



Assessment of human health risk and fluoride contamination in the arid coastal aquifer, Saudi Arabia

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Abstract

A systematic study was performed to explore human health risks for the local populace due to fluoride contamination in the arid coastal aquifer, Saudi Arabia using fluoride contamination zone mapping, contamination index (C_d), chronic daily intake (CDI), and hazard quotient (HQ) calculations. The groundwater ($n = 52$) in the study region is neutral to alkaline, brackish to saline and very hard in nature. Groundwater in 27% of wells surpassed the drinking water fluoride level ($F > 1.5$ mg/l) recommended by the WHO and has $C_d > 0$, which is unpalatable for drinking. Groundwater chemistry in the study area is predominantly influenced by evaporation processes and high fluoride groundwater belongs to the NaCl type. During evaporation, precipitation of carbonate minerals triggered the dissolution of fluoride minerals; consequently, groundwater is enriched with fluoride and salinity. Adverse health effects, calculated using CDI_{oral} and HQ_{oral} , suggested that 23% and 33% of samples show a non-carcinogenic threat to adults and children, respectively. The fluoride contamination zone mapping and the spatial distribution of C_d values and HQ_{oral} substantiated that groundwater in the downstream region is degraded due to higher fluoride content, which can cause a health threat to human beings. In the study area, evaporation along with mineral weathering resulted in fluoride enrichment in the groundwater. Thus, proper treatment is required to remove the fluoride and salinity from the groundwater before use. The outcome of this study can help local municipalities and water management authorities for planning.

Keywords Groundwater · Fluoride · Evaporation · Contamination index · Health risk assessment · Saudi Arabia

Introduction

Groundwater contamination by fluoride is widely reported and grabbed more attention in the world (Esmaeili et al. 2018; Knappett et al. 2018; Djari et al. 2018; Cinti et al. 2019; Elumalai et al. 2019; Li et al. 2019; Radfard et al. 2019; Younas et al. 2019; Zango et al. 2019; Alarcon-Herrera et al. 2020; Alcaine et al. 2020; Gao et al. 2020; Makubalo and Diamond 2020; Mukherjee and Singh 2020; Adimalla and Qian 2021; Rajmohan et al. 2021a; Senthilkumar et al. 2021). Fluoride is an essential element for the human body for skeletal and dental growth. World Health Organization (WHO) prescribed a limit (< 1.5 mg/l) for fluoride in drinking water (WHO 2017). Low concentration ($F < 0.5$ mg/l) in the drinking water causes dental decay for

children and infants, and osteoporosis, while higher concentration ($F > 1.5$ mg/l) results in fluorosis (He et al. 2020). Recent studies reported several adverse effects, namely dental enamel degradation, crippling in major joints and spine, nausea, diarrhea, blood cells damage due to calcification, neurological issues, bone fractures, impaired thyroid function, reduction in birth rate, urolithiasis (kidney stones) formations, and decrease in children intelligence due to high fluoride intake through drinking water (Ozsvath 2009; Perumal et al. 2013; Jiang et al. 2019; Mukherjee et al. 2019).

In the arid and semi-arid regions, groundwater contamination and fluoride enrichment are extensively reported in the literature, namely China (Gao et al. 2020; Li et al. 2020), Mexico (Morales-Arredondo et al. 2016; Knappett et al. 2018; Alarcon-Herrera et al. 2020), Iran (Enalou et al. 2018; Radfard et al. 2019; Rezaei et al. 2019), Gaza strip (Jabel et al. 2014), Tanzania (Ghiglieri et al. 2010), Argentina (Alvarez and Carol 2019; Alcaine et al. 2020), South Africa (Elumalai et al. 2019; Makubalo and Diamond 2020), Pakistan (Rafique et al. 2015; Younas et al.

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2019), Ghana (Zango et al. 2019), Jordan (Abboud 2018), Egypt (Ahmed 2014) and Ethiopia (Furi et al. 2011).

Natural sources are predominantly linked with fluoride enrichment in groundwater compared to anthropogenic sources. Weathering and dissolution of fluorite (CaF_2), cryolite, apatite, hornblende, muscovite, tremolite, biotite, villianmite, topaz, fluorapatite and micas are common sources for fluoride in the aquifer (Chowdhury et al. 2019). In the case of wells located in the sedimentary (i.e., shale) and igneous rocks (i.e., granites), formations have high fluoride in the groundwater. Apart from the geogenic sources, irrigation return flow, application of phosphate fertilizers, brick industries, fly ash and emission from industries are also contributed to fluoride enhancement in groundwater (Datta et al. 1996; Vithanage and Bhattacharya 2015; Kadam et al. 2019). Fluoride accumulation in the aquifer is also linked to other factors, such as high bicarbonate and pH, residence time, thermal springs, volcanic activities, and local climatic conditions (Vithanage and Bhattacharya 2015).

Health risk assessment (HRA) of groundwater is widely performed using a recommended model of United States Environmental Protection Agency (USEPA) to explore the impact of nitrate, fluoride and trace metals on human health (Li et al. 2014; Keshavarz et al. 2015; Narsimha and Rajitha 2018; Shahid et al. 2018; Adimalla et al. 2019; Mukherjee et al. 2019; Rezaei et al. 2019; Zhang et al. 2019; Chen et al. 2020; Fan et al. 2020; Ji et al. 2020; Kumar and Singh 2020; Mukherjee and Singh 2020; Singh et al. 2020; Wagh et al. 2020; Rajmohan et al. 2021a). As fluoride contamination is getting more important, recent studies employed this approach to explore health hazards linked to intake of high fluoride groundwater (Keshavarz et al. 2015; Kadam et al. 2019; Mukherjee et al. 2019; Rajmohan et al. 2021a).

In Saudi Arabia, fluoride contamination in groundwater is identified in various regions (Al-Ahmadi and El-Fiky 2009; Alabdulaaly et al. 2013; Shraim et al. 2013; Ghrefat et al. 2014; Loni et al. 2015; Alharbi et al. 2017; Alfaifi 2019; Rajmohan et al. 2021a; Alqahtany 2021) and is considered as a serious concern in this region. Further, it is well known that natural water resources in Saudi Arabia are very limited and depend on desalination for most of the water demand. Thus, the present investigation was performed in the Al Lusub basin (a) to explore the current status of fluoride contamination and its distribution; (b) to assess the water suitability for drinking; (c) to demark the fluoride contamination zones and (c) to assess the health risks for local populace using USEPA model. The outcome of this study can create awareness about fluoride contamination in the study region and also help local municipalities and water management authorities for future planning.

Materials and methods

Study area

The study was performed in the Wadi Al Lusub basin, which is located in western Saudi Arabia (Latitude: $39^{\circ} 0' - 40^{\circ} 20'$; Longitude: $39^{\circ} 0' - 40^{\circ} 20'$) (Fig. 1). The study area covers 2497 square km and experiences an arid climate. The maximum temperature ranges from 38°C to 43°C , and the minimum temperature varies from 16°C to 33°C . The study area has irregular and highly variable rainfall and it varies from 70 mm in the western part to 120 mm in the eastern region (Basahi et al. 2017). The topography is also highly variable, and the elevation varies from 1443 m above mean sea level (amsl) in the upstream to 1 m amsl in the downstream region.

The study area is in the Arabian Shield and comprises metamorphic and plutonic rocks, which belong to the Precambrian, Tertiary and Quaternary age (Fig. 1). The northeastern part is covered by the Rahat group (Tertiary age), which comprises Shaw Hit and Amah basalt intercalated with alluvial deposits. In the downstream, sedimentary rocks (tertiary age) are overlain by sheets of basaltic lava flows. The sedimentary formations are categorized into two groups as the Usfan and Shumaysi Formations. The Usfan formation is composed of sandstones, shales, marls and fossiliferous carbonate wedges while the Shumaysi formation comprises sandstones, siltstones and oolitic ironstone bands (Chebotarev 1955; El-Didy 1999; Rajmohan et al. 2019). The quaternary formation formed a potential aquifer in the study site, which comprises gravel, sand and sandstone with some intercalations of shale. The aquifer in the study area is unconfined to semi-confined/confined in nature (Sharaf et al. 2001; Rajmohan et al. 2019). The unconfined shallow aquifer is mostly used for irrigation. The groundwater level varies from 5 to 50 mbgl, which is deeper in the central part of the study region (Rajmohan et al. 2019). Groundwater flows from northeast to northwest via the central region.

Groundwater sampling and analysis

In the Al Lusub basin, 52 groundwater samples were collected, in which 49 samples from tube wells and 3 samples from dug wells and temperature, electrical conductivity (EC) and pH were measured in the field using a portable meter (SevenGo Duo SG23, Mettler Toledo). Groundwater sampling, transport, storage, and analysis were performed based on international standard procedures (Keefe et al. 2003; APHA 2017). Water sampling was carried out after the stabilization of EC to ensure freshness and to represent

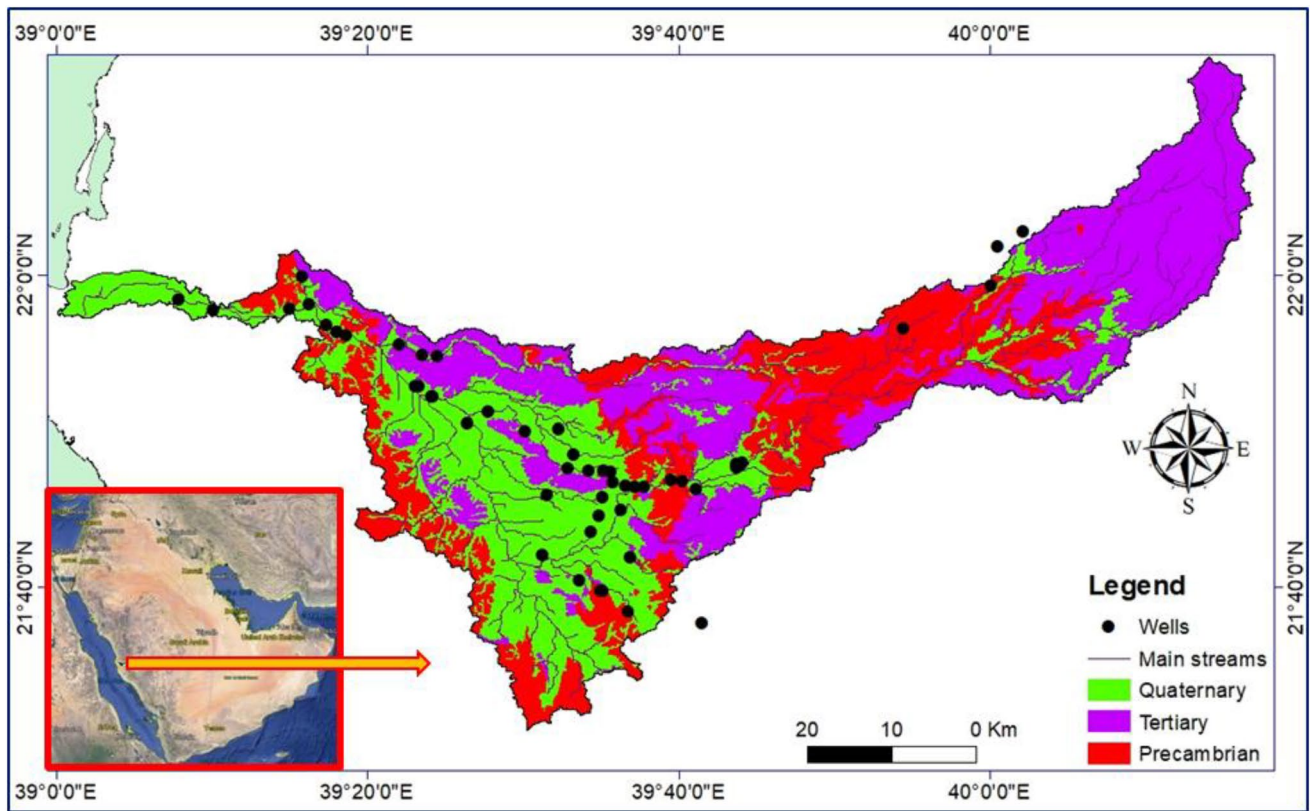


Fig. 1 Groundwater sampling wells, drainage and geology details in the Wadi Al Lusub basin

the aquifer. Pre-cleaned HDPE bottles were used for water sampling and the samples were filtered through a 0.45 μm millipore membrane filter to remove the undissolved impurities. The samples were properly sealed, labeled, stored and transported to the laboratory within 24 h and preserved at 4 $^{\circ}\text{C}$ for the further analyses. Ion chromatography (Thermos scientific, ICS 5000+) was employed to analyze the major ions (Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Cl^- , SO_4^{2-}) and minor ions (NO_3^- , F^- , Br^-). The volumetric titration method was used for determining bicarbonate and carbonate (APHA 2017). The precision and measurement repeatability of each analysis were $<2\%$ and the calculated ion balance error was $\pm 5\%$.

Data analysis

Analytical results were used in the Chadha diagram and Gibbs plots to identify the water types and geochemical processes governing water chemistry, respectively. To evaluate the effect of ingestion of high fluoride groundwater on human health, chronic daily intake (CDI) and hazard quotient (HQ) were calculated using USEPA (2011) model. ArcGIS v10.3 was employed for various spatial maps preparation, namely spatial distribution of fluoride,

fluoride contamination zones, contamination index and HQ. The spatial reference system WGS 1984 was used in the ArcGIS for maps preparation. In the spatial distribution maps preparation, the inverse distance weighted (IDW) interpolation method was employed.

Contamination index

Contamination index (C_d) is generally used to assess the cumulative effect of metal content in the groundwater over the recommended international drinking water standards (Backman et al. 1998). In this study, C_d is used to explore the fluoride contamination in this arid aquifer. The C_d is calculated using the following Eq. (1).

$$C_d = \frac{C_{Ai}}{C_{Ni}} - 1 \quad (1)$$

where C_d is the contamination index, C_{Ai} is the analyzed fluoride concentration in the water sample and C_{Ni} is the fluoride concentration (1.5 mg/l) recommended by the WHO for drinking water.

Health risk assessment

United States Environmental Protection Agency (USEPA) has recommended some models to evaluate the hazards for human beings by various pollutants through water, air and food or dietary sources. Among the various exposurer pathways, the ingestion of pollutants through drinking water is a major concern. In this study, health risk due to the consumption of high fluoride water for adults and children is calculated. The chronic daily intake (CDI) is calculated using Eq. 2. The non-carcinogenic risk due to fluoride in drinking water is estimated by hazard quotient (HQ) (Eq. 3) (USEPA 1989; Wu et al. 2015; He et al. 2020).

$$CDI_{\text{oral}} = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad (2)$$

$$HQ = \frac{CDI_{\text{oral}}}{RfD} \quad (3)$$

where C represents the concentration of F^- in the groundwater (mg/l). Ingestion rate (IR) is 2.5 and 0.78 (l/day) for adults and children, respectively (USEPA 2014). EF is the exposure frequency (days/year), which is 365 days for both adults and children. ED (exposure duration) is 65 and 6 years for adults and children, respectively (Narsimha and Rajitha 2018; Kadam et al. 2019). BW is the average body weight and it is 65 kg and 15 kg for adults and children, respectively. The average exposure time (AT) for adults and children is 23775 and 2190 days, respectively. RfD is the oral reference dose (mg/kg/day) of F^- , which is 0.06 (mg/kg/day) (USEPA 1993). In the groundwater, the CDI_{oral} and HQ_{oral} values greater than 1 possibly cause a health threat to human beings.

Results and discussion

Groundwater in the study area is mostly neutral to alkaline in nature and the pH in 75% of samples is greater than 7. The groundwater pH varies from 6.6 to 7.8 with an average of 7.2 ($n=52$). The EC and TDS in the groundwater range from 1291 $\mu\text{S}/\text{cm}$ to 25,700 $\mu\text{S}/\text{cm}$ and from 646 mg/l to 12,860 mg/l with a mean value of 9780 $\mu\text{S}/\text{cm}$ and 4892 mg/l, respectively. The groundwater in the study area is classified as brackish (71%) to saline (21%) (Freeze and Cherry 1979) and the groundwater is very hard ($TH > 300$ mg/l; Sawyer and McCarty 1967) except for one sample in the study site. Fourteen samples (27%) are not suitable for drinking based on fluoride concentration ($F > 1.5$ mg/l; WHO 2017), which is relatively similar to the earlier studies documented from Saudi Arabia (Ghrefat et al. 2014; Loni et al. 2015; Alharbi et al. 2017; Idriss et al. 2020; Rajmohan et al. 2021a).

Groundwater samples are classified into three groups based on fluoride concentrations, namely group 1 ($F < 0.5$ mg/l; $n=17$), group 2 ($1.5 < F > 0.5$; $n=21$) and group 3 ($F > 1.5$ mg/l; $n=14$) and the descriptive statistical summary of physiochemical parameters analyzed in these groups is given in Table 1. The groundwater fluoride (average) in the group 1, 2 and 3 wells is 0.3, 0.9 and 2.4 mg/l, respectively. Likewise, the average concentrations of TDS in groups 1, 2 and 3 are 1658 mg/l, 4506 mg/l and 9397 mg/l, respectively. The mean EC values are 3317 $\mu\text{S}/\text{cm}$, 9010 $\mu\text{S}/\text{cm}$ and 18,784 $\mu\text{S}/\text{cm}$ in the group 1, 2 and 3 water samples, respectively. Groundwater in group 3 wells has a high salinity and fluoride. Except for HCO_3^- , the concentrations of all the parameters analyzed are also high in the group 3 samples.

Table 1 Statistical summary of physico-chemical parameters analyzed in the groundwater

	pH	EC	TDS	TH	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	HCO_3^-	SO_4^{2-}	NO_3^-	F^-	Br^-
Group 1 ($F < 0.5$ mg/l; $n=17$)														
Min	7.3	1291	646	283	68	1	69	16	72	114	117	7	0.1	0.4
Max	7.8	8920	4460	2464	1151	24	830	306	1996	264	2351	240	0.5	8.5
Average	7.5	3317	1658	1073	336	7	266	99	591	184	862	99	0.3	2.8
STD	0.2	1881	940	671	263	5	186	72	463	45	653	70	0.1	2.2
Group 2 ($1.5 < F > 0.5$ mg/l; $n=21$)														
Min	6.6	2410	1205	743	217	4	184	69	348	57	638	6	0.5	2.4
Max	7.5	24,500	12,260	6297	3241	53	1729	604	8434	659	3913	324	1.5	118.0
Average	7.1	9010	4506	2624	1179	18	645	246	2401	209	1777	111	0.9	19.9
STD	0.2	6273	3138	1602	906	13	444	149	2206	130	912	90	0.3	27.0
Group 3 ($F > 1.5$ mg/l; $n=14$)														
Min	6.6	6650	3330	1552	837	19	491	73	1320	92	740	7	1.6	6.8
Max	7.3	25,700	12,860	6676	4036	48	1513	792	8054	433	5162	810	4.0	97
Average	7.0	18,784	9397	4683	2834	34	1078	484	5483	191	3471	268	2.4	41
STD	0.2	6724	3366	1739	1150	10	354	238	2418	86	1218	270	0.6	22

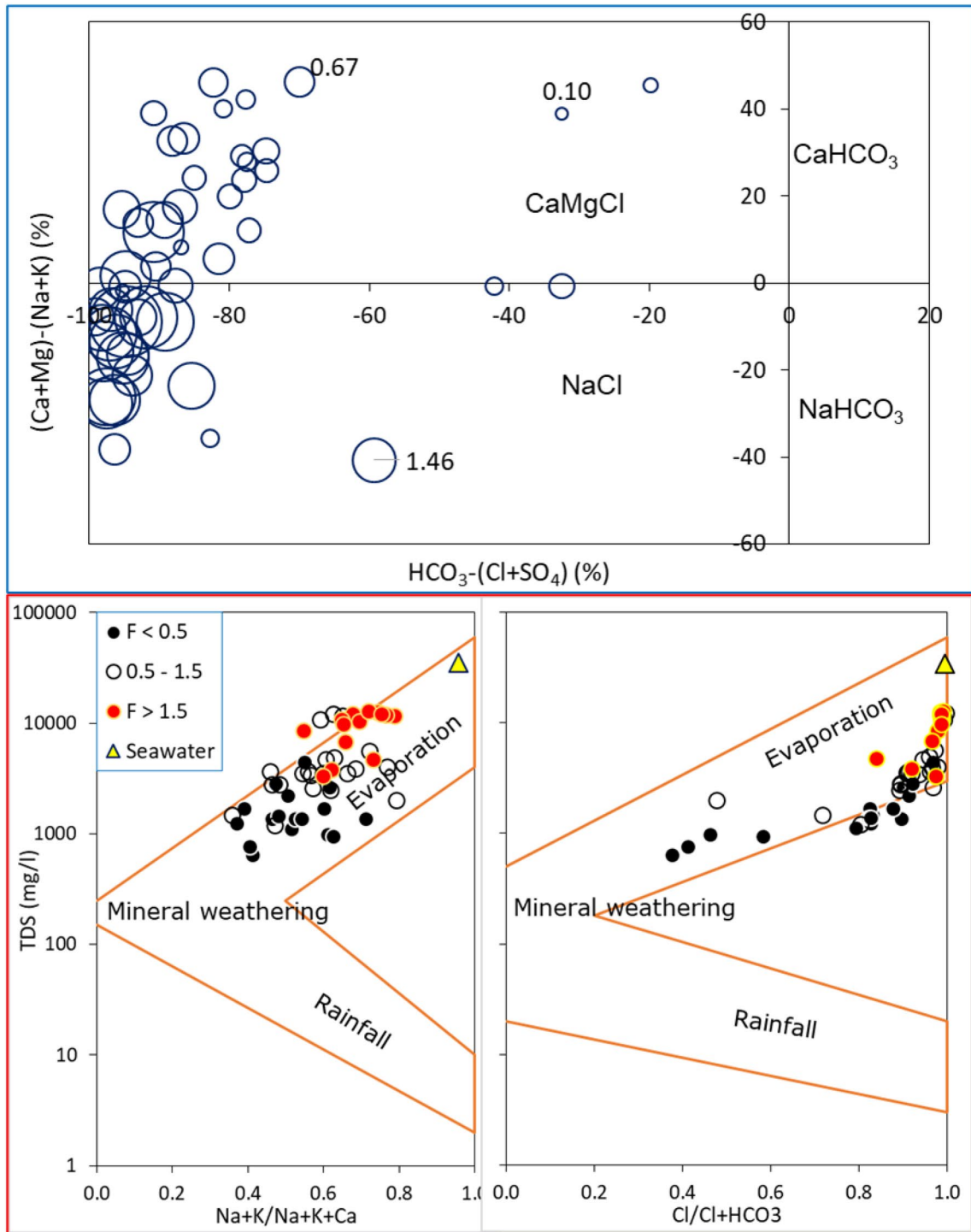


Fig. 2 Groundwater types and their relationship with fluoride concentration in the study area. Bubble size is directly proportional to the fluoride concentration (mg/l) (above). Gibbs plots explain the major

geochemical processes governing water chemistry in the groundwater groups (below)

Relation between fluoride contamination and groundwater types

To identify the water types, groundwater samples are plotted on the Chadha (1999) diagram. The groundwater types and their relationship with fluoride concentration are shown in Fig. 2a, which illustrates that water samples of the study area are classified into CaMgCl water type (50%) and NaCl water type (50%). This observation suggests that water chemistry in the study region is most likely affected by evaporation and saline sources.

Chadha diagram is modified with fluoride concentration to explore the relationship between water types and fluoride concentration. The groundwater samples with high fluoride concentrations are mainly NaCl type and similar observation

is also made in the other arid region (Elumalai et al. 2019). In the NaCl water type, fluoride ranges from 0.13 to 4 mg/l with an average value of 1.58 mg/l; whereas in the CaMgCl type, it varies from 0.1 to 2.74 mg/l with an average of 0.65 mg/l. In the arid coastal aquifers, NaCl water types are predominantly affected by the evaporation process and saline sources (Rajmohan et al 2021a, b; Guo et al. 2007).

Geochemical processes governing fluoride contaminations

The geochemical processes regulating groundwater chemistry are explored using Gibbs plots (Gibbs 1970). Gibbs employed ionic ratios ($Na^+ + K^+ / Na^+ + K^+ + Ca^{2+}; Cl^- / Cl^- + HCO_3^-$) and TDS to explain the role of rainfall,

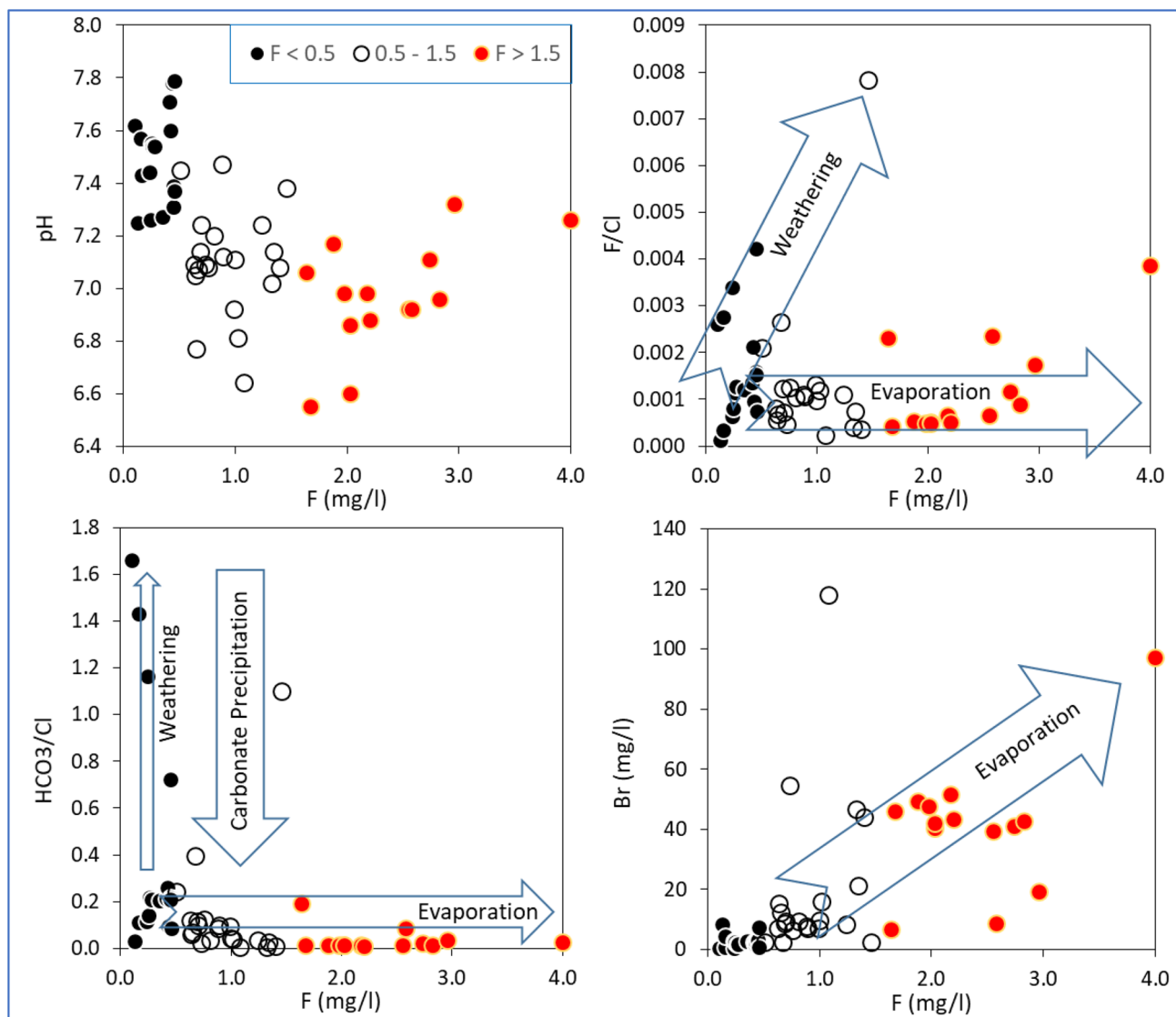


Fig. 3 The influences of evaporation and weathering on fluoride chemistry in the groundwater

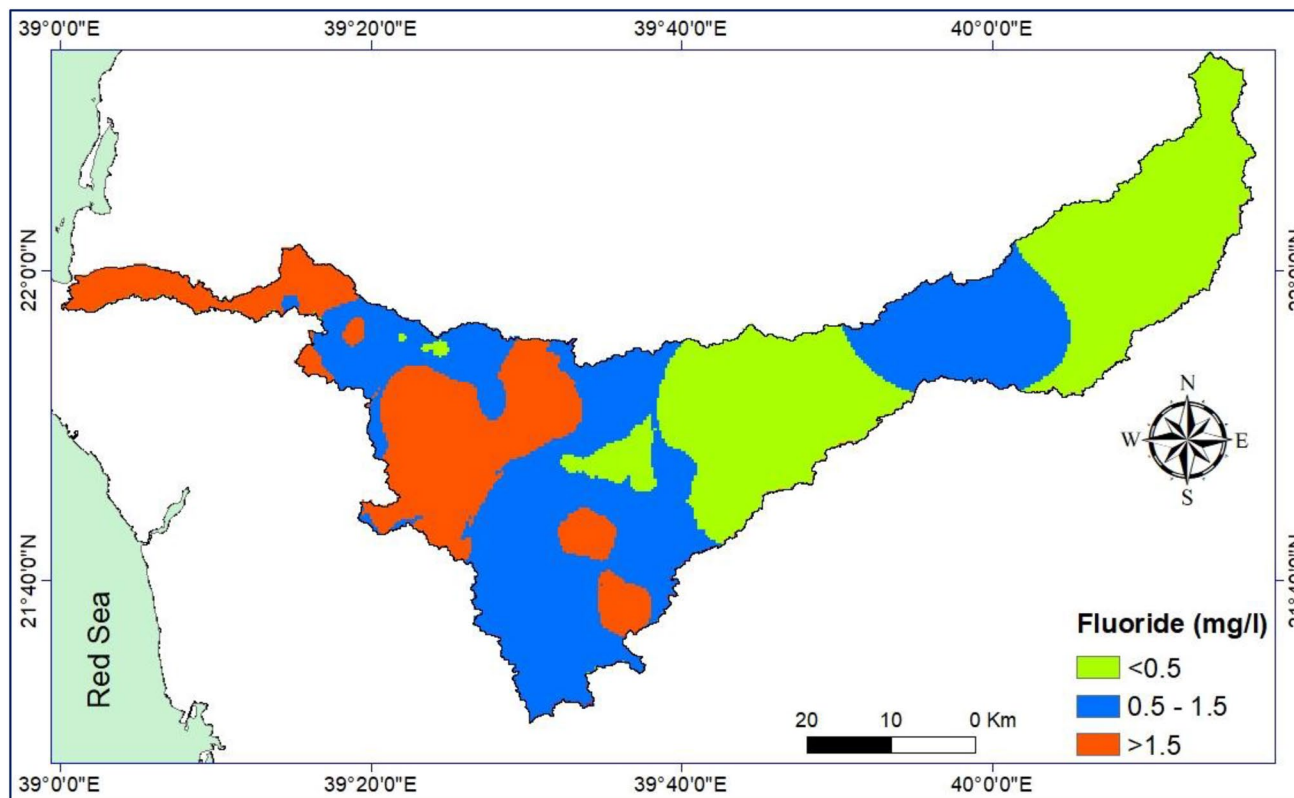


Fig. 4 Fluoride distribution pattern in the Wadi Al Lusub basin groundwater

Table 2 Statistical summary of contamination index (C_d) and health risk assessment calculated for adults and children in the study area

N=52	C_d	Adults		Children	
		CDI (mg/kg/day)	HQ	CDI (mg/kg/day)	HQ
Min	- 0.93	0.004	0.04	0.01	0.05
Max	1.67	0.15	2.56	0.21	3.47
Average	- 0.26	0.04	0.66	0.06	0.89
STD	0.60	0.03	0.57	0.05	0.77

mineral weathering and evaporation on water chemistry. Figure 2b depicts that most of the water samples are plotted on the evaporation zone except few samples in group 1. Figure 2b implies that the evaporation process predominantly affected the water chemistry in the study region. The evaporation process enhances the chloride concentration in the groundwater through the precipitation of carbonate minerals, which increases Na^+/Ca^{2+} and Cl^-/HCO_3^- ratios in the system (Rajmohan et al. 2021b). Among the three groundwater groups, group 3 samples are plotted on evaporation zone with the high TDS content followed by the group 2 samples. Group 1 samples are less mineralised and are plotted on both mineral weathering as well as evaporation zones.

Figure 3 shows the relation between fluoride and other parameters. Group 1 samples have low fluoride content and alkaline pH ($pH > 7.2$). High pH likely facilitates the dissolution of fluoride minerals in group 1 wells (Kadam et al. 2019; Guo et al. 2007). However, wells with high fluoride have slightly acidic pH, which ruled out the role of pH on fluoride contamination. Likewise, HCO_3^-/Cl^- ratios are very low (< 0.3) in the group 2 and 3 wells and decrease with increasing fluoride, which indicates that HCO_3^- is removed in the system by carbonate precipitation due to evaporation. The Molar F/Cl ratio has also justified this conclusion as the F/Cl ratio is lesser than 0.002 in the high fluoride wells and almost constant trend with increasing fluoride. In general, the concentrations of fluoride and chloride ions in the groundwater are increased by the evaporation process, which supports the observation made in the present study that the groundwater contaminated by fluoride is tremendously affected by the evaporation process (Datta et al. 1996; Guo et al. 2007; Rafique et al. 2015; Mukherjee and Singh 2020). Earlier studies also reported that during evaporation, carbonate minerals undergo precipitation, which triggers the dissolution of fluoride minerals (fluorite) to maintain the calcium concentration (common ion effect) in the system (Rafique et al. 2015; Rajmohan et al. 2021b). Consequently,

groundwater is enriched with fluoride and salinity in the study area.

Fluoride contamination zone mapping

Groundwater contamination zones by fluoride are mapped using ArcGIS and presented in Fig. 4. Figure 4 depicts three zones based on fluoride concentration, such as $F^- < 0.5$ mg/l (light green), $1.5 < F^- > 0.5$ mg/l (blue), and $F^- > 1.5$ mg/l

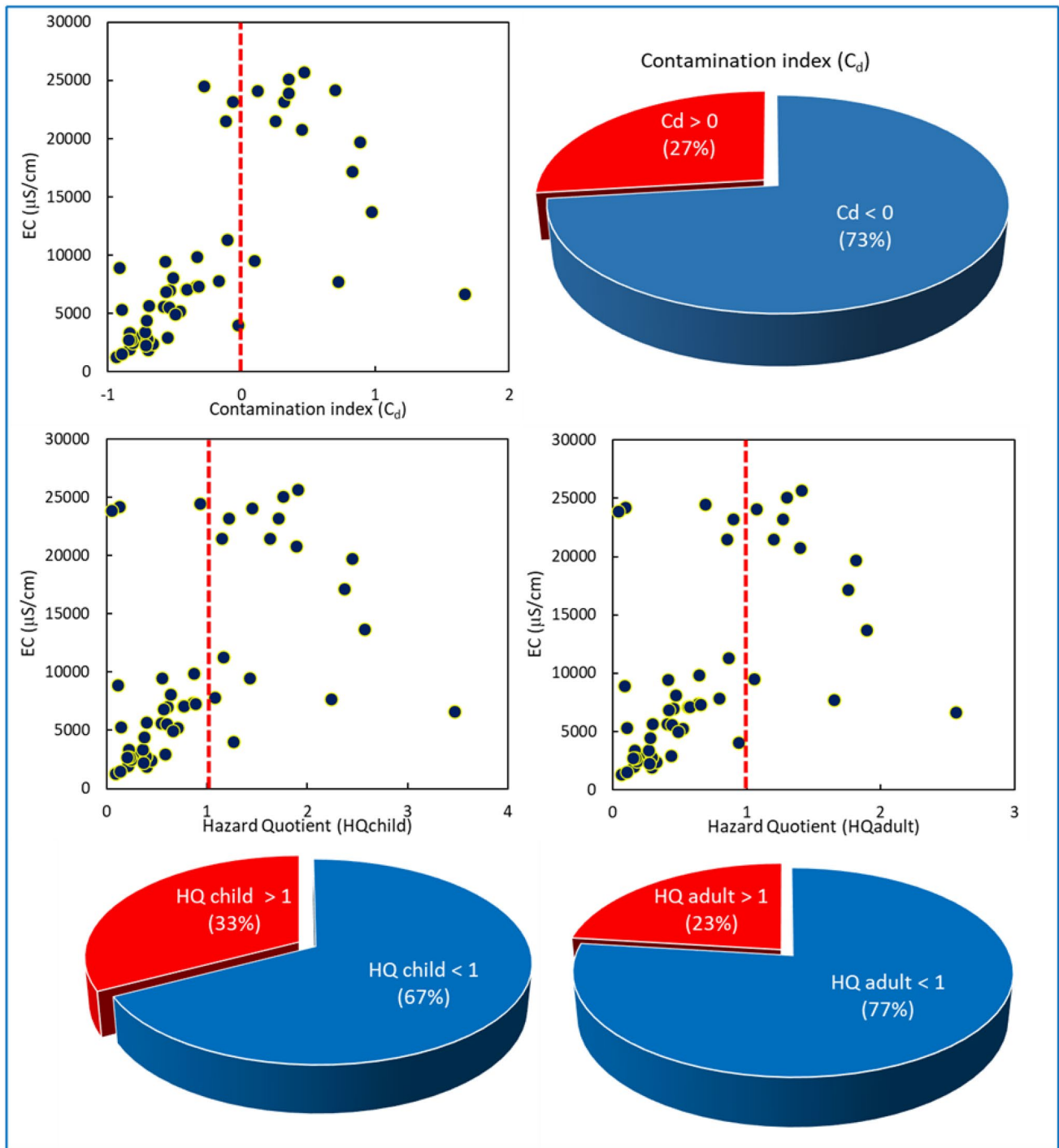


Fig. 5 Contamination index and hazard quotient calculated for adults and children in the study area and their relationship with salinity

(red). Geologically, the upstream region, the eastern side, is covered by the hard rock formations while downstream, the western side, is occupied by the alluvial formations (Fig. 1). The fluoride concentration in the upstream region is very low compared to central and downstream regions. Aforementioned, water chemistry in the low fluoride wells is regulated by mineral weathering processes. Fluoride contamination (red zone) is mostly observed in the downstream, western side, and wells that existed in this zone are unsuitable for drinking. A similar observation is also reported by Guo et al. (2007). Wells in the downstream region are highly susceptible to evaporation due to shallow depth and thus, fluoride enrichment in the downstream wells is predominantly governed by the evaporation processes.

Contamination index

Contamination index (C_d) is generally used to assess water quality based on metal contents. In this study, fluoride contamination is assessed using C_d values. If the C_d value is less than or equal to zero, the water is suitable for drinking,

whereas water samples with higher C_d values ($C_d > 0$) are unpalatable for drinking based on fluoride concentration. In the study area, C_d values in the groundwater samples range from -0.93 to 1.67 with an average of -0.26 ± 0.60 (Table 2). C_d is greater than zero in 14 samples (27%), which are not recommended for drinking (Fig. 5). The relationship between C_d values and EC suggests that even though the C_d value is less than zero in 73% of samples and free from fluoride contamination, the groundwater in the study area is not recommended for drinking due to high salinity. The spatial distribution of the C_d value is illustrated in Fig. 6. In the upstream region (light green zone), groundwater in these wells has C_d values less than zero. But, higher values are noticed in the western downstream region (Blue and red zones, Fig. 6). Hence, wells in downstream regions (blue and red zones) are unsuitable for drinking due to high fluoride content (Fig. 6).

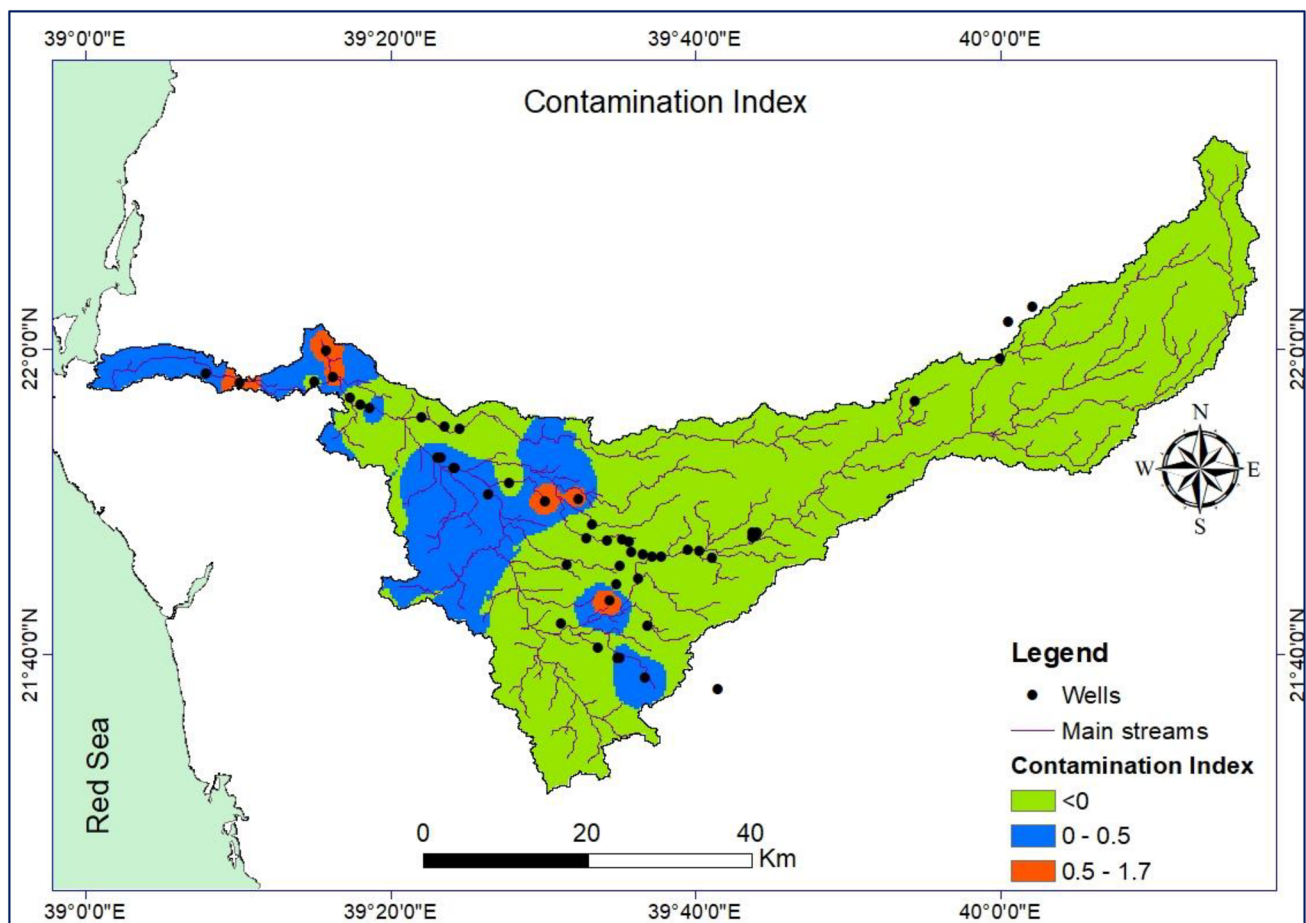


Fig. 6 Spatial distribution of contamination index in the study area

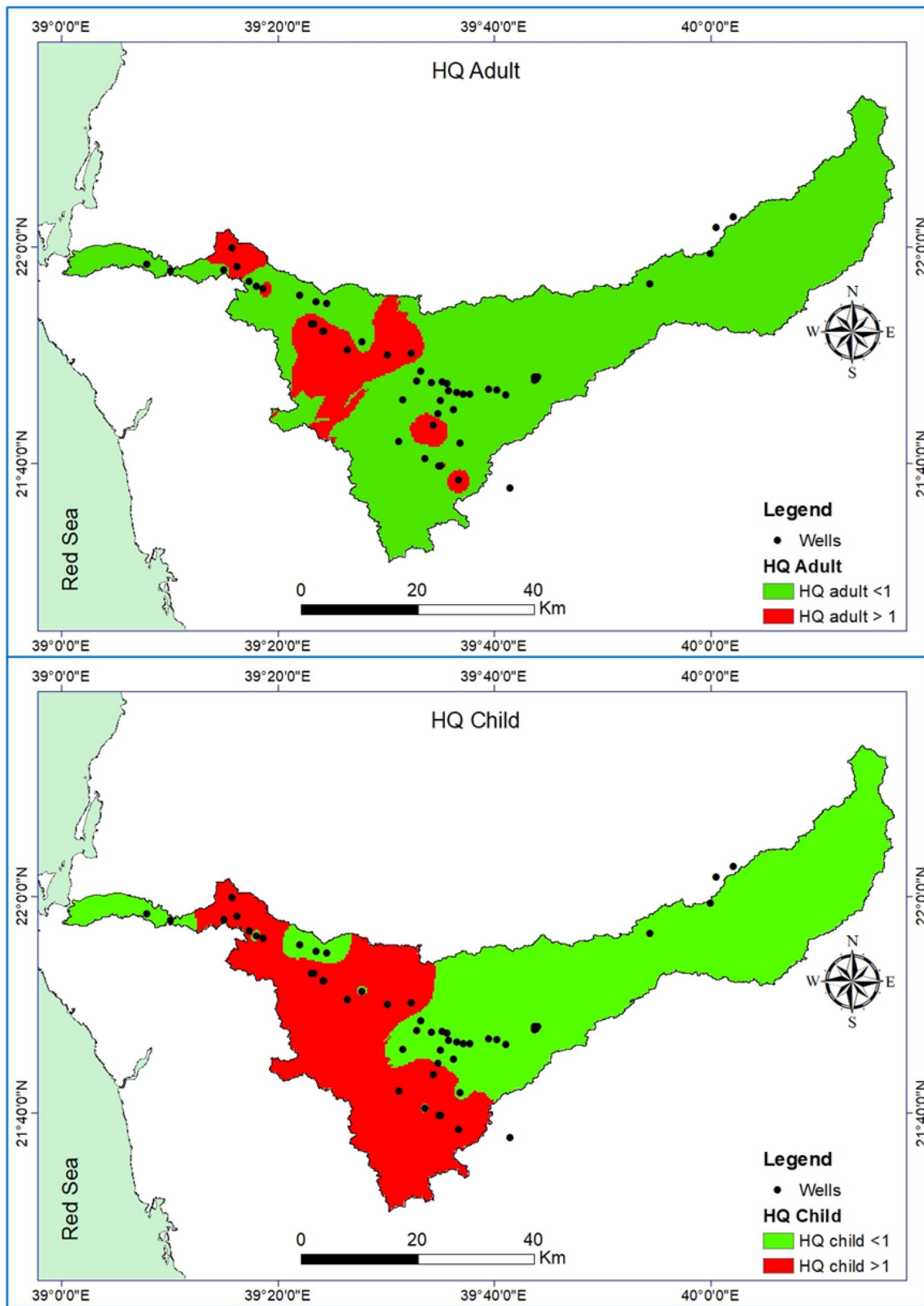


Fig. 7 Spatial distribution of hazard quotient calculated for adults and children in the study area

Health risk assessment

Health risk assessment due to fluoride contamination was carried out in this study using USEPA recommended models. In this study, CDI_{oral} varies from 0.004 to 0.15 with an average of 0.04 mg/kg/day for adults, and it is between 0.01 and 0.21 with a mean value of 0.06 mg/kg/day for children (Table 2). Likewise, the calculated HQ_{oral} values range from 0.04 to 2.56 and 0.05 to 3.47 for adults and children, respectively. The average value of HQ_{oral} is less than 1 for both adults (0.66) and children (0.89) in the study area (Table 2). According to the USEPA recommendation, 23% and 33% of samples show a non-carcinogenic threat to adults and children, respectively (Fig. 5). This finding highlighted that consumption of high fluoride water in the study area may impose a high risk to children compared to adults. In other words, children are highly vulnerable to F^- contamination compared to adults in the study site. Even though 77% (adults) and 67% (children) of samples have low or no health risk to the local populace based on fluoride concentration, high salinity restricts the groundwater usage in the study area (Fig. 5).

Figure 7 depicts the spatial distribution of HQ_{oral} calculated for adults and children. Wells located in the red zone are not recommended for drinking. Red zones mostly occurred on the western side compared to the rest of the area. Furthermore, there is a large variation between adults and children and groundwater pumping on the western side causes health threats to human beings. Hence, proper treatment is required to remove the fluoride from the groundwater before its use.

Conclusion

The present investigation was performed to assess the health risks for the local populace due to ingestion of high fluoride groundwater and to identify the fluoride contamination status in the coastal aquifer.

- The groundwater is neutral to alkaline (75%), brackish (71%) to saline (21%) and very hard ($TH > 300$ mg/l) in nature. High fluoride groundwater is associated with NaCl type.
- Groundwater in 27% of wells has high fluoride ($F > 1.5$ mg/l) and $C_d > 0$, which are unsuitable for drinking.
- Groundwater samples are classified into three groups namely group 1 ($F < 0.5$ mg/l; $n = 17$), group 2 ($1.5 < F < 0.5$; $n = 21$) and group 3 ($F > 1.5$ mg/l; $n = 14$) and the average concentrations of TDS in these groups are 1658 mg/l, 4506 mg/l and 9397 mg/l, respectively.
- Fluoride contamination zones mapping indicates that wells in the upstream region have low fluoride content,

which is likely originated by weathering processes, whereas high fluoride in the downstream (shallow) wells are affected by the evaporation processes.

- Precipitation of carbonate minerals during evaporation facilitated the dissolution of fluoride minerals; consequently, groundwater is enriched with fluoride and salinity in the study area.
- Adverse health effects suggested that the average value of HQ_{oral} is < 1 for both adults (0.66) and children (0.89) in the study site. According to the USEPA recommendation, 23% and 33% of samples show a non-carcinogenic threat to adults and children, respectively and children are highly vulnerable compared to adults.
- The spatial distribution of C_d value and HQ_{oral} implied that higher values of C_d and HQ_{oral} are noticed in the downstream wells, which restricted the usage for drinking.

Thus, proper treatment is required to remove the fluoride and salinity in the groundwater before its use. This study explained the fluoride contamination status in the study area, which will help water management authorities and local municipalities for planning and to provide safe water for the local populace in the study area.

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Availability of data and materials Not applicable.

Code availability Not applicable.

Declarations

Conflict of interest None.

Ethical approval Not applicable.

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