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Exploring the spatial distribution of dissolved heavy metals and health risk assessment of cadmium in groundwater: A case study in Oued M'Zab region, Algeria

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Abstract

Background: Heavy metals are one of the most harmful groundwater contaminants due to their toxicity and persistence in the environment. This study aimed to assess the impacts of heavy metals on the quality of groundwater within the M'Zab Valley used for human consumption and irrigation and its potential impact on public health.
Methods: In this study, the samples taken from eight phreatic aquifer wells situated along the M'Zab Valley, from upstream to downstream, were analyzed, and chronic daily intake (CDI) of cadmium, hazard quotient (HQ), and target organ risk (TOR) for the kidney were computed for child, infant, and adult age groups.
Results: It was revealed that the superficial aquifer water is of poor quality and frequently exceeds the drinking water standards, particularly for Cd, Cr, and Zn, which poses a health risk for inhabitants. The study found that the CDI values for Cd for each age group (infants, children, and adults) were below the safe limit established by the World Health Organization (WHO), but the data reveals that the concentration of the HQ is considerably greater in infants than in children and adult groups, considering that infants have the highest estimated daily intake of Cd and TOR for the kidney. Thus, infants may be exposed to a greater health risk associated with cadmium exposure.
Conclusion: According to the results of the present study, continuous monitoring of water quality and treatment measures to reduce elevated pollutant levels that harm human health are strongly advised to preserve and safeguard groundwater quality from various forms of pollution.
Keywords: Groundwater, Heavy metals, Humans, Drinking water, Environmental pollutants
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Introduction

Groundwater is a vital source of water supply globally (1). It holds several advantages over surface water, providing larger volumes and better-quality water. Approximately 23% of the Earth's freshwater resources are stored as groundwater, which should be conserved and protected from pollution and overuse (2).

Accordingly, this has emerged as a significant concern for water resources due to the rapid growth in population, swift industrialization, uncontrolled urban expansion, and excessive use of fertilizers and pesticides in agriculture (3).

In Algeria, groundwater is polluted from the surface and damaged by saline intrusion. The overexploitation of aquifers undermines its ability to retain water, which causes underlying layers. However, many cities cannot provide sufficient drinking water and sanitation facilities (4).

Water contamination with harmful heavy metals has been a significant concern in recent years (5,6). Cd and Pb are potentially hazardous and have no recognized biological purpose, but Cu and Zn are required (7).

Heavy metals, such as lead, cadmium, copper, zinc, mercury, and arsenic, are among the most harmful groundwater contaminants due to their toxicity. They occur in groundwater due to natural sources or human activities such as service stations and mechanics (8). Hence, the presence of heavy metals in these resources is a serious ecological problem (9). They are highly hazardous due to their persistent nature, the propensity to accumulate in organisms, the potential for biomagnification within food chains, and their resistance to degradation (10).

These metals, at high concentrations, can affect human health and the environment (11). They can have serious health consequences with various symptoms depending on the type and amount of heavy metal consumed (12). These heavy metals affect bodily systems, such as the cardiovascular, gastrointestinal, central nervous, endocrine, renal, hepatic, respiratory, and skeletal systems (10).

This study focuses on the effects of heavy metals on the groundwater quality of the phreatic aquifer and the risks associated with heavy metals contamination in the Oued M'Zab region. It also includes non-carcinogenic and carcinogenic human health risk assessment (HRA) associated with cadmium exposure from the consumption of drinking water sourced from this phreatic aquifer. Therefore, this study examines eight phreatic aquifer wells in M'Zab Valley by applying statistical analysis. For this purpose, this research explores the environmental and health risks of the contaminated water in this region by examining cadmium, chromium, zinc, and lead in the phreatic aquifer.

Materials and Methods

Overview of the study area

This research studies the M'Zab Valley, located in the heart of the northern Sahara, approximately 600 km south of Algiers, the capital of Algeria (Figure 1). The M'Zab Valley includes a basin, which encompasses an estimated area of 5000 km^2, with somewhat uncertain boundaries in its eastern section. It is known as Oued M'Zab, a significant river within this region that flows from west to east for a distance of 320 km in the Botma-Rouila region at an elevation of 750 m and terminates at Sebkhet Safioune at an altitude of 107 m. There is a steep gradient between Ghardaïa and Bounoura (13). The river's magnitude of flow varies, ranging from 1.50 to 2.35 km upstream and gradually narrowing downstream, eventually reaching 0.55 km south of El Atteuf (13-15).

Groundwater resources are the primary source of water in this region, consisting of two layers of water categorized by their depths: the water table in the alluvium of the Wadis and the deep aquifer in the permeable layers of sand and sandstone of the Albian at 300 m (16,17). These two water layers are essential sources for domestic and agricultural purposes in the M'Zab Valley.

Collection of water samples and analysis

The method of data collection and analysis of water quality informs site exploration and water quality assessment; as such, this study explored eight wells of water from the phreatic aquifer for irrigation and drinking purposes in M'Zab Valley in December 2019, using a Magellan GPS device with the UTM metric

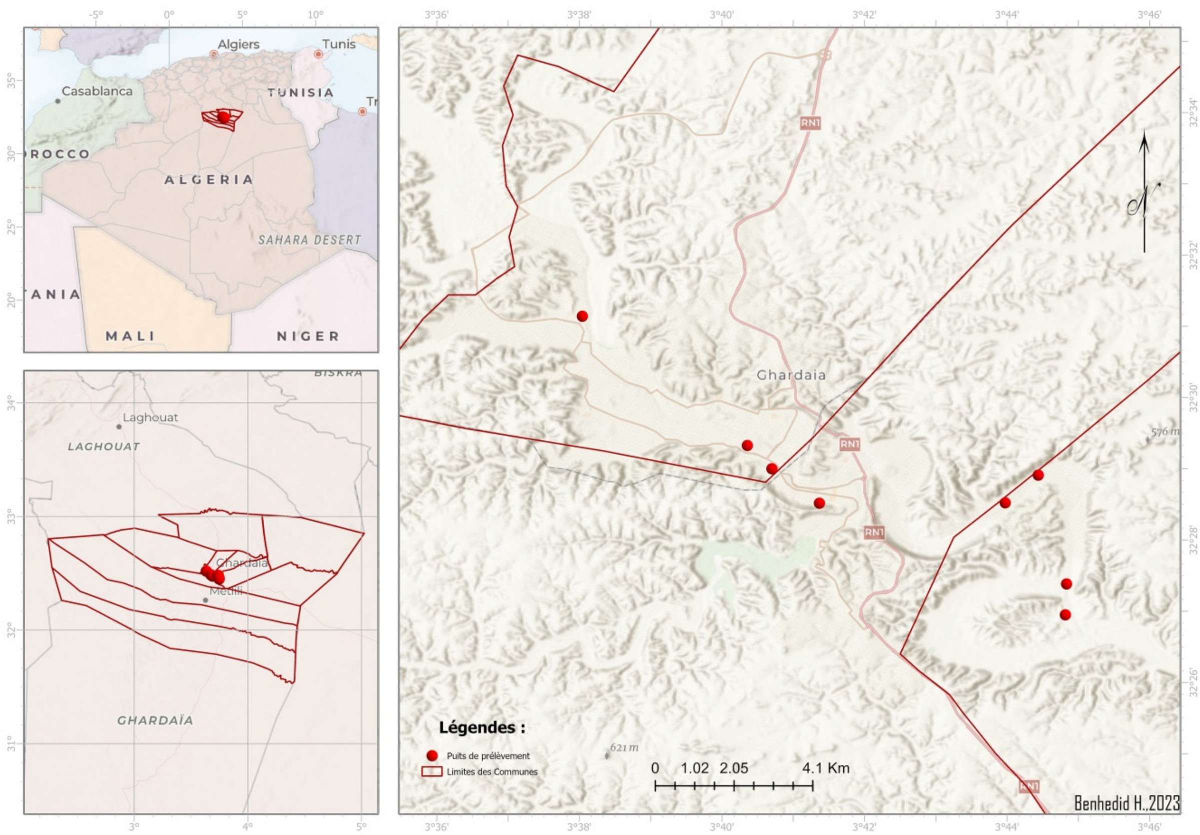

Figure 1. Geographic location of the study area

projection system and the WGS 1984 datum (Figure 2). Moreover, in addressing the water quality issue, the Rodier et al (18) method serves as a useful tool to collect and analyze water samples. The analysis of water samples focused on Cd, Cr, Zn, and Pb concentration in water, using an atomic absorption spectrometer (Perkin Elmer). The results, created with ArcGIS 10.8, were shown on maps, and statistical analysis was conducted using tools available in MS Excel.

Health risk assessment

Given that the HRA examines potential adverse health effects arising from various hazards, encompassing both non-carcinogenic and carcinogenic risks (19), this research evaluated the non-carcinogenic and carcinogenic health hazards associated with cadmium exposure from the consumption of potable water sourced from the phreatic aquifer in the M'Zab Valley. Cadmium consumption can lead to health risks, including cancer risks due to exposure to carcinogenic heavy metals (CDI), as well as hazard quotient (HQ) resulting from exposure to non-carcinogenic substances, which is a measure of the potential for adverse health effects to occur (20). This study applied methodologies outlined by the United States Environmental Protection Agency (US EPA) to conduct this assessment.

The US EPA report presents the equations for calculating the chronic daily intake (CDI) and HQ for cadmium expressed as follows (20):

$$CDI = \frac{Cw\,DI\;\;EF\;\;ED}{BW\;\;AT} \tag{1}$$

Where C_w represents the cadmium concentration in the drinking water (in mg/L), *DI* denotes the daily average drinking water ingestion rate (in l/day), *EF* signifies the exposure frequency (number of days per year), *ED* represents the exposure duration (in years), *BW* corresponds to the individual's body weight (in kg), and *AT* stands for the average time interval between exposures (in days).

The HQ is determined using the following formula (20):

$$HQ = \frac{CDI}{RfD} \tag{2}$$

Where *CDI* represents the estimated daily intake of cadmium (mg/kg/d), *RfD* (reference dose) denotes the RfD (mg/kg/d).

An HQ less than 1 indicates that the exposure level is below the level of concern and is unlikely to cause adverse health effects. An HQ greater than 1 indicates that the exposure level is above the level of concern and there is a potential for adverse health effects to occur. The higher the HQ, the greater the potential for adverse health effects. It is noteworthy that the HQ is a conservative measure of risk. It does not take into account individual factors such as age, health status, or genetics. Additionally, the RfD is based on animal studies, so there is some uncertainty

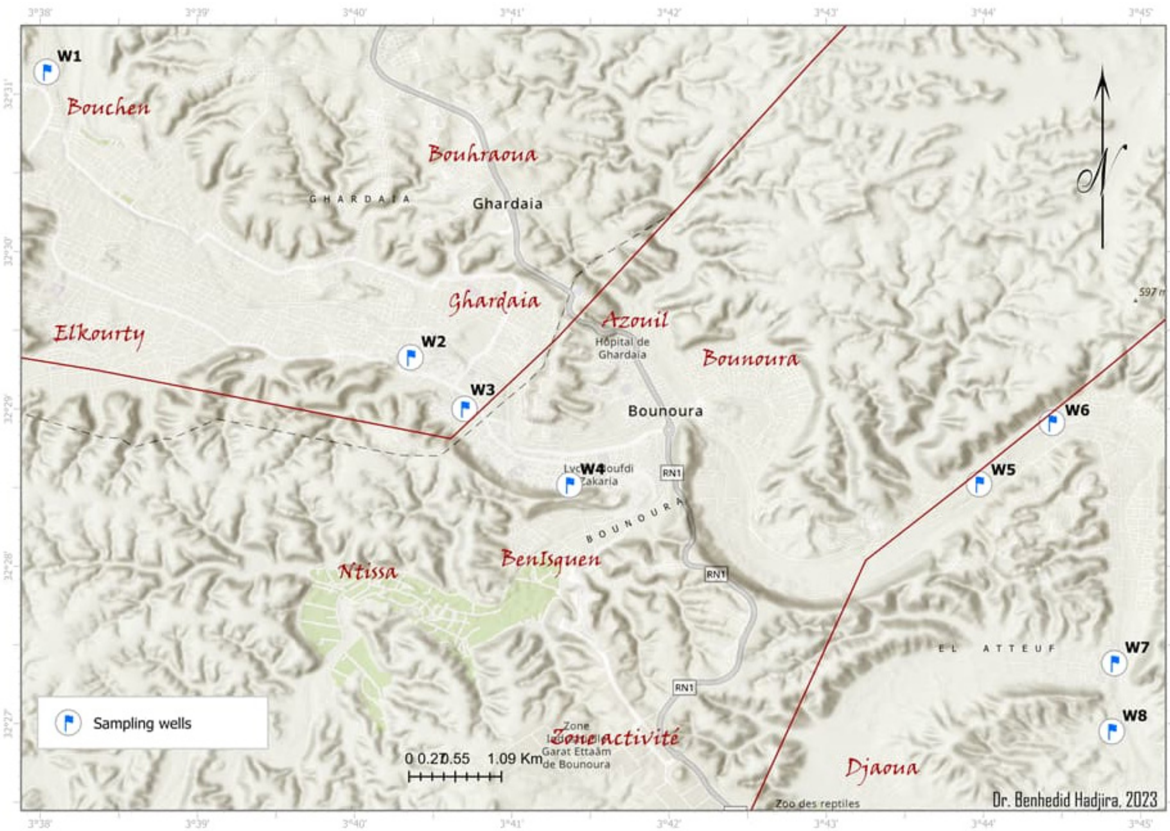

Figure 2. The location of the phreatic aquifer wells in Oued M'Zab

about how well it applies to humans. The RfD value was derived from relevant literature sources (19-23); hence, this study utilized an oral RfD value of 0.0005 mg/kg/d for cadmium in drinking water.

Therefore, in the present research, the probability of developing adverse health effects in a specific organ due to exposure to a particular contaminant (TOR) was estimated (10). Specifically, the TOR of cadmium in groundwater for the kidney (24) was calculated using Eq. (3):

$$TOR = HQ \times OSF \qquad (3)$$

Where *OSF* (oral slope factor) is the toxicity measure that characterizes cadmium's toxicity towards the kidney as the target organ. The OSF for cadmium, as reported in the United States EPA's integrated risk information system (IRIS) in September 2021, is 0.0085 mg/kg/d.

Results

Statistical results and spatial distribution

Heavy metals are pollutants mostly generated by human activity with toxic impacts (25). Figure 3 shows heavy metal concentrations that greatly exceed drinking water standards according to the World Health Organization (WHO), except for lead, with lower concentrations than the other metals.

The results of the analysis of the heavy metals according to their concentration in the water are as follows:

The cadmium in the groundwater of the M'Zab Valley is a matter of concern for the local population, as it may lead to long-term health problems. Figure 4 shows that cadmium in the M'Zab Valley's groundwater ranges from 0.271 mg/L at well W4 to 0.682 mg/L at well W1. This concentration is significantly higher than the WHO drinking water standard (03 µg/L) (18).

Chromium is found in small quantities in the environment, specifically in basic rocks. Generally, its solubility is low, regarding soil leaching phenomena (18).

The chromium concentrations in the wells of the superficial aquifer of the M'Zab Valley are present in amounts between 0 mg/L for W7 and 0.387 mg/L for W8 (Figure 5). These values substantially surpass the WHO drinking water standard (0.05 mg/L) (18).

As seen, despite the low concentration of chromium in the environment, it is considered an environmental pollutant and harmful to human health. The concentration of lead in the groundwater of the M'Zab Valley is also a topic of concern due to its potential impact on human health and the environment. Figure 6 shows lead concentration in the groundwater wells, which ranges from 0.247 mg/L in the W3 to 0.57 mg/L in the W8. These concentrations exceed the WHO recommended limit for drinking water (10 µg/L) (18).

Zinc concentrations in M'Zab Valley's groundwater are between 0 mg/L in the W3 and 0.173 mg/L in the W2 (Figure 7). These levels are below the drinking water

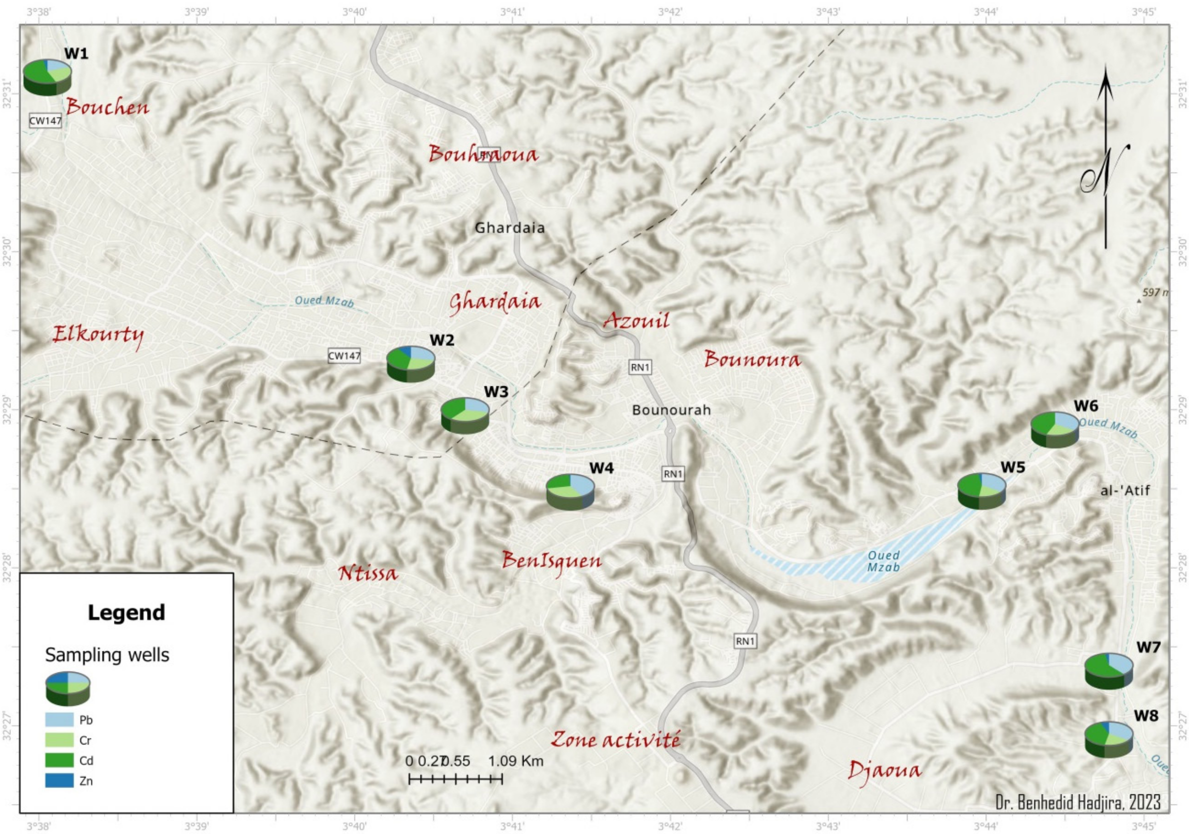

Figure 3. Levels of heavy metals of the Oued M'Zab phreatic aquifer

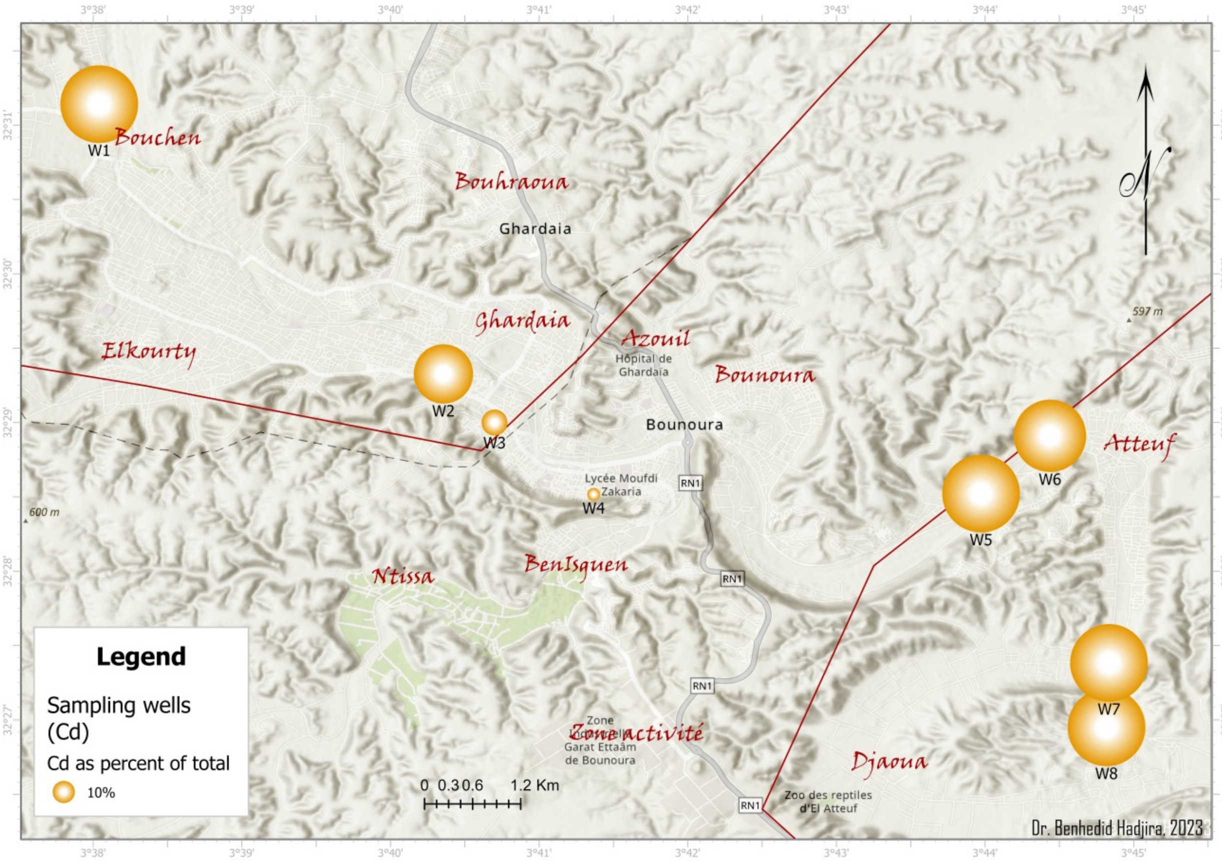

Figure 4. The Cd spatial distribution map of the Oued M'Zab phreatic aquifer

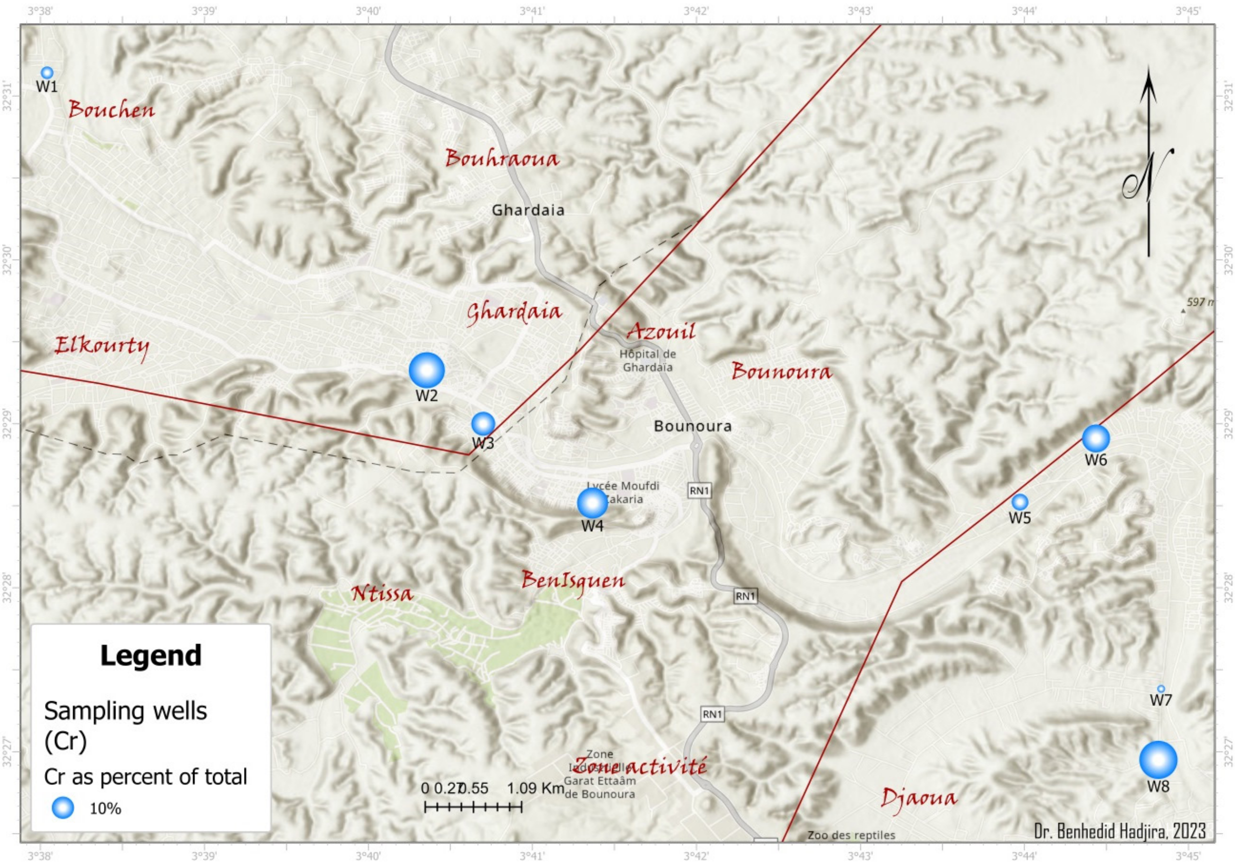

Figure 5. The Cr spatial distribution map of the Oued M'Zab phreatic aquifer

Figure 6. The Pb spatial distribution map of the Oued M'Zab phreatic aquifer

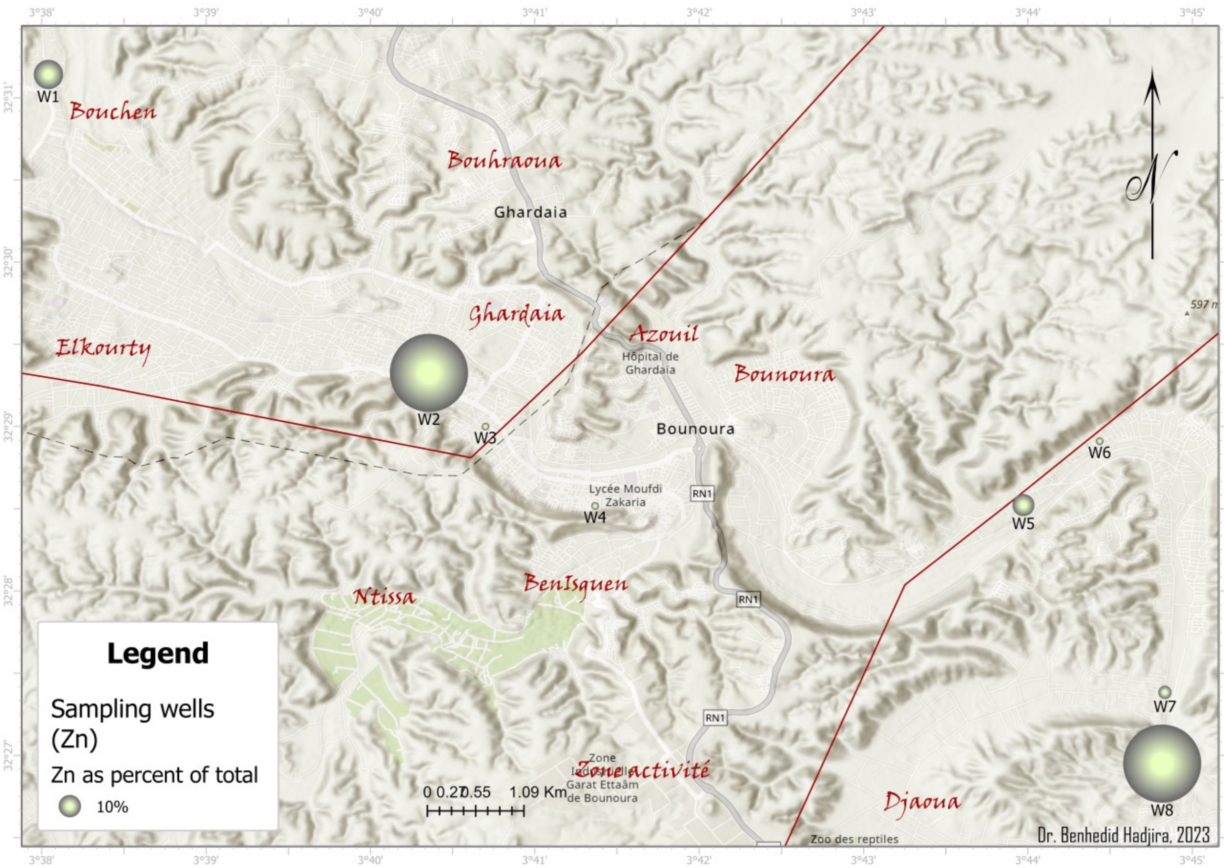

Figure 7. The Zn spatial distribution map of the Oued M'Zab phreatic aquifer

standard according to the WHO (0.3 mg/L) (18).

Health risks caused by cadmium in groundwater

Non-carcinogenic risk assessment

Non-carcinogenic risk assessment identifies the CDI of cadmium from groundwater wells in the valley of the M'Zab region. The CDI values were computed using Eq. (1). As shown in Table 1, CDI measures the amount of cadmium a person ingests daily over drinking water in the longer term. Here, the CDI values reflect the milligrams per kilogram of body weight per day (mg/kg/d) for distinct age categories, including children, infants, and adults.

It is noteworthy that the high CDI values observed in well W1 for children and infants and well W8 for adults indicate the need for immediate intervention to reduce the exposure to cadmium. Nevertheless, the low CDI values observed in well W4 for all age groups suggest it is a safe source of drinking water in the region. Therefore, the mean CDI for children is 0.0648 ± 0.0690 mg/kg/d, within the range of 0.0136 to 0.0341 mg/kg/d. Infants have a higher mean CDI of 0.0604 ± 0.0142 mg/kg/d, within the range of 0.0310 to 0.0779 mg/kg/d. Adults have the lowest mean CDI of 0.0151 ± 0.0035 mg/kg/d, within the range of 0.0077 to 0.0195 mg/kg/d. The standard deviation for the CDI values across all wells and age groups is 0.0095 mg/kg/d.

Table 1. CDI cadmium of the Oued M'Zab phreatic aquifer

		Child	Infant	Adult
Body weight (BW)		03.5	07	70
Samples	W1	0.0341	0.0779	0.0195
	W2	0.0243	0.0554	0.0139
	W3	0.0166	0.0378	0.0095
	W4	0.0136	0.0310	0.0077
	W5	0.0310	0.0707	0.0177
	W6	0.0273	0.0623	0.0156
	W7	0.0315	0.0719	0.0180
	W8	0.0333	0.0761	0.0190
Min		0.0136	0.0310	0.0077
Max		0.0341	0.0779	0.0195
Mean		0.0648 ± 0.0690	0.0604 ± 0.0142	0.0151 ± 0.0035

Carcinogenic risk assessment

While the non-carcinogenic risk assessment informs the CDI to measure the amount of cadmium in groundwater, the carcinogenic risk assessment focuses on the intake of cadmium (HQ) and the target organ risk (TOR), which were computed using Eq. (2 and 3). The data show the estimated daily intake of cadmium (HQ) and the TOR for the kidney in children, infants, and adults (Figures 8 and 9). The RfD of cadmium is 0.0005 mg/kg/d. The mean estimated daily consumption of cadmium was considerably high in infants (119.3 mg/kg/d) compared to children (50.4 mg/kg/d) and adults (24.8 mg/kg/d). The TOR for the kidney was higher in children (0.0318) compared to infants (0.0722) and adults (0.0181).

As discussed, the estimated daily consumption of cadmium varied significantly, with the highest value in infants (155.9 mg/kg/d) and the lowest value in adults (15.5 mg/kg/d), respectively. Similarly, the statistical result analysis of TOR for the kidney also varied extensively, with the highest value in children (0.0341) and the lowest value in adults (0.00775). In turn, the standard deviation (SD) of estimated daily consumption of cadmium was higher in infants (34.1) compared to children (16.8) and adults (7.0), exceeding the estimated daily intake among infants. Here, the SD of TOR for the kidney was highest in infants (0.0297) compared to children (0.0073) and adults (0.0057), exceeding the estimated TOR among infants.

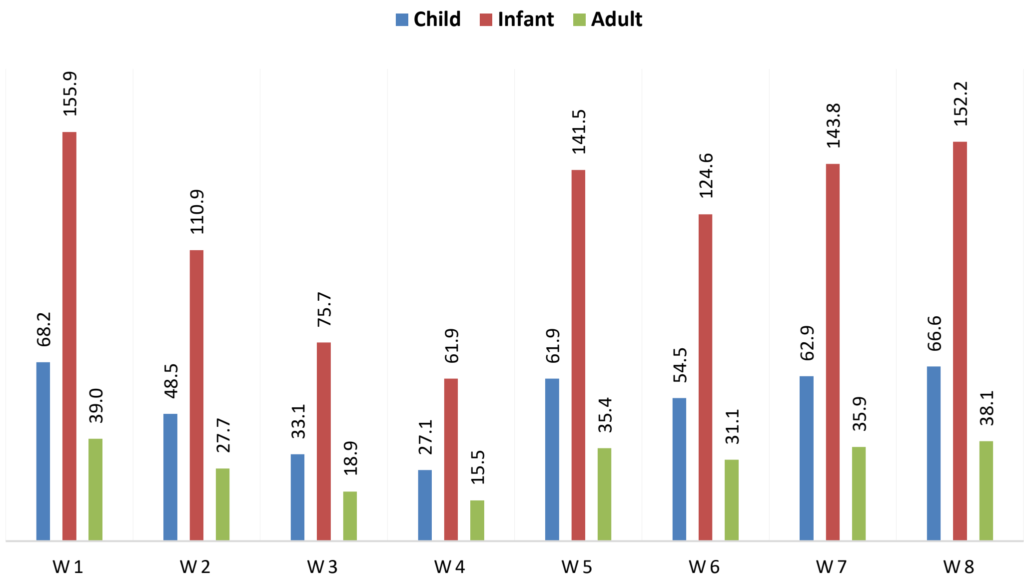

Figure 8. HQ cadmium of the Oued M'Zab phreatic aquifer

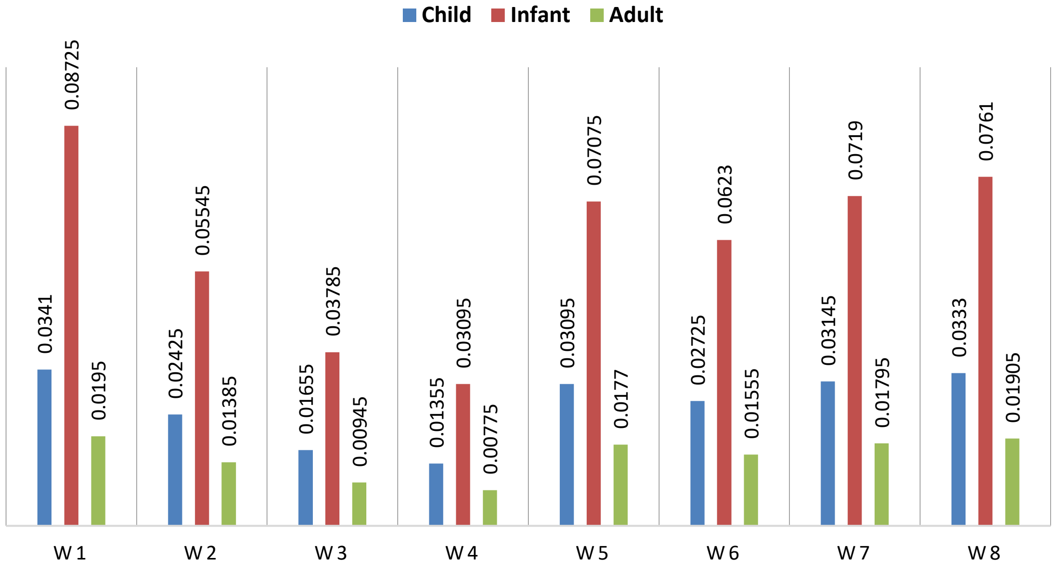

Figure 9. TOR cadmium of the Oued M'Zab phreatic aquifer

Discussion

This study examined eight wells in the M'Zab Valley in December 2019; specifically, it tackles environmental and human health risks resulting from the contamination of underground water. This covers the levels of heavy metals, such as cadmium, chromium, zinc, and lead analysis in the groundwater. By exploring this, this study applied the methodologies of the US EPA to investigate the effects of those heavy metals on human health and the environment. A significant point in this research is that the results showed that wells W1 and W8 have the highest concentrations of cadmium. The exposure to such high levels can cause significant damage to human health.

Cadmium is primarily toxic to the kidneys as chronic exposure to low levels of cadmium in drinking water over time can lead to cadmium nephropathy, a severe and irreversible kidney disease (26). Cadmium can accumulate in bones, leading to a potential reduction in bone density and an increased risk of osteoporosis and fractures (27). Evidence suggests that long-term exposure to cadmium in drinking water may be associated with an increased risk of lung cancer (28).

The high concentrations of cadmium in the wells are due to industrial activities, such as battery production, galvanization, welding, and agricultural practices, which use fertilizers containing cadmium.

Chromium is also a known human carcinogen. Long-term exposure to elevated levels of Chromium in drinking water is associated with an increased risk of gastrointestinal, lung, and other cancers (29). The statistical analysis shows that the average concentration of chromium wells is 0.328 mg/L, with a standard deviation of 0.049 mg/L. Wells W2 and W8 have concentrations higher than the average. The exposure to these concentrations can increase cancer and other health disorders.

The high concentrations of chromium in wells W2 and W8 are caused by either industrial pollution or the use of chromium-containing chemicals in agricultural activities. The presence of chromium in the other wells (W1, W3, W4, W5, W6, and W7) is below the reference threshold but is not necessarily uncontaminated.

For lead concentrations, statistical analysis reveals that the average lead concentration in all wells is 0.383 mg/L, with a standard deviation of 0.107 mg/L. Wells W5, W6, and W8 have lead concentrations higher than the average level, indicating potential lead contamination. Notably, lead with the highest concentration is found in well W8, raising concerns over health issues.

Lead exposure, even at low levels, can lead to irreversible neurological damage, particularly in developing fetuses in young children. It can result in developmental delays, reduced IQ, learning disabilities, and behavioral problems (30). Elevated lead levels in the blood are associated with an increased risk of hypertension, heart disease, and stroke in adults (31).

Further, wells W5, W6, and W8, with high lead concentrations, could be linked to industrial activities, mining, or lead-based pesticide use in agriculture. Lead concentrations in the other wells are below the maximum contaminant level set by the WHO (10 µg/L). However, given the low lead concentrations in the other wells, the issue of water contamination remains a concern in those wells.

Zinc concentrations fall below the drinking water standard set by the WHO. Zinc is a crucial component in the nutritional requirements of both humans and animals. It protects against cadmium and lead while also functioning as an antioxidant against free radicals (18). However, excessive levels of zinc in water can harm human health.

These results are significant compared to the Zn concentration (0 mg/L) from the three wells in January 1991, measured by Daddi Bouhoun (32) in this region. The comparison of our results is close to those recorded by Bouhanna (33), carried out in the Ouargla basin for groundwater of 0.123 mg/L ≤ Cd ≤ 0.354 mg/L and 0 mg/L ≤ Cr ≤ 0.692 mg/L.

In terms of the CDI values for cadmium in the M'Zab Valley, they are below the safe limit established by the WHO. Nevertheless, the potential health risks associated with chronic exposure over time, especially for wells with higher levels of cadmium, prevail as a significant concern. Therefore, it is worth integrating some insights into the health effects of cadmium exposure in other research studies that can significantly develop effective strategies for managing the risks associated with cadmium-contaminated drinking water in the M'Zab Valley.

In this vein, the data suggests that infants have the highest estimated daily intake of cadmium and TOR for the kidney, which may indicate a greater health risk associated with cadmium exposure within this age group. Therefore, future research can confirm and improve these findings to determine the potential health effects of cadmium exposure in different age groups.

Conclusion

In this research, the levels of cadmium, chromium, zinc, and lead in the groundwater of the M'Zab Valley and their potential impact on human health and the environment were investigated. The study reveals considerable variability in the concentrations of these metals in the groundwater wells, with some wells showing elevated contamination. The study suggests that industrial pollution and the use of chemicals in agriculture may be the potential sources of contamination. The findings highlight the importance of monitoring and remediation to ensure clean groundwater for human use and environmental protection. The research also discusses the potential health risks associated with exposure to high concentrations of these metals, especially cadmium, which can cause serious health effects, including kidney damage, respiratory problems, and developmental delays in children.

While the study explored eight phreatic aquifer wells in M'Zab Valley, considering the levels of CDI, HQ, and TOR in those wells, it was concluded that groundwater poses potential health risks. The study found that the CDI values for Cd for each age group (infants, children, and adults) were below the safe limit established by the WHO, but the data reveals that the concentration of the HQ is considerably greater in infants than in children and adult groups. Meanwhile, the TOR for the kidney appears substantially in children compared to infants and adults, which indicates a greater health risk associated with cadmium exposure in this age group.

Overall, the study's findings suggest that the groundwater in the M'Zab Valley is contaminated with heavy metals at levels that may pose a risk to human health. Further research is needed to identify the specific sources of contamination and to assess the full extent of the health risks to the population. Additionally, interventions would reduce exposure to heavy metals and protect the health of the different age groups, particularly infants.

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Authors' contributions

Conceptualization: Hadjira Benhedid, Mansour Achour, Mustapha Daddi Bouhoun.
Data curation: Hadjira Benhedid.
Formal analysis: Hadjira Benhedid, Mansour Achour.
Methodology: Hadjira Benhedid, Mustapha Daddi Bouhoun.
Resources: Hadjira Benhedid, Mansour Achour.
Software: Mansour Achour, Hadjira Benhedid.
Validation: Hadjira Benhedid.
Writing – original draft: Hadjira Benhedid.
Writing – review & editing: Hadjira Benhedid, Mansour Achour.

Competing interests

The authors declare that they have no conflict of interests.

Ethical issues

The authors certify that this manuscript is the original work of the authors, and all data collected during the study are presented in the manuscript, and no data from the study has been or will be published elsewhere separately.

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