and limited fertilizer use (Adimalla and Qian, 2019; Shaibur et al., 2024). Conversely, urban degradation aligns with studies in Bangladesh (Ghosh et al., 2023) and Ethiopia (Belew et al., 2024), where dense populations, industrial effluent, and inadequate waste management exacerbate contamination.

Table 3. *WQI samples and status of the groundwater quality of the study area*

WQI	Water class	Urban area (n =10) No. of Samples (Samples)	% of Samples	Semi-urban (n = 6) No. of Samples (Samples)	% of Samples	Rural area (n = 7) No. of Samples (Samples)	% of Samples
< 50	Excellent	8 (U1, U3-U7, U9, U10)	80	5 (S1-S5)	90	7 (R1 - R7)	100
50 – 100	Good	0	0	1 (S6)	10	0	0
100.1 –200	Poor	1 (U2)	10	0	0	0	0
200.1 –300	Very poor	1 (U8)	10	0	0	0	0
> 300	Unsuitable	0	0	0	0	0	0

Human Health Risk Assessment

HHRA is crucial to evaluate the potential health risks associated with the long-term ingestion of Fe and As, as it is the most abundant heavy metals in the drinking water in plain region of Nepal. Tables 4, 5 and 6 display risk assessment results for children and adults through ingestion of water in the urban, semi-urban and rural areas of the municipality.

Non-carcinogenic health risk. In this study, the HQ value for Fe in urban, semi-urban, and rural regions for both children and adults was below the recommended threshold (HQ_{Fe} < 1), indicating that Fe does not pose a significant non-carcinogenic health risk. However, the HQ value for As exceeded the recommended level (HQ_{As} >1) in all regions for children, suggesting a potential non-carcinogenic health risk from As exposure. In urban areas, some adults also faced non-carcinogenic health risks due to As, as their HQ value surpassed the recommended level (HQ_{As} >1). In contrast, HQ values for As in semi-urban and rural areas remained below unity (HQ_{As} < 1), suggesting no significant non-carcinogenic health risks for adults in these areas (Tables 4, 5, and 6). The HI value represents the combined impact of multiple pollutants (e.g., As and Fe), raising concerns regarding non-carcinogenic health risks. In this study, the HI values for children in urban, semi-urban, and rural areas ranged from 1.55 to 6.31 (mean: 2.61 ± 1.88), 1.55 to 2.01 (mean: 1.74 ± 0.17), and 1.55 to 2.0 (mean: 1.75 ± 0.2), respectively. As these values exceeded the recommended threshold (HI > 1), children across all study areas were at risk of medium to high non-carcinogenic health impacts. In urban areas, some

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Table 4. *Risk assessment results for children and adults through ingestion of water in the urban areas*

Indicators	Children			Adults		
	Min	Max	Mean ± SD	Min	Max	Mean ± SD
HQ_{Fe}	0.002	0.75	0.12 ± 0.26	0.001	0.36	0.057 ± 0.12
HQ_{As}	1.55	5.56	2.49 ± 1.62	0.73	2.62	1.17 ± 0.76
HI	1.55	6.31	2.61 ± 1.88	0.73	2.98	1.23 ± 0.88
CR_{As}	7E-04	2.5E-03	1.1E-03 ± 7.2E-04	3.3E-04	1.2E-03	5.28E-04 ± 3.4E-04

Note: HI value for non-carcinogenic

Table 5. *Risk assessment results for children and adults through ingestion of water in the semi-urban areas*

Indicators	Children			Adults		
	Min	Max	Mean ± SD	Min	Max	Mean ± SD
HQ_{Fe}	0.002	0.018	0.008 ± 0.006	0.001	0.008	0.004 ± 0.003
HQ_{As}	1.55	2.0	1.74 ± 0.16	0.73	0.94	0.82 ± 0.08
HI	1.55	2.01	1.74 ± 0.17	0.73	0.94	0.82 ± 0.08
CR_{As}	7E-04	9E-04	7.8E-04 ± 7.5E-05	3.3E-04	4.2E-04	4.0E-04 ± 3.5-05

Table 6. *Risk assessment results for children and adults through ingestion of water in the rural areas*

Indicators	Children			Adults		
	Min	Max	Mean ± SD	Min	Max	Mean ± SD
HQ_{Fe}	0.002	0.007	0.003 ± 0.001	0.001	0.003	0.002 ± 0.0
HQ_{As}	1.55	2.0	1.75 ± 0.2	0.73	0.94	0.82 ± 0.1
HI	1.55	2.0	1.75 ± 0.2	0.73	0.94	0.82 ± 0.01
CR_{As}	7E-04	9E-04	7.8E-04 ± 9.0E-05	3.3E-04	4.2E-04	4.0E-04 ± 4.2E-05

children face high non-carcinogenic risks (HI ≥ 4), while most children in other areas were exposed to medium risks (HI ≥ 1 and < 4). For adults, the HI values in urban areas ranged from 0.73 to 2.98 (mean: 1.23 ± 0.88), indicating that some adults were also at medium risk, as their HI values were within the limit (HI ≥ 1 and < 4). However, in semi-urban and rural areas, HI values for adults ranged from 0.73 to 0.94 (mean: 0.82), suggesting that adults in these regions face low non-carcinogenic health risks (HI ≥ 0 and < 1). These findings are consistent with previous studies such as Nawaz et al. (2023) reported that both children and adults in urban areas of Lahore, Pakistan, experience significant non-carcinogenic health risks. Similarly, Ogarekpe et al. (2023) found that in the Calabar metropolis of Nigeria, children (mean HI = 82.4) were at greater non-carcinogenic health risks than adults (mean HI = 23.5).

Carcinogenic health risk. In the present study of urban areas, the mean CR values for children (1.1E-03) were higher than for adults (5.28E-04), indicating a greater likelihood of cancer risk among children (Table 4). It further quantifies the risk by estimating that approximately 11 children and 5.28 adults per 10,000 individuals might be affected. In contrast, Nawaz et al. (2023) reported that mean CR values for adults (4.60) were higher than for children (4.37E-03) in urban areas of Lahore, Pakistan. In this study, the mean CR values for children (7.8E-04) were also higher than for adults (4.0E-04), in both semi-urban and rural areas (Tables 5 and 6). These values indicate that, for every 10,000 people in both semi-urban and rural areas, about 7.8 children and 4.0 adults could face a cancer risk. The CR values for children and

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adults across the municipality exceed the recommended safe range of 1E-06 to 1E-04, suggesting an elevated risk of carcinogenic effects. However, this study does not specify the types of cancer associated with As exposure in the study area. Previous studies have documented arsenicosis-related health problems in neighboring country, Bangladesh, with common indicators of arsenicosis include melanosis (98.9%), keratosis (92.7%), hyperkeratosis (45.8%), depigmentation (29.2%), anorexia (26.0%), cough (25.0%), hepatomegaly (3.2%), and squamous-cell carcinoma (Ahmad et al., 1997). Similarly, in Nepal, arsenicosis-related conditions such as dermatosis (1.3%–5.1%), melanosis (95.6%), keratosis (57.8%), and leucomelanosis (3.3%) have been reported. Affected individuals also experience bronchitis, gastroenteritis, peripheral neuropathy, gangrene of limbs, precancerous skin lesions, and cancer (Thakur et al., 2010). Furthermore, Smith et al. (1992) estimated that consuming 1 L/day with an As concentration of 0.05 mg/L could result in a lifetime cancer mortality risk of 13 per 1,000 individuals, with potential cancers affecting the liver, lung, kidney, or bladder. Naturally occurring As contamination in groundwater has been documented in Bangladesh, India, Nepal, Pakistan, and several Southeast Asia countries (Nawaz et al., 2023). Thakur et al. (2010) reported that groundwater of Nepal's plain is primarily affected by geogenic sources, with arsenic mobilization resulting from the dissolution of arsenic-bearing rocks, sediments, and minerals, with hydrogeochemical analysis showing high bicarbonate and low sulfate concentrations, indicating As mobilization through organic matter oxidation and sulfate reduction, while organic matter and Fe oxides/oxyhydroxides act as As carriers, restricting its mobility likely due to bicarbonate-ion complexation with iron or manganese hydroxides, and elevated iron and manganese levels suggest As release through desorption from these minerals, driven by microbial activity and geochemical changes, with additional mechanisms such as sulfide oxidation, phosphate-induced ion displacement, microbial reduction, and transport through sandy aquifers. In the present study, children were found to be 2.12 times more su-sceptible to both non-carcinogenic and carcinogenic health risks than adults. Similarly, Ghosh et al. (2023) reported in Jashor, Bangladesh, that children were 2.33 times more vulnerable to both non-carcinogenic and carcinogenic risks compared to adults. The heightened susceptibility of children higher than adults reflects their lower body weight and higher ingestion rates, consistent with studies in Nigeria (Ogarekpe et al., 2023).

Conclusions

This study assessed shallow tube wells' water quality and associated health risks in Bedkot Municipality, Nepal, where 68.6% of households rely on drinking water. The Water Quality Index (WQI) classified 80% of urban, 90% of semi-urban, and 100% of rural groundwater samples as "excellent" (WQI < 50), with no samples deemed unsuitable (WQI>300). However, significant health risks persist despite favorable WQI ratings. In urban areas, 20% of the samples exceeded WHO guideline values for arsenic (As) and iron (Fe), while turbidity surpassed permissible limits in 20% of urban and 16.67% of semi-urban samples. Total hardness (TH) ranged from "hard" to "very hard" in urban/semi-urban zones and "moderately hard" to "very hard" in rural areas. Overall, the shallow groundwater was identified as freshwater with slightly acidic characteristics in the region. Human Health Risk Assessment (HHRA) revealed alarming non-carcinogenic risks for children across all regions (HI: 1.5–6.31), with some urban adults also facing risks (HI: 0.73–2.98). Carcinogenic risks from As ingestion exceeded acceptable thresholds (1×10^{-6}–1×10^{-4}) for children (7×10^{-4}–2.5×10^{-3}) and adults (3.3×10^{-4}–1.2×10^{-3}), indicating potential long-term cancer risks. Children were 2.12 times more vulnerable to both risks than adults. These findings necessitate urgent policy and practical interventions to safeguards public health. Key recommendations include:

- implement routine shallow tube wells water surveillance, focusing on As and Fe in the region, and enforce WHO standards (WHO, 2017);
- deploy low-cost arsenic removal technologies in high-risk areas and promote deeper aquifer use to reduce reliance on shallow contaminated wells (Ghosh et al., 2023);
- prioritize school-based education on As health risks (e.g., melanosis, cancers) and safe water practices, given children's heightened vulnerability.

Limitations and future directions: Although this study offers critical insights, its single-season sampling and exclusion of microbiological parameters (e.g., E. coli) and other heavy metals (e.g., Cu, Zn, Mn) may underestimate the holistic groundwater quality and its associated health risks. Seasonal fluctuations in groundwater recharge, particularly during the monsoon season, warrant investigation. Furthermore, logistical constraints limited the sample size (n=23) and spatial coverage, potentially affecting the generalizability of

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findings across deeper aquifers or broader geographical regions.

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