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Health risks of groundwater fluoride in the urban coastal area of Béjaïa, North Algeria

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ABSTRACT

Fluoride (F^-) is an essential trace element required for normal bone and dental health; however, prolonged exposure to excessive concentrations through drinking water can lead to adverse health effects ranging from dental to skeletal fluorosis. The World Health Organization (WHO) recommends a permissible limit of 1.5 mg L^{-1} for fluoride in drinking water, beyond which chronic health effects may occur, particularly among vulnerable populations such as children and pregnant women. In the urban coastal area of Béjaïa, fluoride concentrations in groundwater varied substantially between shallow and deep aquifers, with several samples exceeding the WHO guideline value. To quantify potential health impacts, a human health risk assessment (HHRA) was conducted for three exposure groups children, women, and men considering both oral ingestion and dermal contact pathways. The calculated hazard quotients (HQ) for oral exposure revealed that 38.9% of children, 26.7% of women, and 31.1% of men were at potential non-carcinogenic risk (HQ > 1), indicating that fluoride exposure from drinking water may adversely affect a significant portion of the local population. Children exhibited the highest susceptibility due to lower body weight and higher water intake rates per unit body mass. Dermal absorption contributed negligibly to overall exposure (<5%), confirming that ingestion is the dominant pathway of concern. Spatially, elevated fluoride risk zones were mainly associated with areas dominated by mineral dissolution and desorption processes, where prolonged water–rock interaction and alkaline conditions favored the release of fluoride from F-bearing minerals such as fluorite and apatite. In contrast, regions influenced by seawater intrusion or high calcium concentrations exhibited relatively lower fluoride levels due to precipitation control (fluorite equilibrium). The predominance of HQ values exceeding unity in a substantial portion of samples emphasizes an urgent need for fluoride mitigation and safe water supply strategies in affected neighborhoods of Béjaïa. Regular monitoring of groundwater quality, particularly in high-pH and low Ca zones, is essential to prevent further accumulation of fluoride. Public health measures should focus on raising awareness, reducing exposure through blending or treatment (e.g., activated alumina or reverse osmosis), and targeting vulnerable groups such as school-aged children. In summary, the risk assessment demonstrates that fluoride contamination in the Béjaïa coastal aquifers poses a moderate to high non-carcinogenic risk, mainly through oral exposure. Addressing this issue through integrated hydrogeochemical monitoring and public health interventions is vital to ensure the sustainability and safety of groundwater resources in northern Algeria.

Keywords: groundwater, ingestion, fluor, health, cutane.

INTRODUCTION

Groundwater is a vital freshwater resource that supports drinking, domestic, agricultural, and industrial activities across many regions of the world, particularly in semi-arid and Mediterranean coastal environments. In northern Algeria, groundwater constitutes a major source of water supply for urban and peri-urban populations, due to the irregularity of rainfall, high evapotranspiration rates, and limited surface water storage (Cherifi et al., 2019; Rabet et al., 2022). However, the chemical composition of groundwater is governed by a complex interplay of natural and anthropogenic processes, including mineral dissolution, ion exchange, evaporation, and human activities such as agriculture and urbanization (Edmunds and Smedley, 2013; Li et al., 2020). These processes can lead to the accumulation of naturally occurring elements, such as fluoride (F^-), to concentrations that exceed safe levels for human consumption. Fluoride is the 13th most abundant element in the Earth's crust and occurs naturally in several minerals, including fluorite (CaF_2), apatite, amphibole, biotite, and mica. It is commonly released into groundwater through the dissolution of these fluoride-bearing minerals under favorable physicochemical conditions (Li et al., 2020; Wu et al., 2021). In moderate amounts (approximately 0.5–1.0 mg L^{-1}), fluoride contributes to the prevention of dental caries and supports normal bone mineralization. However, long-term ingestion of fluoride concentrations exceeding the World Health Organization (WHO) guideline value of 1.5 mg L^{-1} can lead to serious health problems, including dental and skeletal fluorosis, neurological effects, and kidney dysfunction (Fawell et al., 2006; WHO, 2017; Kim et al., 2021). Globally, high fluoride concentrations in groundwater have been documented in more than 50 countries, exposing over 200 million people to fluoride-related health risks (Ayoob and Gupta, 2006; Li et al., 2022 ; Kissar and Khemmoudj,2025). Major affected regions include India, China, Pakistan, Iran, Ethiopia, Kenya, and parts of North Africa, including Algeria. In Algeria, previous investigations have reported elevated fluoride concentrations in groundwater from several inland and semi-arid regions, particularly in the basins of Batna, Setif, Tébessa, and El Oued (Cherifi et al., 2019; Rabet et al., 2022). However, little is known about the occurrence, distribution, and geochemical behavior of fluoride in coastal aquifers, especially in densely populated areas such as Béjaïa. The coastal zone of Béjaïa, located in northeastern Algeria along the Mediterranean Sea, represents a hydrogeologically complex environment where freshwater–seawater interactions, carbonate formations, and urbanization pressures combine to influence groundwater chemistry. Coastal aquifers are often subject to salinization due to seawater intrusion, but they may also exhibit geochemical conditions (high pH, low Ca^{2+}, and long residence time) favorable for fluoride mobilization (Wu et al., 2021; Wagh et al., 2018, Bouderbala. 2020). In addition, urban and peri-urban land use activities may contribute indirectly to changes in redox conditions, alkalinity, and ionic strength, which can further control the dissolution and precipitation of fluoride-bearing minerals (Li et al., 2020, Kaddour et al., 2022). Despite these factors, studies on fluoride contamination and its health implications in the urban coastal zone of Béjaïa are lacking. Existing Algerian studies have mainly focused on inland aquifers, leaving a knowledge gap regarding the mechanisms controlling fluoride enrichment in coastal systems. Moreover, the health risks associated with fluoride exposure in coastal populations who may rely exclusively on groundwater for domestic use have not been comprehensively quantified. Understanding the geochemical controls and health implications of fluoride in these environments is essential for managing groundwater quality and safeguarding public health in northern Algeria.The mobilization of fluoride in groundwater is largely controlled by several interacting processes. These include: Mineral dissolution and precipitation, primarily involving fluorite and apatite, which release F^- under alkaline and low Ca^{2+} conditions. Ion exchange and desorption, where fluoride replaces hydroxyl ions (OH^-) or competes with bicarbonate (HCO_3^-) and phosphate (PO_4^{3-}) for adsorption sites on mineral surfaces (Edmunds and Smedley, 2013; Li et al., 2020). Evaporation and concentration effects, which increase the total dissolved solids (TDS) and promote the accumulation of fluoride in arid and semi-arid environments (Wagh et al., 2018). Seawater intrusion, which may influence the ionic strength and carbonate equilibria but generally dilutes fluoride concentrations because seawater contains relatively low F^- (0.8–1.4 mg L^{-1}) (Wu et al., 2021).Assessing the human health risks associated with groundwater fluoride requires consideration of both oral ingestion and dermal contact pathways, particularly for populations that use untreated groundwater for drinking, cooking, and bathing (USEPA, 2011). The hazard quotient (HQ) and hazard index (HI) are widely applied to evaluate the potential non-carcinogenic effects of fluoride exposure across different demographic groups (children, women, and men). These indices integrate exposure parameters such as ingestion rate, body weight, and exposure duration, allowing for the identification of high-risk areas and vulnerable populations (Wang et al., 2019; Li et al., 2022). The present study focuses on the urban coastal area of Béjaïa, an important economic and residential zone in northern Algeria. A total of 40 groundwater samples were collected from both shallow and deep aquifers to: (i) determine the spatial distribution and concentration of fluoride; (ii) identify the key hydrogeochemical processes governing its enrichment; and

(iii) evaluate the potential non-carcinogenic health risks associated with fluoride exposure for different population groups.The results are expected to enhance the understanding of fluoride contamination mechanisms in northern Algeria and contribute to developing effective groundwater management and public health protection strategies.

MATERIALS AND METHODS

Study area

The urban basin of Béjaïa City is situated within the lower valley of the Soummam watershed, which itself forms part of the larger Soummam hydrographic system located in northeastern Algeria (Figure 1). The study area lies in the coastal zone of Béjaïa, covering an approximate length of 12 km and a width of 3 km, for a total surface area of about 36 km². This region constitutes one of the most dynamic zones of the Soummam basin, where urbanization, agriculture, and industrial activities exert significant pressure on groundwater resources.Climatically, the area is characterized by a humid Mediterranean climate, with annual precipitation ranging between 600 and 900 mm and average summer temperatures varying from 24 to 28 °C. The relatively high rainfall, combined with a dense hydrographic network, contributes to the recharge of the alluvial aquifers developed in the lower Soummam plain and the Oued Soummam depression. Groundwater constitutes the main source of domestic water supply for Béjaïa's growing population. Hydrographically, the lower Soummam region is drained by several perennial rivers that flow predominantly from west to east. On the left bank, the principal tributaries are Oued Remila, Oued El-Kseur, and Oued Ghir, whereas on the right bank, the system is fed by Oued Amassine and Oued Amizour. These rivers converge downstream toward the Oued Soummam, which ultimately discharges into the Mediterranean Sea near Béjaïa City. This fluvial system plays a key role in both surface groundwater interactions and aquifer recharge processes. From a geological standpoint, the Soummam basin represents a transitional zone between the Northern Tell and Southern Tell structural units (Hassissene, 1989). The Southern Tell, encompassing the Bibans and Babors chains, borders the basin to the south, while the Northern Tell extends to the north and is composed of Kabyle metamorphic massifs, limestone ridges, and flysch formations. Stratigraphically, the lower Soummam region exhibits a wide range of lithostratigraphic units, including Quaternary, Upper Miocene, Pliocene, and Lower Miocene deposits, which outcrop along the valley margins (Duplan and Gravelle, 1960; Amharref et al., 2007). The Quaternary deposits consist mainly of alluvial formations, sands, gravels, and silts, which host the unconfined aquifer system. These materials are highly permeable and play a dominant role in the regional hydrogeological functioning, providing the main water-bearing units exploited for domestic and agricultural purposes. The Pliocene and Miocene formations, composed primarily of marls, sandstones, and limestones, form the confined aquifers at greater depths, locally separated by semi-permeable clayey horizons. The combination of favorable climatic conditions, complex geological formations, and intense anthropogenic activities (urbanization, industry, and agriculture) makes the Béjaïa coastal aquifer a critical system for studying groundwater quality evolution and fluoride enrichment mechanisms in northern Algeria.

Analytical procedures

Physicochemical parameters including pH, electrical conductivity (EC), and total dissolved solids (TDS) were measured in situ using a multiparameter probe (WTW MultiLine® 3420). Major anions (HCO_3^-, Cl^-, and SO_4^{2-}) were analyzed via acid–base titration, argentometric, and turbidimetric methods, respectively. Major cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) were determined by atomic absorption spectrophotometry (AAS; PerkinElmer Fluoride (F^-) concentrations were determined using a fluoride ion-selective electrode (Thermo Orion 9609BNWP), calibrated with standard fluoride solutions in a total ionic strength adjustment buffer (TISAB) to maintain constant ionic strength and pH. The analytical precision was verified by maintaining the ionic balance error within ±5% for all samples.

Human health risk assessment (HHRA)

Human health risk assessment of fluoride

Health risks associated with fluoride exposure were evaluated using the standardized risk assessment framework developed by the United States Environmental Protection Agency (USEPA, 2011). This methodology quantifies potential adverse

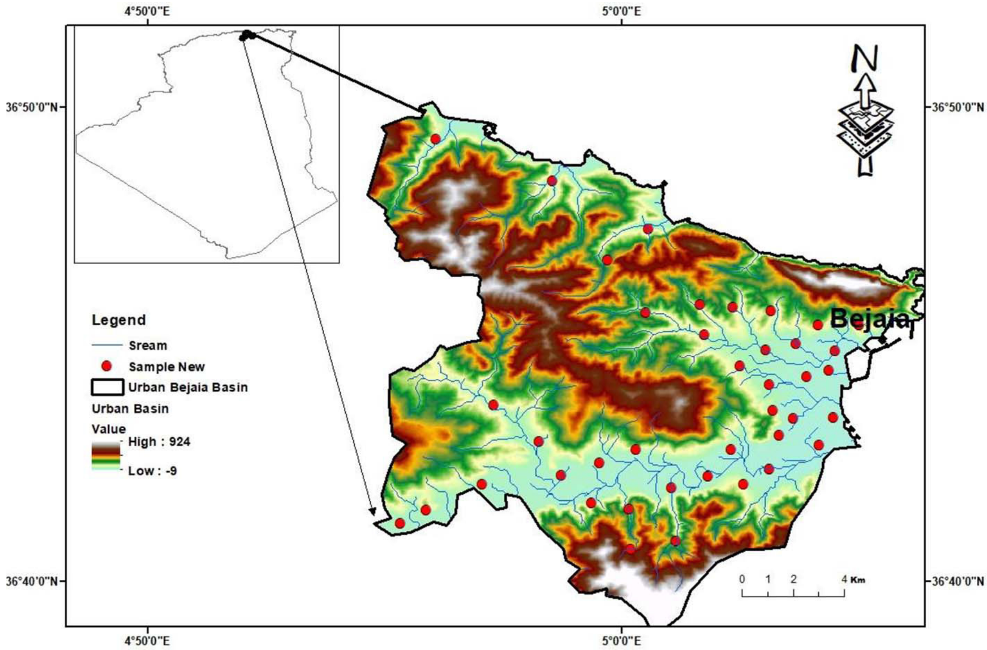

Figure 1. Location and physiography map of the study area

health effects resulting from chemical exposure by estimating the average daily dose (ADD) through different exposure pathways and comparing these values with established reference doses (RfD). In this study, two primary exposure routes were considered: oral ingestion and dermal absorption, which are the main pathways through which fluoride can enter the human body during daily water use.
Oral ingestion :

$$ADD_{ing} = \frac{C \cdot IR \cdot EF \cdot ED}{BW \cdot AT} \quad (1)$$

$$HQ_{ing} = \frac{ADD_{ing}}{RfD_{ing}} \quad (2)$$

where: Cw – fluoride concentration in water (mg L^{-1}), IR – ingestion rate (L day^{-1}), EF – exposure frequency (days year^{-1}), ED – exposure duration (years), BW– body weight (kg), AT – averaging time (days), calculated as ED*365 for non – carcinogenic effect.

The non-carcinogenic risk from cutaneous contact is represented as (Li et al., 2017b):

$$ADD_{derm} = \frac{C \cdot SA \cdot Kp \cdot ET \cdot EF \cdot ED \cdot CF}{BW \cdot AT} \quad (3)$$

where: SA – exposed skin surface area (cm²); Kp – dermal permeability coefficient for fluoride in water (cm/h); ET – exposure time (h/day); CF – conversion factor (1 L/1000 cm³).

Non-carcinogenic health risk estimation

To evaluate the potential for non-carcinogenic health effects, the hazard quotient (HQ) for each pathway was computed as the ratio of the estimated dose to the reference dose:

$$HQ_{derm} = \frac{ADD_{derm}}{RfD_{derm}} \quad (4)$$

The total hazard index (HI) was then obtained as the sum of HQ values from both pathways:

$$THI = HQ_{ing} + HQ_{derm} \quad (5)$$

An 1HI<1 indicates negligible risk, whereas HI>1 suggests potential health concern due to fluoride exposure.

Demographic exposure parameters

Exposure parameters were selected based on USEPA guidelines and previous regional studies, distinguishing between adults and children due to differences in physiology and water consumption behavior. Typical parameter values incude (Table 1).

Data processing and mapping

All analytical and statistical calculations were performed using OriginPro 2022,. The spatial distribution of fluoride concentration, hazard quotient (HQ), and hazard index (HI) were mapped using ArcGIS 10.8 with the Inverse Distance Weighting (IDW) interpolation method.

RESULTS AND DISCUSION

Physicochemical characteristics of groundwater

The statistical summary of the analyzed parameters (Table 1) reveals that fluoride concentrations ranged from 0.35 to 3.39 mg L^{-1}, with a mean of 1.69 mg L^{-1}, exceeding the WHO (2017) guideline of 1.5 mg L^{-1} in 42.5% of samples. The groundwater was generally neutral to slightly alkaline (pH 6.1–9.3), with moderate to high mineralization (EC: 149–3456 µS/cm). Elevated Ca^{2+} (33.72–420.6 mg L^{-1}) and HCO_3^- (55.1–427 mg L^{-1}) levels indicate dominance of carbonate weathering, while moderate Na^+ (5.44–290 mg L^{-1}) and Cl^- (7.19–279 mg L^{-1}) suggest local mixing or anthropogenic inputs.The variation in fluoride concentration correlated positively with HCO_3^- and pH, and negatively with Ca^{2+}, suggesting that fluorite dissolution under low Ca^{2+} and alkaline conditions is the main mechanism of F^- enrichment in the Béjaïa coastal aquifers.

Spatial distribution of total hazard index (THI) for men

The spatial variation of the THI for men in the urban Béjaïa Basin is presented in Figure 2. The THI values, representing the combined non-carcinogenic health risk from oral ingestion and dermal absorption of fluoride, range from 0.2 to 1.95. Spatially, the THI distribution reveals marked heterogeneity across the study area, delineating three distinct risk zones.The low-risk zone (THI = 0.2–0.7), represented by the green area, occupies the western and southwestern sectors of the basin. These regions correspond mainly to zones of relatively low fluoride concentrations (<1.0 mg L^{-1}) and moderate electrical conductivity, suggesting limited geochemical mobilization of fluoride. The groundwater in these areas is largely controlled by carbonate weathering and exhibits neutral pH, which reduces fluoride solubility and minimizes health risks. The moderate-risk zone (THI = 0.7–1.0), shown in yellow, dominates the central portion of the basin. Here, THI values approach the safety threshold of 1, indicating a potential concern for long-term fluoride exposure. This zone coincides with transitional hydrogeochemical environments where cation exchange and bicarbonate enrichment promote partial fluoride mobilization. Moderate alkalinity (pH 7.5–8.2) and reduced calcium concentrations contribute to the progressive increase in dissolved fluoride levels. In contrast, the high-risk zone (THI = 1.0–1.95), depicted in red, is concentrated in the eastern and northeastern parts of the basin, particularly around Béjaïa City and its surrounding coastal sectors. In these areas, groundwater fluoride concentrations frequently exceed the WHO permissible limit of 1.5 mg L^{-1}. The elevated THI values indicate a significant non-carcinogenic risk for adult men consuming groundwater in these localities. These hotspots are geochemically characterized by alkaline conditions (pH > 8.0), low calcium contents, and extended water–rock interaction, which collectively favor fluorite (CaF_2) dissolution and fluoride desorption from clay minerals. Anthropogenic influences, such as

Table 1. Table of exposure parameters

Parameter	Symbol	Unit	Children	Women	Men	Source
Body weight	BW	kg	15	60	70	USEPA (2011)
Water ingestion rate	IR	L day^{-1}	1.0	2.0	2.5	Wang et al. (2019)
Exposure duration	ED	years	6	30	30	Li et al. (2022)
Exposure frequency	EF	days $year^{-1}$	365	365	365	USEPA (2011)
Averaging time	AT	days	2190	10,950	10,950	USEPA (2011)
Skin surface area	SA	cm^2	6600	18,000	21,000	USEPA (2011)
Dermal permeability	Kp	cm h^{-1}	0.001	0.001	0.001	USEPA (2011)
Exposure time	ET	h day^{-1}	0.58	0.58	0.58	USEPA (2011)

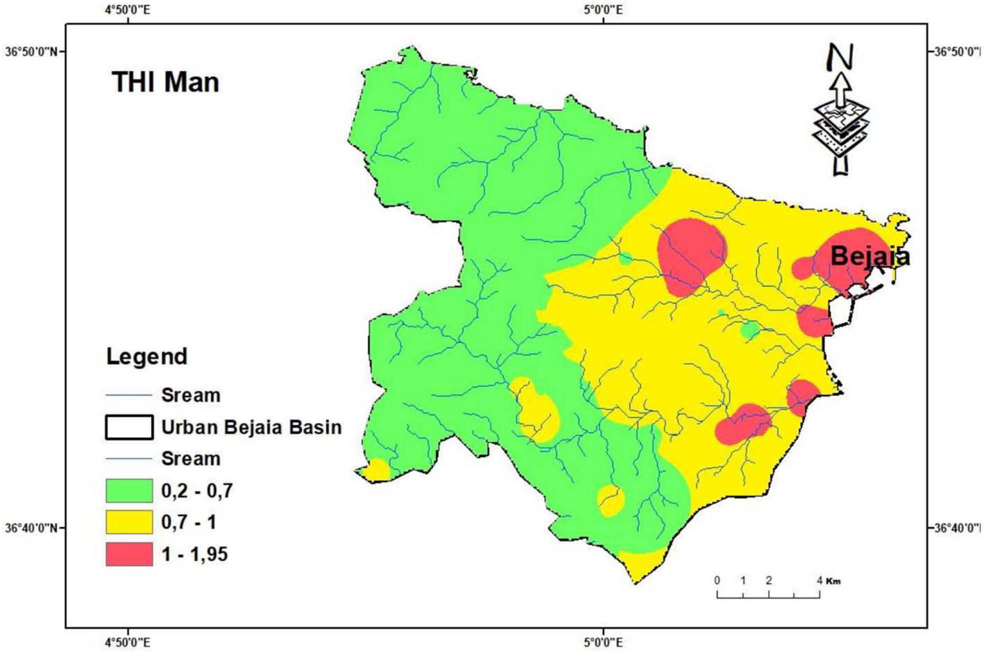

Figure 2. Spatial distribution map of THI man

industrial effluent infiltration and urban wastewater recharge, may further exacerbate fluoride concentrations in these confined aquifer zones. The spatial distribution pattern emphasizes that fluoride-related health risks are not uniformly distributed across the Béjaïa Basin. Instead, they are governed by the interplay between hydrogeochemical processes, lithological composition, and anthropogenic pressure. For adult men, whose average daily water intake is relatively high (2.5 L/day), the presence of THI values exceeding unity signifies a potential public health concern that warrants immediate intervention. Mitigation strategies should prioritize fluoride removal in identified high-risk zones, implementation of safe drinking water alternatives, and continuous monitoring to assess seasonal variability. The integration of GIS-based spatial risk mapping, as demonstrated in this study, provides an effective decision-support tool for local authorities to develop targeted water management policies and public health protection plans in the urban coastal region of Béjaïa.

Spatial distribution of total hazard index (THI) for women

The spatial distribution of the THI for women in the urban coastal Béjaïa Basin is illustrated in Figure 3, with values ranging from 0.19 to 1.82. Similar to the THI map for men, the spatial pattern for women exhibits clear geographical variability, reflecting the combined influence of fluoride concentration, hydrogeochemical conditions, and population exposure factors.The low-risk zone (THI = 0.19–0.73), represented in green, dominates the western and southwestern parts of the basin. In these regions, groundwater fluoride concentrations remain below 1.0 mg L^{-1}, and the hazard index values are well below the safety limit of unity, indicating no significant health threat to women from fluoride exposure. These areas are generally characterized by neutral pH, moderate calcium content, and carbonate-dominated geochemistry, which limit the dissolution of fluoride-bearing minerals such as fluorite.The moderate-risk zone (THI = 0.73–1.0), indicated in yellow, extends over much of the central basin, where the water chemistry shows a gradual increase in alkalinity and sodium concentration. These hydrogeochemical conditions favor partial fluoride desorption from clay minerals and the replacement of calcium by sodium in the aquifer matrix. In this transitional zone, groundwater fluoride concentrations approach the WHO (2017) threshold of 1.5 mg L^{-1}, leading to potential chronic exposure risks for women, particularly those with prolonged groundwater consumption.The high-risk zone (THI = 1.0–1.82), shown in red, is concentrated in the eastern and northeastern sectors, especially around Béjaïa City, Ihaddaden, and Amizour.

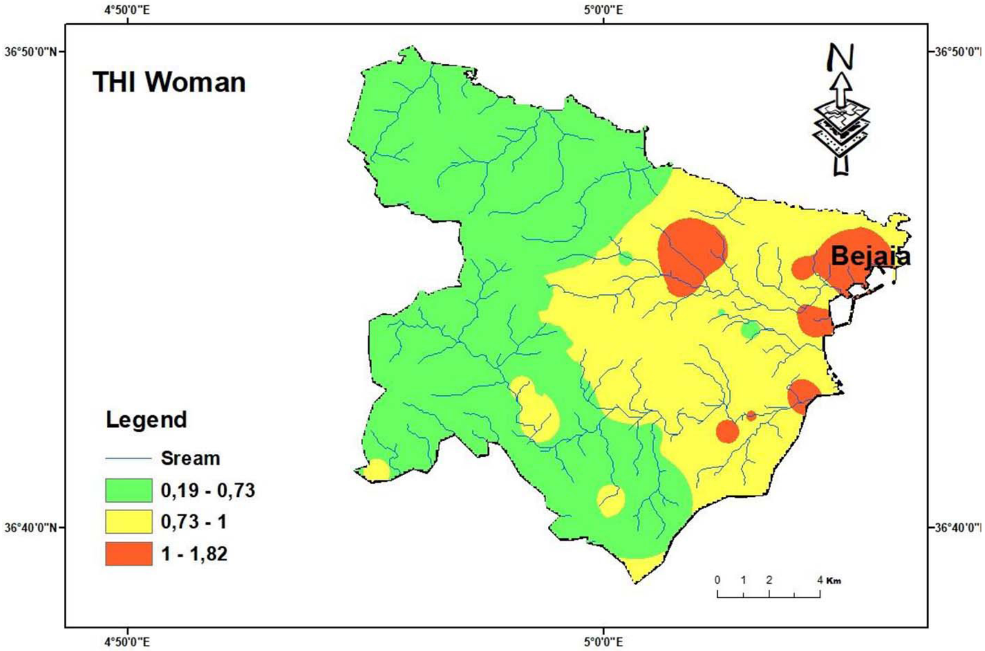

Figure 3. Spatial distribution map of THI woman

These areas coincide with the highest fluoride concentrations (up to 3.39 mg L^{-1}) and elevated pH (>8.0) conditions that enhance fluoride mobilization through fluorite dissolution and anion exchange. In these regions, THI values exceeding unity suggest that adult women face significant non-carcinogenic health risks, particularly through oral ingestion, which represents the dominant exposure pathway (>95% of total risk).Although women generally exhibit lower daily water intake (2.0 L/day) compared to men (2.5 L/day), their longer exposure duration (30 years) and slightly lower body weight increase their cumulative fluoride dose. Consequently, 26.7% of the female population in the study area may experience fluoride-related health effects, including dental or skeletal fluorosis, if current groundwater consumption continues without treatment or dilution.The spatial pattern of THI for women closely mirrors the fluoride distribution trends and underscores the importance of hydrogeochemical control on health risk variability. The coastal and eastern Béjaïa sectors, which coincide with urbanized and industrial zones, are the most critical areas requiring targeted monitoring and mitigation. Public health authorities should prioritize these regions for fluoride defluoridation programs, safe water alternatives, and community awareness campaigns focused on the health effects of long-term fluoride exposure.

Spatial distribution of total hazard index (THI) for children

The spatial distribution of the THI for children (Figure 4) reveals a distinct and alarming pattern compared with that of adults. The THI values for children range between 0.14 and 1.36, showing a clear east–west gradient, with high-risk areas concentrated in the eastern and coastal sectors of Béjaïa. This spatial variability directly reflects both the geochemical heterogeneity of fluoride in groundwater and the greater physiological susceptibility of children to fluoride exposure.The low-risk zone (THI = 0.14–0.5), represented in green, dominates the southwestern and northwestern parts of the study area. In these zones, groundwater fluoride concentrations remain below 1.0 mg L^{-1}, resulting in THI values well below unity. The absence of significant health risk in these areas can be attributed to the dominance of bicarbonate–calcium water types, moderate pH, and limited rock–water interactions that restrict the dissolution of fluoride-bearing minerals.The moderate-risk zone (THI = 0.5–1.0), shown in yellow, occupies the central basin, where a gradual shift toward $Na–HCO_3$ water types is observed. This change indicates increasing water–rock interaction and partial ion exchange between sodium and calcium, which enhances fluoride mobility. In these areas, children may begin to experience

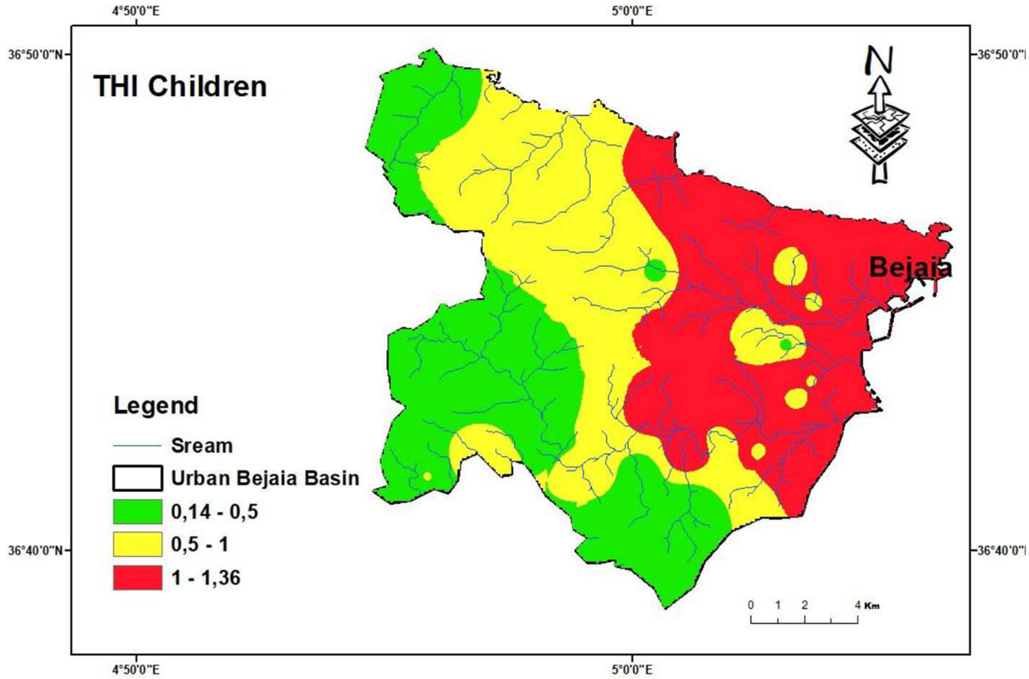

Figure 4. Spatial distribution map of THI Children

mild dental fluorosis with long-term exposure, as the THI values approach the threshold limit of 1.The high-risk zone (THI = 1.0–1.36), indicated in red, is primarily located in the eastern and northeastern sectors, encompassing Béjaïa City, Ihaddaden, Tichy, and adjacent coastal plains. These areas correspond to fluoride concentrations exceeding 1.5 mg L^{-1}, often reaching up to 3.39 mg L^{-1} in localized wells. The elevated THI values indicate that children are the most vulnerable group, as their daily fluoride intake per body weight is significantly higher than that of adults due to lower body mass, higher water consumption rates (1 L/day), and incomplete enamel mineralization. Consequently, the non-carcinogenic health risk exceeds unity, suggesting a potential for adverse effects such as dental mottling and skeletal deformities if exposure persists.This spatial pattern emphasizes that the coastal and eastern Béjaïa zones represent critical fluoride-risk areas for the child population. The combination of high groundwater fluoride concentrations, alkaline pH (>8.0), and sodium enrichment favors fluoride desorption and dissolution of fluorite. Furthermore, anthropogenic inputs from urbanization, wastewater infiltration, and industrial activities may exacerbate fluoride mobilization in these aquifers.Overall, the THI distribution demonstrates that children are the most affected demographic, with more than one-third of the study area posing potential health risks. Therefore, urgent mitigation strategies are required in high-risk zones, including:Installation of community-level defluoridation systems (activated alumina, reverse osmosis). Public awareness programs to inform families about safe water practices.Regular monitoring of fluoride concentration in wells and urban water supplies.Promotion of alternative drinking sources in fluoride-prone areas. These results align with findings from similar fluoride-affected coastal regions in North Africa and South Asia (e.g., Amini et al., 2008; Kundu et al., 2015; Rahman et al., 2020), confirming that children's exposure to fluoride through groundwater consumption remains a significant environmental health concern in semi-arid, coastal aquifer systems such as Béjaïa.

Comparative risk assessment by population group

The comparative analysis of THI values among men, women, and children (Figures 2–4) reveals significant differences in fluoride exposure and vulnerability across population groups within the urban coastal Béjaïa Basin. These disparities stem from physiological, metabolic, and behavioral factors that influence the rate of fluoride intake and its retention in the human body.

Overall, THI values for all population groups exhibit a spatial trend increasing from the western to the eastern part of the study area, where the fluoride concentration in groundwater is higher. However, the magnitude of health risk varies substantially, following the general order: Children > Women > MenThis gradient indicates that children are the most susceptible group, while adult men are the least affected, despite sharing the same water sources.

THI variation by demographic group

- Men:

THI values for adult men range from 0.2 to 1.95, with most areas showing values below unity. The low to moderate risk zones (green and yellow areas) cover nearly 80 % of the basin, primarily in the western and central sectors. Elevated THI values (> 1.0) are confined to localized zones in the east and northeast, reflecting higher fluoride concentrations (> 1.5 mg L^{-1}). The relatively lower risk among men is attributed to their higher average body weight, resulting in a lower fluoride dose per unit body mass.

- Women:

For adult women, THI values range from 0.19 to 1.82, slightly lower in range but spatially more extensive than in men. Moderate to high-risk zones (yellow to red) dominate the central and eastern basin, particularly around Béjaïa City, Tichy, and Ihaddaden. Due to lower body weight and distinct metabolic factors, women exhibit higher fluoride absorption efficiency, increasing their susceptibility to dental and skeletal fluorosis. Prolonged exposure could also affect reproductive health, as suggested by studies in similar semi-arid aquifer systems (Amini et al., 2008; Kundu et al., 2015).

- Children:

Children show THI values ranging from 0.14 to 1.36, but with a far greater proportion of the study area exceeding the safe threshold (THI > 1). Nearly 40–45 % of the basin, mainly in the eastern and southeastern parts, falls within the high-risk category. This elevated risk is due to higher water consumption relative to body weight, lower renal clearance, and developing bone and dental tissues, which accumulate fluoride more efficiently (Rahman et al., 2020). The map clearly identifies the urban coastal and peri-urban zones of Béjaïa as critical hotspots for fluoride toxicity in children.

Spatial and public health implications

The overlapping high-risk areas for all three demographic groups coincide with the coastal plain and eastern Béjaïa zones, where Na–HCO_3-type waters with alkaline pH (> 8) favor fluoride desorption from aquifer minerals such as fluorite and biotite. This consistency confirms that natural geochemical processes, enhanced by urbanization and anthropogenic recharge, are the dominant drivers of fluoride enrichment.From a public health standpoint, the findings emphasize the urgent need for age-specific risk mitigation strategies. For children, this includes the implementation of school-based safe water programs and defluoridation technologies. For women, particularly pregnant or lactating mothers, nutritional interventions (adequate calcium intake) could help mitigate fluoride absorption. Finally, regular monitoring and community awareness campaigns are crucial to prevent chronic fluorosis and ensure sustainable groundwater management.Overall, this comparative assessment highlights the multidimensional nature of fluoride risk, where both hydrogeochemical factors and demographic sensitivity determine exposure outcomes. It reinforces the importance of integrating spatial risk mapping, demographic analysis, and public health perspectives in groundwater quality management in coastal regions such as Béjaïa, North Algeria.

CONCLUSIONS

This study presents a comprehensive assessment of fluoride contamination and associated health risks in the urban coastal area of Béjaïa, situated in northeastern Algeria. Forty groundwater samples from shallow and deep aquifers were analyzed to elucidate the hydrogeochemical processes controlling fluoride mobility and to evaluate potential non-carcinogenic health risks across different population groups.The results demonstrate that fluoride concentrations ranged from 0.35 to 3.39 mg L^{-1}, with an average value of 1.69 mg L^{-1}, exceeding the World Health Organization (WHO, 2017) guideline limit of 1.5 mg L^{-1} in approximately 40% of samples. The enrichment of fluoride is predominantly controlled by mineral dissolution and precipitation, cation exchange, and desorption processes, while evaporation and seawater intrusion play a minimal role. In particular, the dominance of

$Na–HCO_3$-type waters and alkaline pH conditions (7.3–9.3) facilitates the dissolution of fluorite (CaF_2) and desorption of fluoride from clay minerals, in agreement with findings reported by Jacks et al. (2005) and Amini et al. (2008). Spatially, the highest fluoride concentrations were recorded in the eastern and coastal sectors of Béjaïa, notably in Ihaddaden, Tichy, and adjacent areas, where longer groundwater residence time, higher bicarbonate content, and ion exchange favor fluoride accumulation. Conversely, the southwestern and central parts of the basin exhibit lower fluoride levels, likely due to faster groundwater flow and limited rock–water interaction (Kundu et al., 2015; Guissouma et al., 2017). Health risk assessment using the THI revealed a clear hierarchy of susceptibility among the population groups: children > men > women. Specifically, THI values exceeded unity for 38.9% of children, 31.1% of men, and 26.7% of women, implying potential non-carcinogenic health hazards due to chronic exposure. Children are particularly vulnerable due to their higher water intake per body weight, lower excretion capacity, and developing skeletal and dental systems (Mohapatra et al., 2009; Rahman et al., 2020). The integration of hydrogeochemical modeling and spatial GIS-based risk mapping provides valuable insights into the distribution of fluoride-related health risks in the Béjaïa region. The findings highlight the necessity for immediate mitigation measures, including:Implementation of defluoridation technologies (activated alumina, bone char, or reverse osmosis). Routine monitoring of groundwater quality, particularly in high-risk coastal zones. Public awareness programs emphasizing the safe use of drinking water and dietary interventions to minimize fluoride intake. Inclusion of fluoride risk management in regional water resource planning frameworks. Overall, this study contributes to a deeper understanding of the hydrogeochemical mechanisms of fluoride enrichment and their implications for public health in northern Algeria. It establishes a scientific foundation for sustainable groundwater management and can serve as a reference for similar coastal aquifer systems in semi-arid regions worldwide.

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