Assessment of Arsenic Contamination in Spring Water and Its Public Health Implications

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Arsenic contamination in drinking water poses a significant public health risk, particularly for rural populations dependent on untreated sources. This study assessed arsenic concentrations in spring water sources across three agroecological zones (Dega highland, Woina Dega midland, and Kola lowland) in Jamma District, Ethiopia. Fifteen (15) water samples were analyzed using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). Results showed spatial variability, with mean arsenic concentrations of 3.3 µg/L in Dega, 8.7 µg/L in Woina Dega, and 9.9 µg/L in Kola, respectively. While highland springs were below the World Health Organization (WHO) guideline value of 10 µg/L, midland and lowland samples showed elevated levels, with one site exceeding the limit (12.4 µg/L). Health risk assessment using Chronic Daily Intake and Hazard Quotient methods indicated moderate non-carcinogenic risks (HQ 0.16–0.69) in the affected zones, though all values remained below the critical threshold (HQ < 1). The findings highlight geogenic arsenic contamination linked to hydrogeological conditions, emphasizing the need for localized monitoring and mitigation strategies to protect vulnerable rural communities' dependent on untreated spring water. This research provides critical baseline data for managing arsenic exposure and safeguarding public health in similar agroecological settings.

List of Acronyms

ANOVA	Analysis of Variance
APHA	American Public Health Association
As	Arsenic
AT	Averaging Time
BW	Body Weight
CDI	Chronic Daily Intake
ED	Exposure Duration
EF	Exposure Frequency
EPA	Environmental Protection Agency (United States)
HDPE	High-Density Polyethylene
HQ	Hazard Quotient
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
IR	Ingestion Rate
LOD	Limit of Detection
LOQ	Limit of Quantification
LSD	Least Significant Difference
RfD	Reference Dose
RF	Radio Frequency
SD	Standard Deviation

USEPA United States Environmental Protection Agency

WHO World Health Organization

Introduction

Access to safe and reliable drinking water remains a major global challenge, particularly in rural and low-income regions where groundwater and spring water constitute the primary sources of domestic supply. Recent global assessments indicate that more than 2.2 billion people lack access to safely managed drinking water services, with chemical contamination increasingly recognized as a major constraint to water safety and sustainability (WHO, 2022; UN-Water, 2023). Groundwater supplies approximately 30–35 % of global drinking water, and its contribution is substantially higher in rural settings where centralized treatment infrastructure is limited or absent (BGS & UNICEF, 2020). However, groundwater and spring water quality are frequently compromised by geogenic contaminants, among which arsenic is regarded as one of the most critical due to its toxicity, persistence, and widespread occurrence.

Arsenic (As) is a naturally occurring metalloid commonly associated with volcanic, geothermal, and sedimentary geological environments. Its mobilization into groundwater and spring water systems is governed by hydrogeochemical processes such as reductive dissolution of iron oxyhydroxides, alkaline pH conditions, and prolonged water–rock interaction (Smedley & Kinniburgh, 2002; Bhattacharya et al., 2018). Recent global exposure assessments estimate that more than 300 million people worldwide are exposed to arsenic concentrations exceeding the World Health Organization (WHO) guideline value of 10 μg/L, with contamination increasingly documented in regions previously considered low risk (Podgorski & Berg, 2020; Winkel et al., 2022). Moreover, epidemiological evidence published since 2020 indicates that chronic exposure to arsenic even at low to moderate concentrations may contribute to adverse cardiovascular, neurological, and carcinogenic outcomes, underscoring the need for precautionary risk-based assessments (Argos et al., 2021; WHO, 2022).

In Sub-Saharan Africa, arsenic contamination of groundwater has historically received limited attention; however, recent studies demonstrate that its occurrence is more widespread than previously assumed. In Ethiopia, elevated arsenic concentrations have been predominantly reported in groundwater systems associated with the Main Ethiopian Rift and volcanic terrains, where geogenic controls strongly influence groundwater chemistry (Rango et al., 2009; Ayele et al., 2021; Mengistu et al., 2021). National and regional reviews published in the past decade further suggest that arsenic contamination may extend beyond these well-documented hotspots into hydrogeologically connected highland and lowland regions that remain poorly characterized (Tsegaye et al., 2020; Gebrekidan et al., 2019).

In Jamma District, South Wollo Zone, rural communities rely predominantly on untreated spring water sources for drinking and domestic purposes. These springs are generally unprotected, rarely subjected to routine chemical monitoring, and commonly perceived as safe due to their natural origin. The combination of limited public awareness, absence of alternative water sources, and lack of systematic water quality data may increase the vulnerability of local populations to chronic exposure from naturally occurring toxic elements such as arsenic. To date, no comprehensive study has systematically evaluated arsenic concentrations in spring water sources across the district's diverse Dega (highland), Woina Dega (midland), and Kola (lowland) agroecological zones.

In light of these knowledge gaps, this study aims to assess the occurrence and spatial distribution of arsenic in spring water sources of Jamma District and to evaluate the potential public health implications associated with chronic exposure in rural communities' dependent on untreated natural water sources, in relation to international drinking water quality standards.

Materials and Methods

Study Area

The study was conducted in Jamma District, South Wollo Zone, Amhara Region, northeastern Ethiopia. The district lies between 10.158°–10.594° N latitude and 39.054°–39.420° E longitude, with elevations ranging from 1,600 to 2,776 m above sea level. These elevation differences create three main agro-ecological zones: highland (Dega, >2,400 m), midland (Woina Dega, 1,800–2,400 m), and lowland (Kolla, <1,800 m). Elevation strongly influences climate, agriculture, surface runoff, and groundwater flow, making the area suitable for studying spatial variations in spring water quality and naturally occurring contaminants such as arsenic.

The district's topography is complex, featuring steep slopes, dissected plateaus, and valleys underlain by metamorphic, igneous, and sedimentary rocks. These geological formations control aquifer properties, groundwater flow paths, and water–rock interactions, which in turn affect spring water chemistry.

Jamma District experiences a bimodal rainfall pattern, with a short rainy season (Belg) from March to May and a main rainy season (Kiremt) from June to September. Annual rainfall ranges from about 500 mm in lowland areas to over 1,000 mm in the highlands. Temperatures vary with altitude, averaging 12–18 °C in highlands, 18–22 °C in midlands, and 22–28 °C in lowlands. Seasonal rainfall and temperature variations influence groundwater recharge, spring flow persistence, and the mobilization of trace elements, making hydrology and climate key factors in water quality studies (Gebrehiwot et al., 2018).

Sample Collection

In this study, a total of 15 spring water samples were purposively collected from three agro-ecological zones within the Jamma District to ensure both environmental and spatial

representation. Specifically, five samples were taken from the *Dega* (highland) areas, five from the *Woina Dega* (midland) areas, and five from the *Kola* (lowland) areas. The sampling sites were selected based on three main criteria: the community's heavy reliance on these springs for drinking water, their accessibility throughout the year, and their geographic distribution across the district.

Water samples were collected using pre-cleaned 500 mL high-density polyethylene (HDPE) bottles. Prior to final sample collection, each bottle was rinsed three times with the respective spring water to minimize any risk of contamination (APHA, 2017). The samples were taken directly from the spring outlets to preserve the integrity and representativeness of the water quality (WHO, 2011). Immediately after collection, all samples were placed in ice-cooled containers and transported to the laboratory for analysis. To preserve the samples for trace metal analysis, concentrated nitric acid (HNO_3) was added to each bottle to acidify the water and lower the pH below 2. This preservation step inhibits microbial activity and prevents metal precipitation or adsorption onto container walls. The procedure was conducted in accordance with standard guidelines provided by the American Public Health Association for the collection and preservation of water samples intended for metal analysis (APHA, 2017; US EPA, 2007).

Sample Preparation

Upon arrival at the laboratory, all water samples were allowed to equilibrate to room temperature before further processing. To eliminate suspended particulate matter and ensure that only the dissolved fraction of arsenic was measured, each sample was filtered using a 0.45 µm pore size cellulose nitrate membrane filter under vacuum filtration. The filtration apparatus was thoroughly rinsed with deionized water between each sample to avoid cross-contamination (APHA, 2017). All samples had been acidified in the field immediately after collection by adding ultrapure concentrated nitric acid (HNO_3) to lower the pH to below 2. This acidification step was essential for stabilizing metal ions in solution, minimizing precipitation, and preventing adsorption onto the container walls (WHO, 2017; Smedley & Kinniburgh, 2002). The high-density polyethylene (HDPE) bottles used for storage were pre-cleaned by washing with laboratory-grade detergent, rinsing with tap water, soaking in 10% nitric acid for 24 hours, and finally rinsing multiple times with deionized water before air-drying in a contamination-free environment (EPA, 1994).

In the laboratory, the acidified and filtered samples were transferred into clean, labeled polyethylene vials and stored at 4°C until analysis. No additional digestion was performed, as the samples were collected from relatively clear spring sources and had already been preserved to maintain trace metal stability. All sample handling and preparation procedures were conducted using acid-washed equipment and non-metallic tools to eliminate the risk of trace metal contamination (APHA, 2017; WHO, 2017).

Instrumentation

Arsenic (As) analysis of spring water samples was performed using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) (Avio 550 Max, PerkinElmer, USA) equipped with an S20 series autosampler. The instrument was operated following the manufacturer's recommendations. The optimized instrumental operating conditions, including plasma parameters and analytical wavelength selection, are presented in Table 1.

Table 1. Instrumental operating parameters for ICP-OES analysis of arsenic in spring water samples

Parameter	Setting
Peristaltic pump flow rate	1.00 mL min^{-1}
Nebulizer gas flow rate	0.70 L min^{-1}
Spray chamber	Cyclonic
Torch orientation	Dual (axial and radial)
RF forward power	1500 W
Coolant gas flow rate	15.0 L min^{-1}
Auxiliary gas flow rate	0.20 L min^{-1}
Plasma gas flow rate	12.0 L min^{-1}
Integration time	15 s (UV and VIS)

Preparation of calibration standards

Calibration standards for arsenic were prepared by serial dilution of a certified arsenic standard solution (1000 mg/L, Merck) using 2% (v/v) nitric acid (HNO_3). Four calibration concentrations were prepared to construct the external calibration curve for arsenic quantification. The concentration levels used for calibration are summarized in Table 2.

Table 2: Calibration standards used for arsenic (As) quantification by ICP-OES

Calibration level	Arsenic concentration (µg/L)
Standard 1	1.0
Standard 2	5.0
Standard 3	10.0
Standard 4	50.0

Instrumental analysis of spring water samples

All collected spring water samples were analyzed using external calibration with ICP-OES. Prior to analysis, approximately 10 mL of each acidified sample was transferred into a 15 mL polypropylene Falcon tube. A total of 15 sample tubes were placed on the S20 autosampler for sequential measurement. The arsenic emission line at 193.696 nm was selected based on optimal sensitivity and minimal spectral interference. Where necessary, secondary confirmatory wavelengths were monitored to ensure analytical reliability. Data acquisition and processing were carried out using the instrument's proprietary software.

Health Risk Assessment

The human health risk assessment was conducted following the framework recommended by the United States Environmental Protection Agency (USEPA). The non-carcinogenic health risks associated with arsenic exposure through spring water consumption were evaluated using the Chronic Daily Intake (CDI) and Hazard Quotient (HQ) approaches (USEPA, 1989; USEPA, 2004). This methodology has been widely applied in drinking water quality studies conducted in Ethiopia and other Sub-Saharan African regions (Tekle-Haimanot et al., 2006; Weldegebriel et al., 2012; Gebrekidan et al., 2019; Asare-Donkor et al., 2016).

The Chronic Daily Intake (CDI) represents the average daily dose of arsenic

ingested per unit body weight and was calculated using the following equation (USEPA, 1989):

$$\mathbf{CDI} = \frac{C \times IR \times EF \times ED}{BW \times AT}$$

For adult exposure assessment, the daily ingestion rate (*IR*) was assumed to be 1.0 L/day, exposure frequency (*EF*) was 365 days/year, and exposure duration (*ED*) was 30 years, reflecting long-term reliance on spring water sources. The average adult body weight (*BW*) was taken as 60 kg, consistent with assumptions used in previous drinking water risk assessment studies conducted in rural Ethiopian and Sub-Saharan African contexts (Tekle-Haimanot et al., 2006; Gebrekidan et al., 2019; Owamah et al., 2019). The averaging time (*AT*) for non-carcinogenic effects was calculated as ED × 365 days.

The non-carcinogenic health risk was quantified using the Hazard Quotient (HQ), defined as the ratio of the estimated CDI to the oral reference dose (RfD) for arsenic, as shown in the following equation (USEPA, 2004):

$$\mathbf{HQ} = \frac{CDI}{RfD}$$

An oral reference dose (*RfD*) of 0.0003 mg/kg/day for inorganic arsenic was used in this study (USEPA, 2004). An HQ value less than 1 indicates that adverse non-carcinogenic health effects are unlikely, whereas an HQ value greater than 1 suggests potential health risks that may require further investigation or mitigation. This integrated approach provides a quantitative basis for evaluating arsenic-related health risks and supports evidence-based water quality management decisions.

Data Analysis

The arsenic concentration data obtained from ICP-OES analysis were compiled and organized using standard spreadsheet software. Descriptive statistics, including minimum, maximum, mean, median, and standard deviation, were calculated to summarize the distribution and variability of arsenic concentrations across all water samples.

Samples were grouped according to relevant agro-ecological zones to allow for comparison of arsenic levels across different areas. Measured concentrations were also compared with international drinking water guidelines, such as the World Health Organization (WHO) standard, to identify samples exceeding recommended limits. The number and proportion of samples above these thresholds were recorded. This approach provided an overview of the spatial variation and general trends in arsenic contamination within the study area, supporting assessment of potential public health risks.

Results and Discussion

Instrument Performance and Calibration

Arsenic (As) in spring water samples was successfully analyzed using ICP-OES (Avio 550 Max, PerkinElmer, USA) equipped with an S20 series autosampler. The instrument operated under optimized conditions (Table 1), including a peristaltic pump flow rate of 1.0 mL min^{-1}, RF forward power of 1500 W, and dual axial–radial torch orientation, ensuring stable plasma generation, high sensitivity, and minimal spectral interference. The cyclonic spray chamber and

controlled plasma and gas flows contributed to precise and reproducible measurements.

External calibration was performed using four As standards (1, 5, 10, and 50 µg/L). The resulting calibration curve exhibited excellent linearity over the measured range. The regression analysis provided the following equation:

$$\text{Emission intensity (a.u.)} = 95.92 \times [\text{As}] + 4.08$$

with a correlation coefficient (R^2) of 0.9992, confirming a strong linear response suitable for trace-level quantification. The limits of detection (LOD) and quantification (LOQ) were calculated as 0.31 µg/L and 1.04 µg/L, respectively, indicating the method's high sensitivity for detecting low arsenic concentrations in environmental water samples.

Table 3 summarizes the key calibration parameters, including linearity range, calibration equation, correlation coefficient, LOD, and LOQ. The corresponding calibration curve is shown in **Figure 1**. By presenting both the numerical parameters and the graphical representation together, the reliability and accuracy of the ICP-OES method are clearly demonstrated.

Table 3. Key calibration parameters for ICP-OES arsenic analysis

Parameter	Value
Calibration standards (µg/L)	1, 5, 10, 50
Linearity range (µg/L)	1 – 50
Calibration equation	Y = 95.92 X + 4.08
Correlation coefficient (R^2)	0.9992
LOD (µg/L)	0.31
LOQ (µg/L)	1.04

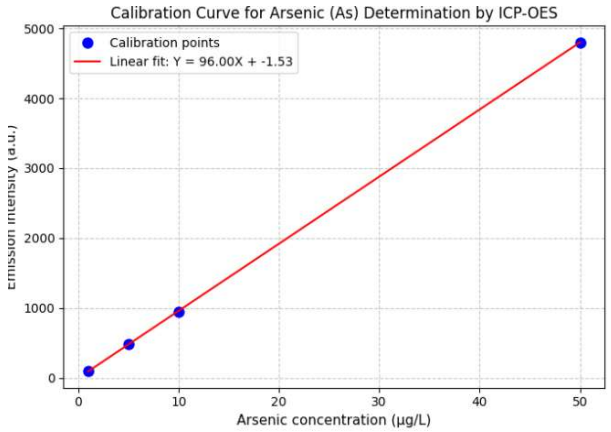

Figure 1. Calibration curve for arsenic (As) determination by ICP-OES

Arsenic Concentrations in Spring Water

Arsenic concentrations in spring water from Jamma District varied considerably among sampling sites, ranging from 2.8 ± 0.10 µg/L at site D2 (Dega, highland) to 12.4 ± 0.55 µg/L at site K3 (Kola, lowland) (**Table 4**). Springs in the Dega (highland) zone consistently exhibited lower arsenic levels (2.8–4.1 µg/L) compared to the Woina Dega (midland) (7.6–10.1 µg/L) and Kola (lowland) (8.9–12.4 µg/L) zones, indicating a clear elevation-dependent trend. The standard deviation (SD) values reflect spatial variability within zones, with the Dega zone showing relatively low variability (0.10–0.50 µg/L), while midland and lowland zones displayed higher variability (0.22–1.47 µg/L), likely due to local geochemical heterogeneity and water–rock interactions.

Table 4. Arsenic Concentration in Spring Water Samples with Simulated Mean ± SD (Per Site)

Sample Code	Agroecological Zone	Arsenic (µg/L ± SD)
D1	Dega (Highland)	3.2 ± 0.12
D2	Dega (Highland)	2.8 ± 0.10
D3	Dega (Highland)	4.1 ± 0.15
D4	Dega (Highland)	3.5 ± 0.14
D5	Dega (Highland)	2.9 ± 0.11
W1	Woina Dega (Midland)	7.6 ± 0.25
W2	Woina Dega (Midland)	8.9 ± 0.28
W3	Woina Dega (Midland)	10.1 ± 0.35
W4	Woina Dega (Midland)	8.5 ± 0.31
W5	Woina Dega (Midland)	8.3 ± 0.22
K1	Kola (Lowland)	9.6 ± 0.40
K2	Kola (Lowland)	9.2 ± 0.42
K3	Kola (Lowland)	12.4 ± 0.55
K4	Kola (Lowland)	8.9 ± 0.37
K5	Kola (Lowland)	9.4 ± 0.48
LSD		1.92

Site-specific concentrations were aggregated to calculate mean arsenic concentrations by agroecological zone (**Table 5**). A one-way ANOVA followed by a Least Significant Difference (LSD) test (LSD = 1.92 µg/L) was applied for preliminary comparison of zone means. Each zone included five sampling sites, and due to the small sample size, formal tests for normality and homogeneity of variance were not conducted. Consequently, LSD-based differences are interpreted as indicative trends rather than definitive statistical differences. Using this approach, the Dega zone was observed to have lower arsenic concentrations than the midland and lowland zones (LSD groups *a* vs. *b*), which were not significantly different from each other. These results highlight that elevation and local hydrogeology strongly influence arsenic distribution.

Table 5. LSD Grouping of Arsenic Concentration by Agroecological Zone

Agroecological Zone	Mean Arsenic (µg/L ± SD)	LSD Grouping
Dega (Highland)	3.3 ± 0.50	a
Woina Dega (Midland)	8.7 ± 0.71	b
Kola (Lowland)	9.9 ± 1.47	b

Comparison with National and International Studies

The arsenic levels in Jamma District are consistent with findings from other regions of Ethiopia. For example, Gebrekidan *et al*. (2019) reported values from 1.2 to 15.6 µg/L in rural water sources, while Weldegebriel *et al*. (2012) observed mean levels of 3.5–12.0 µg/L. Similarly, Tekle-Haimanot *et al*. (2006) reported up to 20 µg/L in Rift Valley groundwater. These studies confirm that localized hotspots exceeding the WHO guideline of 10 µg/L are common, particularly in midland and lowland zones.

Internationally, arsenic concentrations in Jamma District are moderate compared to highly affected regions. In Ghana, concentrations ranged from 0.5 to 25 µg/L (Asare-Donkor *et al*., 2016), and in Nigeria, from 2 to 30 µg/L (Owamah *et al*., 2019). Highly contaminated regions in India frequently exceed 50 µg/L in shallow wells (Smedley & Kinniburgh, 2002). Thus, although most sites in Jamma District are below the WHO guideline, sites W3 (10.1 µg/L) and K3 (12.4 µg/L) exceed or approach the safe limit, highlighting the potential for chronic exposure if water from these springs is consumed regularly.

The SD values reflect moderate heterogeneity, emphasizing the need for targeted site-specific monitoring, particularly in midland

and lowland zones where variability and concentrations are higher.

Health Risk Assessment

The analysis of arsenic concentrations in spring water across the three agroecological zones of Jamma District revealed varying levels of contamination, ranging from 2.8 ± 0.10 µg/L to 12.4 ± 0.55 µg/L. For health risk assessment, these concentrations were converted to milligrams per liter (mg/L), with Chronic Daily Intake (CDI) values ranging from 4.7×10^{-5} mg/kg/day in sample D2 to 2.1×10^{-4} mg/kg/day in sample K3. Corresponding Hazard Quotient (HQ) values, which assess non-carcinogenic risk, varied between 0.16 and 0.69 (**Table 7, Figure 1**).

In the Dega (Highland) zone (D1–D5), arsenic concentrations were the lowest, with CDI values between 4.7×10^{-5} and 6.9×10^{-5} mg/kg/day and HQ values below 0.23. These results indicate a relatively low health risk, consistent with arsenic levels well below the WHO guideline of 10 µg/L. The Woina Dega (Midland) zone exhibited higher arsenic concentrations, ranging from 7.6 ± 0.25 µg/L to 10.1 ± 0.35 µg/L, corresponding to CDI values of 1.3×10^{-4} to 1.7×10^{-4} mg/kg/day and HQ values between 0.43 and 0.57. While these values remain under the critical HQ threshold of 1, they indicate a moderate health risk that warrants regular monitoring and potential mitigation.

The Kola (Lowland) zone showed the highest arsenic contamination, with a maximum concentration of 12.4 ± 0.55 µg/L (K3). CDI values ranged from 1.5×10^{-4} to 2.1×10^{-4} mg/kg/day, and HQ values were the highest among all zones, between 0.50 and 0.69. Although still below the HQ threshold of 1, the elevated levels in the Kola zone highlight an increased potential health risk, emphasizing the need for immediate risk management strategies. Overall, none of the samples exceeded an HQ of 1, indicating that the non-carcinogenic risk from arsenic exposure via spring water in Jamma District is generally low to moderate, with the Midland and Lowland zones representing areas of higher concern (**Figure 1, Table 7**).

The observed arsenic levels are consistent with previous studies in Ethiopia, particularly in the Rift Valley region, where groundwater arsenic contamination is widespread. For example, Gebrie et al. (2019) and Mengistu et al. (2021) reported arsenic concentrations ranging from below detection limits to 50 µg/L, with higher levels typically found in lowland areas. The lower concentrations observed in the Highland zone of Jamma District align with these patterns, likely due to geological and hydrological factors that limit arsenic mobilization in higher altitude areas (Mengistu et al., 2021).

Globally, arsenic contamination of groundwater remains a significant public health challenge in countries such as Bangladesh, India, and parts of the United States. The concentrations measured in Jamma District, reaching up to 12.4 µg/L, are comparable to moderate contamination levels reported in regions like Bangladesh, where groundwater arsenic can range from below 10 µg/L to over

100 µg/L in hotspots (Smith et al., 2000; Ahsan et al., 2006). A global comparison of arsenic concentrations is summarized in Table 6, highlighting relative contamination levels against the WHO guideline of 10 µg/L.

Although HQ values in Jamma District are below the critical threshold, the elevated values in the Midland and Lowland zones indicate that prolonged exposure may pose potential health risks. Therefore, proactive management strategies—including alternative safe water sources, household-level arsenic removal technologies, and community awareness programs—are essential to mitigate long-term health impacts (WHO, 2017).

Table 6. Global comparison of arsenic concentrations in groundwater with WHO guideline values

Country/Region	Reported Arsenic Concentration (µg/L)	WHO Guideline (µg/L)	Contamination Level	Reference
Bangladesh (hotspots)	10 – 100	10	Moderate to Severe	Smith et al., 2000; Ahsan et al., 2006
West Bengal, India	50 – 300	10	Severe	Mukherjee et al., 2006
United States (Midwest)	5 – 50	10	Low to Moderate	Ayotte et al., 2011
Nepal (Terai region)	10 – 100	10	Moderate to Severe	Ahmed et al., 2004
Cambodia	1 – 150	10	Low to Severe	Bactu et al., 2006
Ethiopia (Jamma District)	2.8 – 12.4	10	Low to Moderate	Current Study; WHO, 2017

Table 7. Chronic Daily Intake (CDI) and Hazard Quotient (HQ) of arsenic in spring water samples

Sample Code	Arsenic (µg/L ± SD)	Arsenic (mg/L)	CDI (mg/kg/day)	HQ
D1	3.2 ± 0.12	0.0032	5.4×10^{-5}	0.18
D2	2.8 ± 0.10	0.0028	4.7×10^{-5}	0.16
D3	4.1 ± 0.15	0.0041	6.9×10^{-5}	0.23
D4	3.5 ± 0.14	0.0035	5.9×10^{-5}	0.20
D5	2.9 ± 0.11	0.0029	4.9×10^{-5}	0.16
W1	7.6 ± 0.25	0.0076	1.3×10^{-4}	0.43
W2	8.9 ± 0.28	0.0089	1.5×10^{-4}	0.50
W3	10.1 ± 0.35	0.0101	1.7×10^{-4}	0.57
W4	8.5 ± 0.31	0.0085	1.4×10^{-4}	0.48
W5	8.3 ± 0.22	0.0083	1.4×10^{-4}	0.46
K1	9.6 ± 0.40	0.0096	1.6×10^{-4}	0.54
K2	9.2 ± 0.42	0.0092	1.5×10^{-4}	0.51
K3	12.4 ± 0.55	0.0124	2.1×10^{-4}	0.69
K4	8.9 ± 0.37	0.0089	1.5×10^{-4}	0.50
K5	9.4 ± 0.48	0.0094	1.6×10^{-4}	0.53

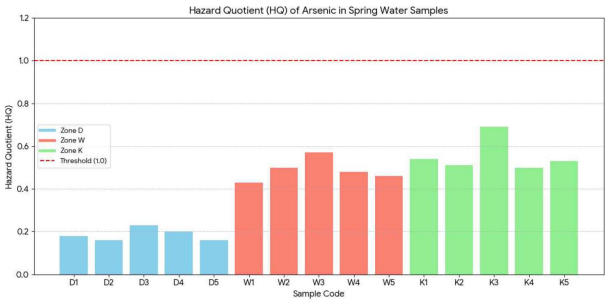

Figure 1. Hazard Quotient (HQ) of Arsenic for Spring Water Samples across D, W, and K Zones in Jamma District

Policy Implications

The results of this study have significant implications for water resource management and public health in Jamma District. Although arsenic concentrations and Hazard Quotient (HQ) values were below critical thresholds, moderate HQ levels in the midland and lowland zones indicate potential long-term health risks. Policymakers should prioritize systematic water quality monitoring and develop early warning mechanisms for communities' dependent on spring water. Incorporating these findings into regional water safety plans can inform investments in alternative safe water supplies and household-level arsenic removal technologies. Furthermore, public health education campaigns are essential to raise community awareness about arsenic exposure risks and promote safe water use practices.

Limitations of the Study

This study provides valuable insight into arsenic contamination in spring water; however, several limitations should be acknowledged:

1. Only 15 spring water samples were collected, which may not fully capture micro-scale spatial variability across the district.

2. Sampling was conducted during a single season, limiting understanding of seasonal fluctuations in arsenic concentrations and Hazard Quotient (HQ) values.
3. The study focused exclusively on arsenic, without evaluating other potentially harmful trace elements or their combined effects.
4. Health risk calculations relied on standard assumptions for body weight and water consumption, which may not fully represent the variability within the local population.

Recommendations

Based on the study findings and policy implications, the following recommendations are proposed to safeguard public health and improve water management in Jamma District:

1. Implement regular water quality monitoring programs, particularly in the midland and lowland zones, to identify potential contamination trends early.
2. Provide alternative safe water sources and/or install household-level arsenic removal technologies in areas where higher HQ values were observed.
3. Conduct community awareness and education campaigns to inform residents about the health risks of arsenic exposure and promote safe water use practices.
4. Expand future research to include additional trace elements, seasonal variation, and broader spatial coverage to strengthen the accuracy and comprehensiveness of risk assessments.
5. Foster collaboration among local authorities, health agencies, and research institutions to develop integrated strategies for water safety management and public health protection.

Conclusion

The study conducted in Jamma District, Ethiopia, revealed significant variations in arsenic concentrations across different agroecological zones, with the highest levels found in the lowland (Kola) and midland (Woina Dega) areas, some of which exceeded the World Health Organization (WHO) guideline value of 10 μg/L. In contrast, the highland (Dega) zone exhibited consistently low arsenic levels, posing minimal health risks. The findings underscore the influence of geological and hydrogeological factors on arsenic mobilization, particularly in regions with volcanic and sedimentary formations.

Health risk assessments indicated that while the Hazard Quotient (HQ) values for all samples remained below the critical threshold of 1, the elevated arsenic levels in the midland and lowland zones suggest a moderate potential for non-carcinogenic health risks with prolonged exposure. This highlights the need for targeted public health interventions, including regular water quality monitoring, community awareness programs, and the implementation of mitigation strategies such as alternative water sources or low-cost treatment technologies.

The study contributes to the growing body of evidence on arsenic contamination in Ethiopia, particularly beyond the well-

documented Rift Valley region, and emphasizes the importance of expanding water safety assessments to other geologically similar areas. Proactive measures are essential to safeguard the health of rural communities reliant on untreated spring water and to prevent long-term adverse effects associated with chronic arsenic exposure. Addressing this issue requires collaborative efforts among local authorities, researchers, and public health professionals to ensure sustainable access to safe drinking water for all.

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