Dynamics of Spatiotemporal Variation of Groundwater Arsenic in Central Rift Vally of Ethiopia: A Serial Cross-Sectional Study

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Dynamics of Spatiotemporal Variation of Groundwater Arsenic in Central Rift Vally of Ethiopia: A Serial Cross-Sectional Study

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ABSTRACT

BACKGROUND: Arsenic is a well-known, highly poisonous metalloid that affects human health and ecosystems and is widely distributed in the environment. Nevertheless, data on the spatiotemporal distribution of arsenic in groundwater sources in Ethiopia are scarce.

OBJECTIVE: The principal aim of this study was to assess the extent of arsenic in groundwater sources and analyze the spatiotemporal variations in the central rift valley of Ethiopia.

METHODS: The study employed a serial cross-sectional study design and census sampling methods. The concentrations of arsenic in the groundwater samples were determined using inductively coupled plasma mass spectrometry (ICP-MS) at the Ethiopian Food and Drug Authority laboratory. Descriptive statistical analyses were performed using IBM SPSS version 29 software. Additionally, ArcGIS software was utilized to map the spatiotemporal distribution of arsenic. Furthermore, Minitab statistical software version 21.4 was employed to assess the correlation between spatiotemporal variations of arsenic concentrations in groundwater sources.

RESULTS: The mean values of arsenic in the groundwater samples were 11.2 μg/L during the dry season and 10.7 μg/L during the rainy season. The study results showed that 18 wells (42.2%) and 22 wells (48.8%) had higher arsenic concentrations (>10 μg/L) during the dry and rainy seasons, respectively. Thus, arsenic levels in 42.2% and 48.8% of the samples exceeded the maximum threshold limit set by WHO, USEPA, and Ethiopian standards (10 μg/L), respectively, during the dry and rainy seasons. Furthermore, our analysis revealed a significant positive correlation between arsenic in groundwater and well depth ($r = .75$, $P < .001$), indicating a strong association between higher arsenic concentrations and deeper wells. Similarly, we observed a substantial positive correlation between arsenic concentration in groundwater and season ($r = .9$, $P < .001$), suggesting notable variations in arsenic levels between dry and rainy seasons.

CONCLUSIONS: The majority of the groundwater sources in the studied area are unfit for human consumption because they contain high amounts of arsenic, which poses a significant risk to human health. Moreover, the arsenic concentration varied spatially and temporally. Therefore, special attention is needed to reduce arsenic exposure and associated health risks.

KEYWORDS: Arsenic, groundwater, spatiotemporal variation, cross-sectional studies, ICP-MS, Ethiopia

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Introduction

Arsenic is a well-known, highly toxic metalloid that is ubiquitous and widely distributed in the atmosphere, hydrosphere, and biosphere at varying concentrations.[1] However, arsenic species' concentrations and specific nature vary due to many factors, such as weathering, pH, physical, chemical, biological (microbial), and anthropogenic activities.[2-4]

Arsenic is becoming a significant public health problem around the globe due to its impact on human health. Therefore, arsenic is an extremely deadly chemical commonly referred to as "the king of poisons" and "the poison of kings."[5] Moreover, inorganic arsenic is widely recognized as a class I human carcinogen. Prolonged exposure to arsenic through drinking water can cause a broad range of adverse health effects, including dermatological diseases and cancer of the skin, urinary bladder, kidney, lung, pancreas, prostate, and ovary, as well as several non-carcinogenic diseases.[6-12]

The levels of arsenic in natural surface or groundwater vary significantly from country to country and from area to area, even in the same country. The fluctuation in arsenic levels in groundwater depends on the aquifer's specific geology, hydrogeology, and geochemical properties, as well as climatic influences and human actions.[13,14] The natural fluctuation in arsenic concentrations is attributed to climatic and seasonal changes during dry and wet seasons.[14]

The spatial distribution and seasonal variation of As concentrations in groundwater exhibit heterogeneity and can vary substantially from area to area and from time to time.[15] These findings suggest that human exposure and the resulting health hazards can differ from region to region and area to area within the same country, depending on the levels of arsenic in the groundwater and the quantity consumed as drinking water.[16] These indicate that human exposure and associated health risks may also vary from region to region and area to area, corresponding to variations in the level of arsenic in the groundwater and the amount consumed as the source of drinking water.[17] However, this spatiotemporal variation has been overlooked, and the standard health risk assessment approaches need to address the neglected spatiotemporal variation.[17] The spatial variability in groundwater sources raises concerns about potential temporary changes in arsenic concentrations.[18] Furthermore, the spatial and temporal distribution of As, as well as the resulting health impacts of human exposure to the pollutant, have been the main focus of interest in numerous studies.[19] For example, Rahman[4] reported that temporal variation in arsenic concentrations is important for public health research. However, only a few studies have considered space and time in investigating the impact of arsenic exposure on human health.

In Ethiopia, the precise extent and severity of arsenic exposure and its possible effects on humans have yet to be well investigated and acknowledged due to limited research. Furthermore, there is a lack of understanding or knowledge regarding the spatial and temporal distribution of arsenic in groundwater sources in Ethiopia. The spatial and temporal distribution of arsenic will inform decision-makers, policymakers, researchers, and the affected population about the severity and extent of the problem.[15] The spatiotemporal variation was also essential to establish mitigation or develop the right intervention when the concentration of As is increasing in the area. Therefore, this study aimed to assess the spatiotemporal variation of arsenic concentration in groundwater sources in central rift valley areas of Ethiopia.

Materials and Methods

Study area and population

The study was conducted in the Adami Tulu Jido Kombolcha district, which is located in the East Shoa Zone of the Oromia region. The district is located 160 km from Addis Ababa, the capital of Ethiopia, and 115 km from the province's capital city of Adama.[20] The latitude and longitude of the district are 7°56′N and 38°43′E, respectively (Figure 1). The study area's elevation ranges from 1500 to 2365 m above sea level, and Mount Aluto (Alutu) is the highest point. The study area has dry and semi-arid agroclimatic zones. Rainfall in the area varies greatly between and within years, with an annual total of between 600 and 800 mm. The study area experiences bimodal rainfall, with two distinct seasons: a short one from March to May and a longer one from June to September, followed by a dry season from October to February. In the study area, the relative humidity is 60%, and the mean annual temperatures range from 12°C to 27.2°C.[20] In 2022, the Ethiopian Central Statistical Agency projected a population of 211 827 individuals for the district, consisting of 106 205 males and 105 622 females. The estimated land area was 1274.54 km^2, resulting in a population density of 193.5 individuals per square kilometer.[21]

The study area is located in the Central Rift Valley of Ethiopia and is characterized by unique hydrogeological conditions that influence the distribution, availability, and quality of groundwater resources. The presence of hydrothermal systems in the area can influence groundwater temperatures, chemistry, and flow patterns, creating unique hydrogeological conditions. Groundwater recharge in the Rift Valley primarily occurs through precipitation and infiltration from rivers and streams, as well as from the percolation of water through permeable volcanic and sedimentary formations. Also, the area experiences climatic variations ranging from arid to semi-arid conditions, influencing the availability and recharge of groundwater resources. Climate change may further impact groundwater dynamics in the region.[22-25]

Furthermore, the area is surrounded by Lakes Ziway, Shala, Abiyata, and Langano, which are rich in volcanic rocks and sediments from different ages. Rivers like Bulbula, Jido, Hora Kario, and Gogessa also surround the district. These lakes and rivers play a crucial role in the hydrology of the region, influencing groundwater recharge, discharge, and water quality. The Meki and Ketar Rivers are the main sources of water for Lake Ziway, while the Bulbula River serves as its outflow, finally leading to the drainage of water into Lake Abijata. Lake Ziway has a crucial role as a primary water source for Batu town and its neighboring areas. Also, it is connected to the same water table as crucial groundwater aquifers.[26,27] In addition to surface water (lake Ziway), groundwater is a significant source of residential water supply. The study area is an industrial and agricultural zone, and human activities such as industrial and agricultural practices can induce arsenic into the environment and affect the quality of surface and groundwater sources.[28]

Study design and study periods

The study employed a serial cross-sectional study design to assess the dynamics of the spatiotemporal variation of arsenic in groundwater sources. Repeated samples from groundwater wells were taken during the end of the dry and wet seasons. We collected the water samples during the dry season (winter) from June 5th to 9th, 2022, and the rainy season (summer) from September 25th to 29th, 2022.

Source and study population

The source population consisted of all existing public and private shallow and deep wells in the study area, while the study population consisted of all existing functional and accessible public and private deep and shallow wells at the time of the survey.

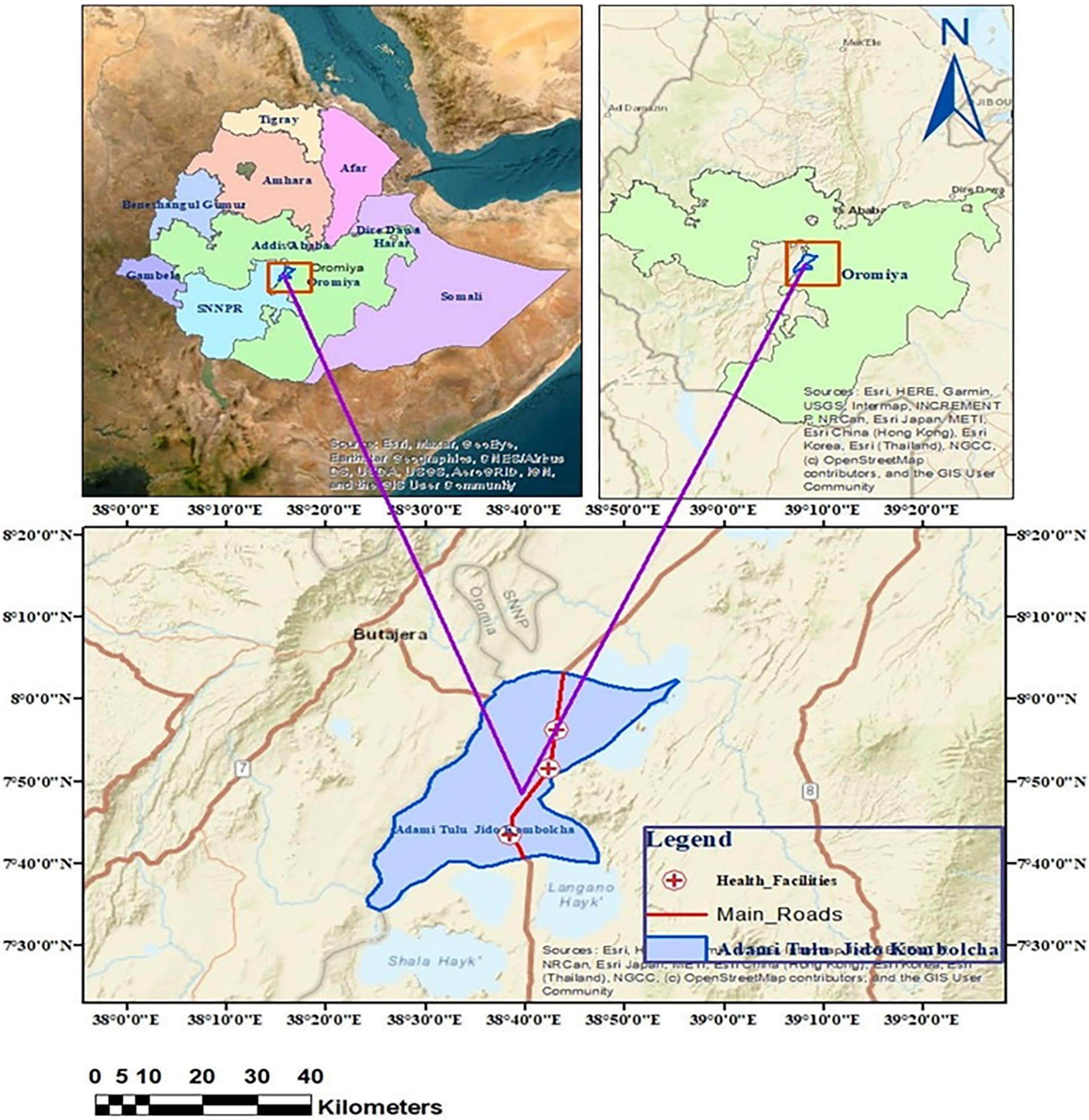

Figure 1. Map of Adami Tulu Jido Kombolcha District.

Inclusion and exclusion criteria

Inclusion criteria. The study included public and private deep and shallow wells that were functional in the study area at the time of sample collection.

Exclusion criteria. The study excluded those deep and shallow wells, whether public or private, that were not functional at the time of the study.

Sampling and well selection

The study utilized census sampling methods to assess the level of arsenic in groundwater sources and spatio-temporal variations. This study included all public and private wells that were functional and accessible at the time of the survey. In the study area, the community has access to domestic water, primarily from public or private wells. As a result, the primary water sources in the studied area are either public or private, deep or shallow wells, in contrast to other sources. Considering the nature of the study, we collected water samples in two rounds during the dry and wet seasons to assess the spatio-temporal dynamics. During the first round, between June 5 and 9, 2022, we collected 45 water samples from wells that met the inclusion criteria. Likewise, during the second round, we collected 45 water samples from previously identified and sampled wells between September 25 and 29, 2022. Overall, ninety (90) groundwater samples were collected and analyzed for this study. Among the collected water samples, 18 were from

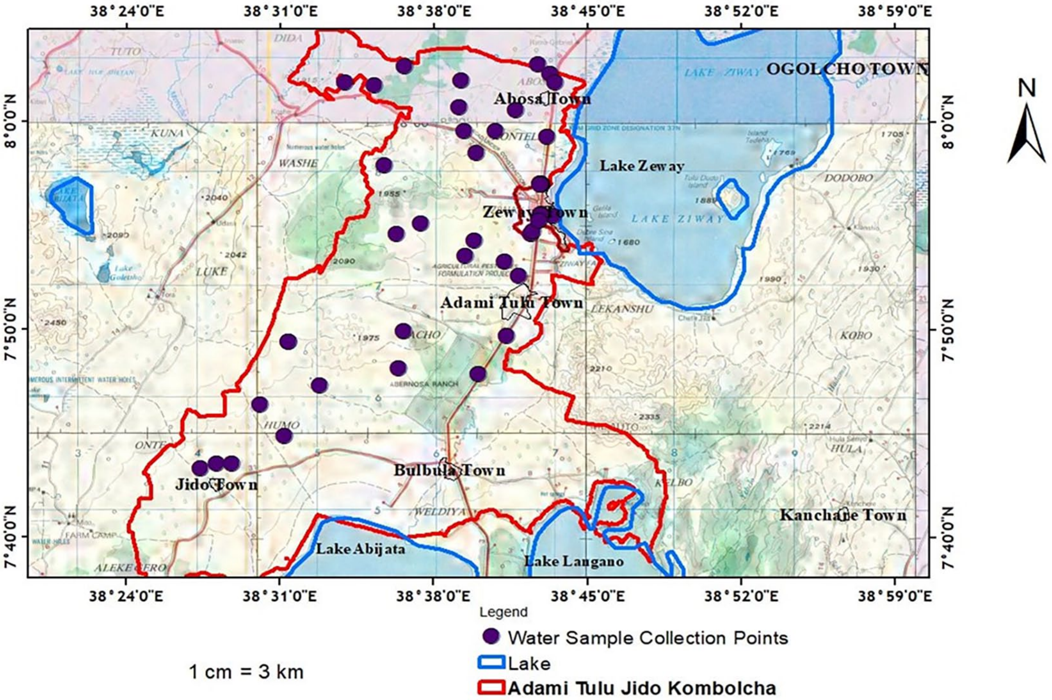

Figure 2. Water sample collection points.

shallow wells, while the reset 27 samples were from deep wells. GPS coordinates were gathered from all sampling sites using a portable Garmin device (Figure 2).

Sample collection, processing and analysis

In the present study, we collected repeated water samples from all public and private wells in the study area during the dry and wet seasons. We collected the water samples from the wells using a tightly capped polyethylene bottle, washed and rinsed them with 2% nitric acid and deionized water, labeled them, stored them in an icebox at the field level, and transported them to the Ethiopian Food and Drug Authority laboratory. Then, we acidified the prepared samples by adding 2 ml of 70% NHO_3 to 100 ml of water. After filtering the acidified samples using 0.2 microns (μm) syringe filters, we transferred 14 ml of the samples to a falcon tube for analysis and stored them in a refrigerator at 4°C until analysis. To ensure quality control, we prepared blank samples following the same protocols, excluding water samples. In addition, we constructed calibration curves using various known concentrations of standard solutions. The levels of arsenic in groundwater samples were measured using the Agilent 7900 ICP-MS instrument at the Ethiopian Food and Drug Authority laboratory.

Chemicals, reagents and solutions

Analytical-grade Ar (99.99%), NHO_3 (70%), and HCl (37%) were used during sample digestion and analysis. In addition, throughout the analysis, we used high-purity deionized water to dilute the standards and prepare the samples. Moreover, standard solutions of 1.0, 5.0, 10.0, 20.0, 50.0, and 100 ppb were prepared for the calibration curve.

Statistical analysis

In this study, we analyzed the descriptive statistics, including frequencies, percentages, mean, and standard deviations, using SPSS statistical software version 29 for Windows. ArcGIS software was used to locate the spatiotemporal distribution of arsenic with different exposure categories. Moreover, Minitab statistical software version 21.4 was used to assess the correlation of spatiotemporal variations of arsenic concentrations in groundwater sources. Also, Pearson's correlation coefficient was used to assess the correlation between seasonal variations and arsenic concentration by the depth of the well. However, before running Pearson's correlation coefficient (r), the test of normality was conducted, and the Kolmogorov-Smirnov and Shapiro-Wilk tests showed that the data for groundwater samples were normally distributed ($P > .05$). Since the data were normally distributed, the assumption of normality was satisfied, and the data was valid for the correlation analysis.

Quality control and assurance

We used the newest ICP-MS Agilent 7900 series equipment to find out how much arsenic was in groundwater samples for this study. This equipment has a low detection level, good resilience, high accuracy, and a wide dynamic range.[29] Additionally, to minimize errors and ensure the sensitivity and accuracy of the instrument, we used high-purity chemical reagents in this study. Furthermore, we closely adhered to the manufacturer's operating protocol during the analysis. To clean the glassware used for the analysis, we immersed it in 10% nitric acid overnight, rinsed it with distilled water, sealed it, and allowed it to dry at room temperature. Regular calibration of the instruments is also used to ensure accuracy and reliability, minimizing the potential for systematic errors. Furthermore, we used a standard reference solution as a control sample. After analyzing each batch of ten samples, a control sample was analyzed to verify the accuracy of the ICP-MS instrument. We calculated the percentage recovery (spike recoveries) to assess and validate the accuracy and precision of the ICP-MS measurements.[28] The recovery percentage was 110%. According to Ilieva et al,[30] the acceptable percentage of recovery was in the range of 80% to 120%. As a result, the recovery rate for this study was within an acceptable range, indicating that the method was accurate for determining arsenic concentrations.

Ethical considerations

Ethical clearance was not required since the study did not involve human participants. However, the district health office was informed of the purpose of the study through a formal letter from Addis Ababa University and the Oromia Regional Health Bureau. Also, oral consent was obtained from the respective office and the owner of the water wells.

Results and Discussion

Determination of arsenic in groundwater

The present study quantified the levels of As in groundwater sources at the end of dry and rainy seasons and assessed the spatial and temporal variations. The mean and standard deviation values were $10.7 \pm 8.16\,\mu g/L$ in the wet season and $11.2 \pm 9.38\,\mu g/L$ in the dry season, ranging from below the detection limit (BDL) to 29 μg/L and from below the detection limit (BDL) to 40 μg/L, respectively. During the dry and wet seasons, the analysis of water samples showed that arsenic levels surpassed 10 μg/L in 42.2% and 48.8% of instances, respectively.[28] The maximum allowable or acceptable threshold for As in drinking water in Ethiopia is 10 μg/L.[31] This indicates that nearly half of the water sources in the study area are unfit for human consumption and pose a threat to humans. In turn, the majority of the residents in the study area are at risk of ingesting water that exceeds the established limit for arsenic concentration. In view of this, the long-term health impacts of arsenic are a significant concern among the residents in the studied area due to limited research, insufficient data, inadequate monitoring and surveillance, and the absence of arsenic removal technologies.

The highest concentration of arsenic was observed during the dry season. Arsenic concentration in groundwater tends to be higher during the dry season compared to the rainy season due to several interrelated factors like redox conditions, groundwater flow dynamics, water table fluctioans, human activities, auifer geochemistry, and other factors. Furthermore, the studied area exhibits distinctive hydrogeological characteristics that impact the spatial distribution, accessibility, and caliber of groundwater resources. The existence of hydrothermal systems in the region can impact the temperature, chemical, and flow patterns of groundwater, resulting in distinct hydrogeological circumstances. The combination of these variables leads to elevated levels of arsenic in groundwater during the dry season in comparison to the rainy season.

The redox conditions of the aquifer strongly influence the form of arsenic present. During the dry season, when groundwater levels drop, the aquifer becomes more oxidized. This oxidizing environment helps turn arsenite, which is more mobile and toxic, into arsenate. As a result, arsenate sticks to minerals in the aquifer more strongly, which could make it more concentrated in the water. On the other hand, during the rainy season, increased precipitation and groundwater recharge can dilute the arsenic concentration in aquifers. The increased flow can also flush out some arsenic from the aquifer matrix, reducing its concentration in groundwater. During the dry season, as water levels drop, water is withdrawn from deeper parts of the aquifer, where arsenic concentrations are often higher due to longer residence times and less contact with oxidizing conditions. Furthermore, the study area is an agricultural zone, and agricultural practices like irrigation activities are prevalent during the dry season, and these activities can induce arsenic into the environment. As a result, human activities, such as increased groundwater pumping during the dry season, can exacerbate arsenic contamination. Thus, pumping can induce changes in groundwater flow patterns and withdrawal from deeper, more arsenic-affected zones. Also, dry seasons typically promote more stagnant conditions in the aquifer, potentially concentrating arsenic through desorption and dissolution processes. Therefore, management techniques for reducing arsenic pollution frequently take into account seasonal concentration fluctuations and the fundamental geochemical mechanisms that control arsenic movement in underground water sources.

The average percentage change in arsenic readings between the dry and rainy seasons was 4.3%, with an overall mean difference of 0.48 μg/L. Arsenic levels in the study area were high since the average concentration of arsenic in drinking water for the dry and rainy seasons in this study was higher than the current maximum permitted limits of the USEPA, WHO, and Ethiopian guidelines (10 μg/L). A study conducted in Ethiopia[23] also supports the findings of this study. Nevertheless, the study's results exceed the mean values reported in Ethiopia,[32] but are lower than the mean values reported in Ethiopia,[23] Bangladesh,[33] Nepal,[34] Vietnam,[35] India,[36] and the USA.[37]

Previous studies have established a correlation between long-term exposure to persistently low concentrations of arsenic and an elevated risk of developing many types of cancer, including skin, lung, bladder, liver, kidney, pancreatic, and

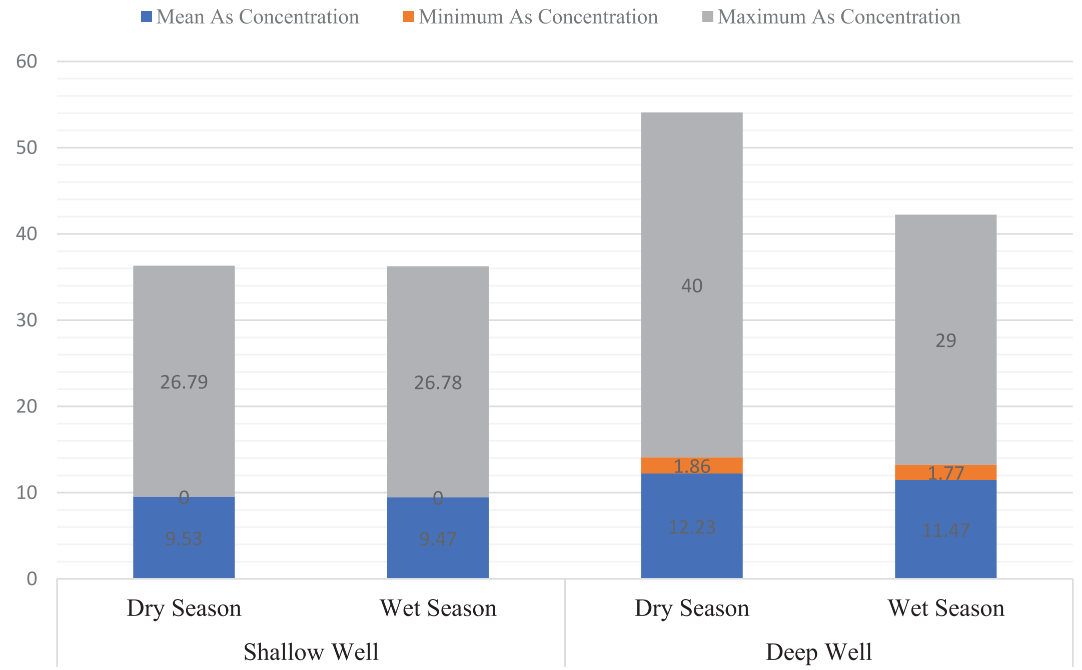

Figure 3. Arsenic concentration in shallow and deep wells during dry and wet seasons in Adami Tulu Jido Kombolcha District, Ethiopia, 2022.

prostate cancer. In addition to cancer, long-term exposure to low concentrations of As can lead to various health concerns, such as skin lesions (arsenicosis), cardiovascular illnesses, hypertension, diabetes mellitus type II, anemia, neurological and mental disorders, and respiratory, liver, and kidney disorders.[8-11,38-41]

Furthermore, another study also reported that the consumption of arsenic (As), even at a minimal level of 2 µg/L for an extended duration, resulted in the development of skin, lung, bladder, liver, and kidney cancers[42] and non-cancer risks encompass a range of health conditions, including but not limited to cardiovascular illnesses, hypertension, anemia, diabetes, liver and kidney abnormalities, and neurological and mental disorders.[12] Moreover, extended exposure to As concentrations exceeding 10 µg/L has been documented to elevate the occurrence of skin, lung, bladder, and other forms of cancer and increase mortality rates from cancer and non-carcinogenic health risks.[43] Furthermore, arsenic exposure during pregnancy presents substantial dangers for both mothers and fetuses.[44] Arsenic exposure during pregnancy increases the risk of miscarriage and stillbirth in pregnant women,[45] due to the easy transfer of arsenic across the placenta to the fetuses.[46]

In this study, we discovered that the average concentration of arsenic (As) in groundwater sources throughout both dry and wet seasons in the studied area exceeded the maximum recommended allowable value of WHO and Ethiopian standards and the recommended cutoff value (10 µg/L) for the chronic exposure range for cancer and non-cancer risks. As a result, high levels of arsenic (As) exposure through drinking water increase the risk of cancer and non-cancer disorders for individuals in the research area due to its toxic nature and associated health hazards. The recent study by Demissie et al[28] in the study area reveals that the risk of cancer and noncancer from drinking water exposure to As exceeds acceptable levels in both dry and rainy seasons, aligning with the present study. Therefore, it is crucial to make additional efforts to protect them from future risks.

Spatiotemporal variability of arsenic in groundwater

Spatial distribution of arsenic in groundwater sources. The study showed spatial variability of arsenic concentrations among wells in dry and rainy seasons (Figures 3 and 4). The mean concentration of arsenic (As) in shallow wells is 9.6 µg/L during the dry season and 9.5 µg/L during the wet season. However, the average concentration of arsenic in deep wells is 12.2 µg/L during the dry season and 11.5 µg/L during the rainy season. The minimum As concentrations recorded for shallow wells were consistently below the detection level (BDL) during both dry and rainy seasons, whereas the maximum recorded As concentrations were 26.79 µg/L during the dry season and 26.78 µg/L during the rainy season. However, the minimum concentrations of arsenic detected in deep wells are 1.9 and 1.8 µg/L during the dry and wet seasons, respectively.

In contrast, the maximum concentrations of arsenic recorded are 40 and 29 µg/L during the dry and rainy seasons, respectively. As a result, deep wells exhibited the highest documented levels of As content throughout both dry and rainy seasons. Thus, higher arsenic concentrations are prevalent in deep wells than in shallow wells. This is due to geological conditions, the presence of specific minerals in the ground's deeper layers, and other geological factors. Arsenic concentrations in groundwater

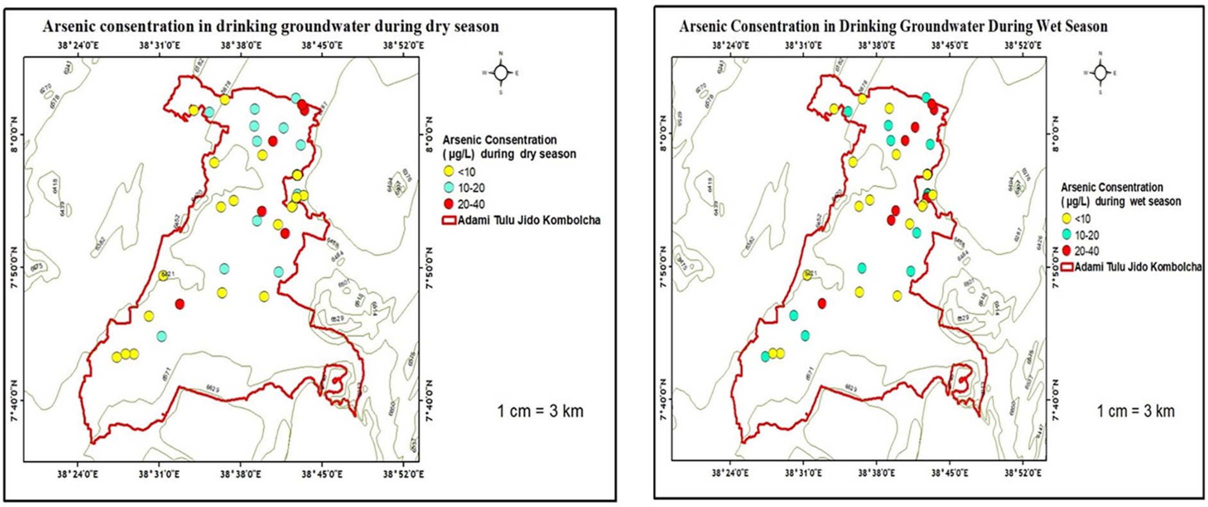

Figure 4. Spatial distribution of As concentration during dry and wet seasons in Adami Tulu Jido Kombolcha District, Ethiopia, 2022.

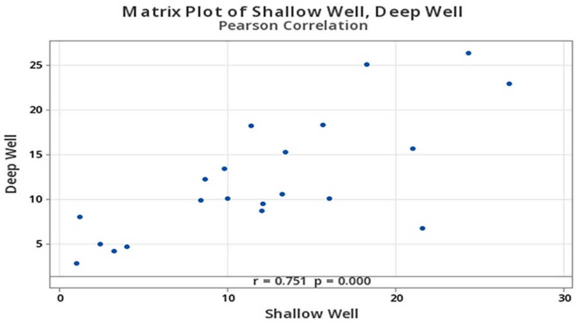

Figure 5. Correlations between arsenic concentration and well-depth in Adami Tulu Jido Kombolcha District, Ethiopia, 2022.

can vary vertically at different locations and depths, highlighting the intricate nature of its occurrence.[47] This highlights the significance of considering the depth of the well when assessing potential arsenic contamination.

The current study utilized Pearson's correlation coefficient to assess the relationship between the concentration of arsenic and well depth or spatial changes. As depicted in Figure 5, Pearson's correlation coefficient analysis revealed a strong positive correlation ($r = .75, P < .001$) between the concentration of As and the depth of the well. We found a strong positive correlation between As concentration in groundwater and the spatial distribution of As in shallow and deep wells. Arsenic concentrations vary with well depth. Moreover, the concentration of arsenic also exhibited variation even among wells that were in close proximity. This study's results suggest that the arsenic (As) level rises in proportion to the depth of the well and, conversely, decreases as the depth decreases. Therefore, the results of this study align with the studies done in Nepal,[48] Bangladesh,[49] Mexico,[50] Mongolia,[51] and the USA.[52] The geochemical composition of the groundwater in that region accounts for the elevated levels of arsenic (As) detected in the deep wells. On the contrary, a study from Bangladesh[6,53] and China[18] reported that a high concentration of As is more prevalent in shallow wells than deep wells.

The spatial distribution of arsenic (As) in groundwater sources can exhibit significant variability, even within a geographically limited area. Various factors can influence the spatial variability of As concentrations between deep and shallow wells. The spatial variations of arsenic concentrations in relation to well depth may be attributed to the disparities in local geological and hydrogeological conditions.[6] Also, deep wells tend to have a higher arsenic concentration compared to shallow wells, while these wells typically contain groundwater with elevated pH levels or altered geochemical conditions that increase the mobility of arsenic.[52]

Additionally, the depth at which a well is located can also impact the geological formations and aquifers the water passes through, which may contribute to variations in As concentrations. However, researchers have yet to ascertain the exact reason for the significant variation in As levels within closely located wells. Thus, the spatial variation of arsenic (As) in groundwater sources is a critical environmental concern in the studied area, while elevated levels of arsenic can pose serious health risks to human populations.

Furthermore, understanding the spatial heterogeneity and contamination levels of arsenic in groundwater within a specific nation is valuable for formulating strategies to pinpoint the areas with significant contamination, which require a particular focus for effective management.[54] Therefore, continuous monitoring of arsenic levels in groundwater is essential for understanding its spatial distribution and trends over time. Likewise, it is imperative to undertake mitigation strategies, such as utilizing alternative water sources and applying treatment methods to purify water contaminated with arsenic, to manage the issue of arsenic contamination effectively.

Temporal variation of arsenic in groundwater sources. The mean arsenic concentrations in the groundwater samples were 11.2 and 10.7 µg/L, respectively, during the dry and rainy seasons. During the dry season, the maximum concentration of As exceeded that of the rainy season, suggesting a significant difference (Figure 5). In dry and wet seasons, 42.2% and 48.8% of

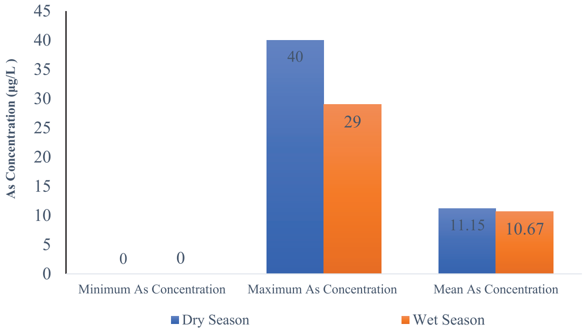

Figure 6. Seasonal variability of As in groundwater sources in Adami Tulu Jido Kombolcha District, Ethiopia, 2022.

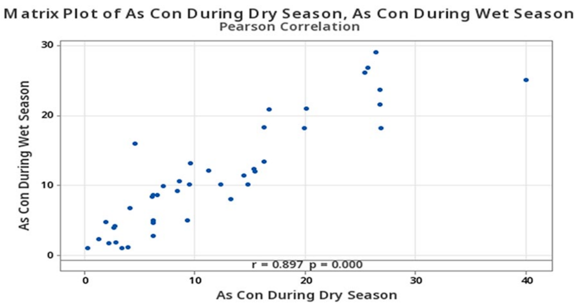

Figure 7. Seasonal As variation among sampled wells during dry and rainy seasons in Adami Tulu Jido Kombolcha District, Ethiopia, 2022.

groundwater samples exceeded the permissible values of the WHO and Ethiopia drinking water guideline standard of µg/L for drinking water. The average percent difference (dry minus wet) in arsenic values between the dry and wet seasons was 4.3%, with an overall mean difference of 0.48 µg/L. These findings suggest the presence of a significant difference in arsenic levels between the wet and dry seasons. This difference can potentially affect the selection of water treatment technologies, the implementation of standard water treatment procedures, and the development of intervention strategies.

The seasonal distribution of arsenic in water samples exhibited a lower concentration during the wet season and a higher concentration during the dry season. Also, temporal variation was observed in all wells during both dry and wet seasons. We found that high arsenic concentrations are more prevalent in the winter than in summer. Thus, arsenic concentrations in groundwater sources have clear temporal and seasonal variability (Figures 6 and 7).

In addition, a Pearson's correlation coefficient was employed to assess the association between the concentration of arsenic in groundwater sources and temporal or seasonal variations. The study found significant differences in mean concentrations between the dry season (11.5 ppb) and the wet season (10.7 ppb), with a P-value of $<.0001$. The analysis of Pearson's correlation coefficient showed a statistically significant positive correlation between the concentration of arsenic and the temporal or seasonal change, as depicted in Figure 8. A strong positive relationship ($r=.9$, $P<.001$) was observed between the concentration of arsenic in groundwater and its temporal and seasonal distribution. The P-value was $<.001$, indicating a significant difference in As concentration relative to the seasons. The findings suggest that the concentrations of arsenic were higher during the dry season than during the rainy season. The results of this study align with those undertaken in the Philippines, Vietnam, India, Nepal, and China. This is because a variety of factors, including natural processes, human activities, and environmental conditions, can influence the temporal variation of arsenic levels in the environment.

On the contrary, the studies conducted in Nepal,[55] China,[18] and India[36,56,57] have proved higher concentrations of arsenic reported in the wet season than in the dry seasons. Various factors can influence the seasonal variation of arsenic concentrations in environmental media, such as water and soil. Those factors are precipitation and runoff, redox conditions, temperature, vegetation growth, human activities, and groundwater dynamics, all contributing to arsenic seasonal variability.[58,59] Hence, it is important to consider these factors when assessing potential risks associated with elevated levels of arsenic during specific times of the year.

Previous studies conducted in Bangladesh and the USA have indicated that rainfall is an unreliable indicator of arsenic concentrations in groundwater.[37,60] This means that the amount of rainfall does not necessarily correlate with the levels of arsenic found in these water sources. On the contrary, Farooq et al[61] reported that increasing rainfall intensity of dilution increases, which reduces the level of arsenic in the groundwater. Other factors, such as geological conditions, human activities, and other contaminants, may significantly determine arsenic levels.[14,62,63] As a result, understanding the seasonal variations of arsenic is crucial for managing water quality and mitigating the health risks linked to exposure to arsenic.

Therefore, it requires a comprehensive approach involving both short-term mitigation measures and long-term strategies dealing with high arsenic pollution in the study area. Monitoring, research studies, and understanding the temporal variation of arsenic levels are crucial for assessing potential health risks and implementing appropriate mitigation strategies. Regular testing of water sources, along with ongoing research, helps to track and manage arsenic contamination. Also, awarness and education, regulations and practices aimed at reducing anthropogenic sources of arsenic can contribute to minimizing its effects on the ecosystem and human health. In conclusion, combining these short-term and long-term measures in an integrated approach is crucial for effectively addressing arsenic pollution in the Rift Valley area and ensuring access to safe drinking water for all residents. Also, collaboration among stakeholders, adequate funding, and continuous monitoring and evaluation are essential for the success of these interventions.

Strengths and limitations of the study

The strength of this study was that it measured the concentration of arsenic among all public and private wells that are functional in the studied area during the end of dry and wet seasons

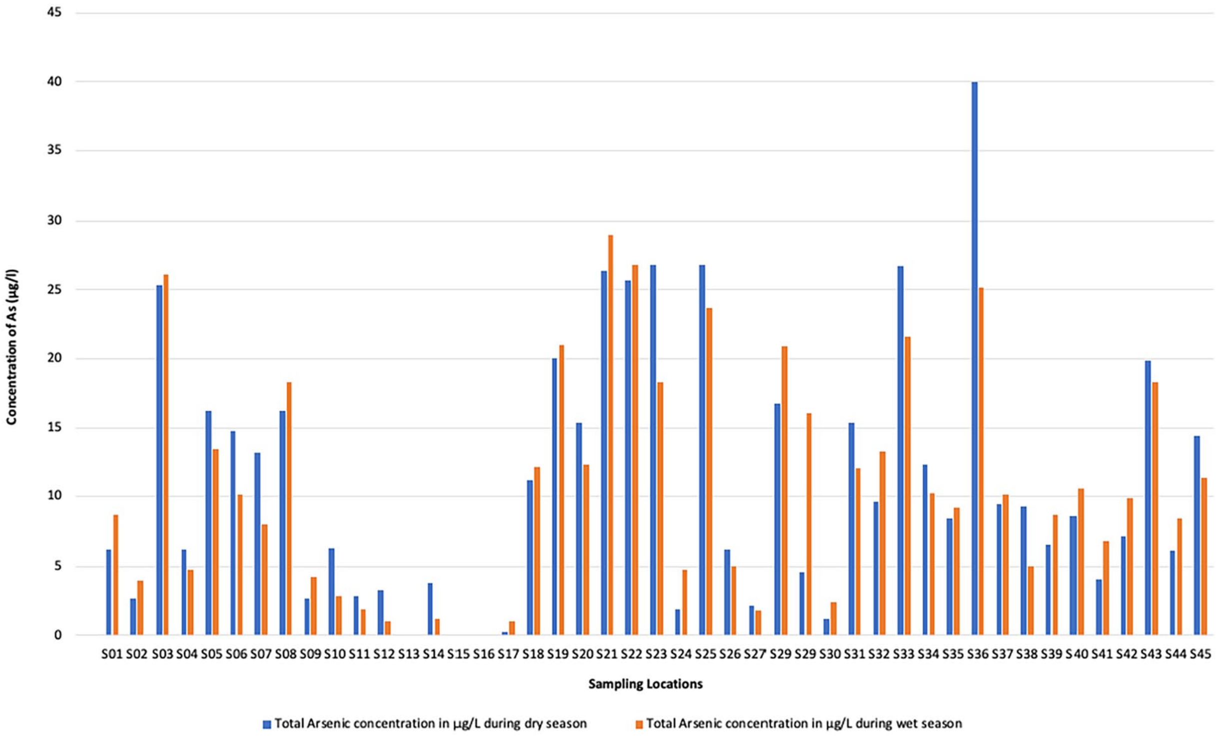

Figure 8. Correlations between arsenic concentration in dry and wet seasons in Adami Tulu Jido Kombolcha District, Ethiopia, 2022.

to assess the spatial and temporal variation. However, a limitation of the study was that it did not consider all three seasons in Ethiopia (Bega, Belg, and Kiremt) due to financial constraints, which prevented an investigation into the spatiotemporal variation of arsenic observed among the three seasons. Another limitation of the study is the nature of the data reported (cross-sectional observation), which does not directly allow the establishment of causality between potential independent factors and the observed spatiotemporal variation of arsenic in the surveyed groundwater sources.

Conclusions

This study assessed the spatiotemporal variation of arsenic concentration in groundwater sources in the study area. The average concentration of arsenic (As) in groundwater sources exceeded the maximum permissible guideline value set by the World Health Organization and national standards. Therefore, the majority of the water sources examined were unfit for human consumption and posed a threat to humans in the studied area. Deep wells showed higher As concentrations than shallow wells, and dry season As concentrations were higher than wet season. Moreover, we found a significant positive correlation between groundwater arsenic concentration and variations in space, time, and well depth. Thus, the study area exhibits a notable variation in space and time in the concentration of arsenic in groundwater sources. The study concluded that the arsenic concentrations in the study area varied spatially and temporally.

Long-term monitoring and further studies are needed to comprehend arsenic's spatial, temporal, and seasonal dynamics. Additionally, local regulations and water management strategies are essential for mitigating arsenic contamination and ensuring safe drinking water sources. Therefore, this study's results could offer crucial insights and scientific data to the government, policymakers, and researchers. To this end, effective monitoring, modeling, and mitigation efforts are essential to address this environmental and public health concern. Furthermore, addressing the issue of arsenic contamination in the Central Rift Valley of Ethiopia requires collaboration among researchers, public health officials, experts, and policymakers. In light of our findings, we recommend factoring data on spatiotemporal variation of arsenic in revisiting and redesigning existing interventions employed to ensure groundwater potability. Additionally, we argue that longitudinal studies are warranted to further understand this emerging issue on groundwater quality in the region.

CRediT Authorship Contribution Statement

SD: Conceptualized and searched for literature; conducted methodology, investigation, and analysis; wrote an original draft; reviewed and edited the manuscript; funded acquisition; and managed project administration and supervision. **BM, SM, and TA** conceptualized and were involved in validation, supervision, and data curation, as well as reviewing and editing the manuscript.

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Data Availability Statement

Data will be made available on request.

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