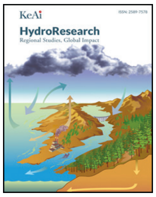
HydroResearch 8 (2025) 167–177

Contents lists available at ScienceDirect

HydroResearch

journal homepage: http://www.keaipublishing.com/en/journals/hydroresearch/



Full Length Article

Pollution indicators and human health risk assessment of fluoride contaminated drinking groundwater in southern Pakistan

Shakeel Ahmed Talpur [a,b,*], Muhammad Rashad [b], Aziz Ahmed [c], Gianluigi Rosatelli [a], Muhammad Yousuf Jat Baloch [d], Aqib Hassan Ali Khan [e], Hafeez Ahmed Talpur [f], Javed Iqbal [g]

[a] *DiSPUTer, Department of Psychological, Health and Territory Sciences, University ''G. d'Annunzio'' Chieti-Pescara, 66100 Chieti, Italy*
[b] *Department of Pharmacy, "G. d'Annunzio" University of Chieti-Pescara, Via Dei Vestini 31, 66100 Chieti,Italy*
[c] *School of Plant, Environment and Soil Sciences, Louisiana State University Agricultural Centre, Baton Rouge, LA 70803, USA*
[d] *College of New Energy and Environment, Jilin University, Changchun 130021, China*
[e] *International Research Centre in Critical Raw Materials and Advanced Industrial Technologies, Universidad de Burgos, Burgos 09001, Spain*
[f] *Department of Engineering and Geology, University ''G. d'Annunzio'' Chieti-Pescara, 66100 Chieti, Italy*
[g] *School of Environmental Studies, China University of Geosciences, Wuhan 430074, PR China*

ARTICLE INFO

Article history:
Received 21 August 2024
Received in revised form 10 October 2024
Accepted 26 October 2024
Available online 28 October 2024

Keywords:
Badin
Fluoride contamination
Hazard quotient
Human health risk assessment
Groundwater pollution

ABSTRACT

This study investigated fluoride contamination in groundwater and associated health risks in the Badin district of Pakistan. Fifty-seven groundwater samples were analyzed for fluoride, turbidity, iron, and total dissolved solids (TDS). Pollution indices and health risk models were employed to assess contamination levels and potential health impacts. Results showed that 47 % of samples exceeded the WHO fluoride limit of 1.5 mg/L, with a mean concentration of 1.92 mg/L. Spatial analysis revealed high contamination in northern and southern areas. Health risk assessments indicated that children, particularly females, faced the highest risk of fluorosis. TDS, turbidity, and iron levels also exceeded WHO limits in significant portions of the samples. This investigation uniquely combines multiple pollution indicators, spatial analysis, and age-specific health risk assessments, presenting vibrant insights for targeted interventions, policy development, and resource allocation to address this critical public health issue in fluoride-endemic regions.

1. Introduction

The right to safe and clean drinking water is a basic human entitlement, vital for sustaining good health and well-being for all individuals (Arcentales-Ríos et al., 2022; Ghani et al., 2022; Iqbal et al., 2023a; Kapani et al., 2024; Talpur et al., 2024a). Groundwater serves as a critical source of drinking water for numerous rural communities across the globe (Iqbal et al., 2021; Ullah et al., 2022a; Zhu et al., 2022). As global changes continue resulting change in precipitation patterns and negatively impact both the quality and quantity of groundwater, the escalating demand for water poses a significant risk to the health of the poorest segments of the population. (Jat Baloch et al., 2021). Groundwater is susceptible to contamination due to its passage through aquifers, which are themselves at risk of pollution. As a result, pollutants can permeate these aquifers from both surface and subsurface sources, leading to potential water quality degradation (Baloch et al., 2020; Talpur et al., 2024b). Various sources can lead to the pollution of groundwater, including agricultural runoff, industrial activities, the mishandling of waste materials, and natural processes such as the weathering of mineral-bearing rocks. (Baloch et al., 2022; Liu et al., 2023; Zheng et al., 2019).

The occurrence of fluoride in groundwater happens as fluoride ions (F^-) are released from rock minerals via weathering processes, subsequently becoming dissolved in the water within underground aquifers (Iqbal et al., 2023b). Weathering processes involving minerals like fluorite (CaF^2) and apatite ($Ca_5(PO_4)_3F$), which contain fluoride, lead to the release of fluoride ions into groundwater as these minerals break down and dissolve (Salve et al., 2008; Talpur et al., 2020). The weathering process that releases fluoride ions from minerals into groundwater is driven by an array of physical, chemical, and biological factors. These include fluctuations in temperature, variations in pressure, and the presence of water and oxygen, all of which contribute to the breakdown of fluoride-containing minerals (Rashid et al., 2020). The chemical reaction demonstrating the weathering process of fluorite (CaF_2) is as follows ($CaF_2 + H_2O \rightarrow Ca^{2+} + 2F^- + 2OH^-$). In this reaction, the dissolution of fluorite in the presence of water leads to the release of calcium ions (Ca^{2+}), fluoride ions (F^-), and hydroxide

---

* Corresponding author at: DiSPUTer, Department of Psychological, Health and Territory Sciences, University ''G. d'Annunzio'' Chieti-Pescara, 66100 Chieti, Italy.
E-mail addresses: shakeel.talpur@unich.it, talpurshakill@yahoo.com (S.A. Talpur).

https://doi.org/10.1016/j.hydres.2024.10.005

ions (OH^-) into the groundwater. This process contributes to the uptake of fluoride ions into the water supply (Mukherjee and Singh, 2018). Also, the dissolution of apatite, which contains fluoride, is showing in this chemical reaction ($Ca_5(PO_4)_3F + H_2O \rightarrow Ca^{2+} + 5PO_4^{3-} + F^- + 3OH$). This reaction shows how apatite ($Ca_5(PO_4)_3F$) interacts with water, resulting in the release of calcium ions (Ca^{2+}), phosphate ions (PO_4^{3-}), fluoride ions (F^-), and hydroxide ions (OH^-) into the groundwater. This process is another way through which fluoride can become part of the water supply (Srinivasamoorthy et al., 2012). The rate and intensity of these chemical reactions are influenced by a range of factors, including the nature of the rock minerals, the composition of the water, and the prevailing weathering conditions. Each of these elements contributes to how readily fluoride can release from minerals into the groundwater. (Brindha et al., 2011; Zango et al., 2021).

The contamination of water sources with fluoride poses a considerable public health challenge, as it carries ongoing risks to human health (Kapani et al., 2024; Thapa et al., 2019; Yousefi et al., 2018; Zhang et al., 2023). The World Health Organization (WHO) recommends a maximum fluoride concentration of 1.5 $mg.L^{-1}$ in drinking water to prevent adverse health effects. However, in numerous areas, especially within developing nations, fluoride concentrations in groundwater often surpass this guideline, posing a risk to the health of local populations (Iqbal et al., 2023b; More et al., 2021; Talpur et al., 2020). Many developing countries face constraints in resources and access to advanced water treatment technologies, which makes it challenging to adequately address groundwater contamination. As a result, communities in these regions are frequently compelled to rely on water sources that do not meet safety standards, leading to the consumption of potentially unsafe water (Ayoob and Gupta, 2006; Talpur et al., 2020; Ullah et al., 2023). The health effects of fluoride in drinking groundwater can vary depending on the level of exposure and duration (Mekal et al., 2023; Yousefi et al., 2019). Dental fluorosis stands as the most prevalent health effect, marked by discoloration and damage to the teeth. In its more severe forms, this condition can result in the loss of teeth and associated discomfort. A graver condition, skeletal fluorosis, manifests through damage to bones, causing joint pain, rigidity, and a heightened susceptibility to bone fractures (Ullah et al., 2022b; Yousefi et al., 2018). In extreme cases, skeletal fluorosis may result in debilitating bone deformities. Beyond dental and skeletal fluorosis, prolonged exposure to excessive fluoride levels can elevate the risk of various other health issues (Iqbal et al., 2023b; Keramati et al., 2019). Research has indicated a potential link between fluoride exposure and a heightened risk of osteosarcoma, a form of bone cancer (Bassin et al., 2006; Gelberg et al., 1995). There is evidence to suggest that exposure to fluoride might be correlated with a higher incidence of thyroid issues, renal impairment, and neurological conditions. (Rashid et al., 2018; Talpur et al., 2020).

This study presents a comprehensive and multifaceted approach to examining fluoride contamination in the Tando Bago subdistrict of Badin, Pakistan. What sets this research apart is its innovative integration of multiple pollution indicators (PI, FPI, FRI) to assess the severity and spatial distribution of fluoride contamination, along with age- and gender-specific chronic daily intake (CDI) and hazard quotient (HQ) calculations, offering unprecedented insights into vulnerable population segments. The study incorporates a holistic analysis of co-occurring contaminants (TDS, turbidity, iron), employs advanced spatial mapping techniques, and considers socio-economic factors within a developing region context. However, it's important to acknowledge the study's limitations. The research was confined to a specific geographical area, potentially limiting the generalizability of findings to regions with different geological and socio-economic characteristics. Reliance on a single round of sampling doesn't account for potential seasonal variations in groundwater quality. Additionally, while the health risk assessment provides valuable insights, it doesn't consider potential synergistic effects of multiple contaminants or long-term chronic exposure impacts. Despite these constraints, this integrated approach not only provides a more accurate assessment of the current situation but also serves as a model for future studies in similar geopolitical contexts. By offering a multidimensional perspective on fluoride contamination, this research aims to inform targeted interventions, policy development, and resource allocation to address this critical public health issue effectively, with far-reaching implications for groundwater management, public health policy, and sustainable development in fluoride-endemic regions worldwide. Future research could build on this foundation by conducting longitudinal studies, expanding geographical coverage, and performing more extensive toxicological assessments.

2. Methodology

2.1. Study area

The Badin district, situated in the southern part of Sindh, Pakistan, is geographically positioned at 24.8°N latitude and 68.5°E longitude, as depicted in Fig. 1. Covering an area of 5521 km^2, it is home to approximately 1.8 million people. The district is predominantly agrarian, with most of its inhabitants relying on agriculture as their mainstay. The land here is exceptionally fertile, supporting a variety of crops such as rice, sugarcane, wheat, and cotton. Additionally, fishing and livestock rearing contribute significantly to the livelihoods of the locals. Characterized by a semi-arid climate, Badin experiences hot summers, mild winters, and a monsoon season that extends from June to September, bringing with it the bulk of the yearly precipitation (Ahmed et al., 2013). The district borders the Arabian Sea, and its coastline is dotted with coastal mangrove forests and wetlands, which provide a habitat for a diverse range of flora and fauna. Despite its rich natural resources, Badin is comparatively underdeveloped, with an infrastructure that is lagging and basic services that are scarce. The population predominantly resides in small villages and rural communities, where access to healthcare, education, clean drinking water, and other fundamental necessities is often inadequate (Talpur et al., 2020).

2.2. Samples collection and analysis

Groundwater samples were systematically collected from Tando Bago, a subdistrict of the Badin district. A total of 57 samples were collected into 200 mL sterile bottles from boreholes and wells between 15 and 40 m deep. Each bottle was clearly marked with the collection date, time, and specific location. To preserve the consistency of the samples and prevent from chemical changes, each sample was acidified on-site with 65 % HNO_3 to achieve a $pH < 2$. Prior to analysis, samples underwent pre-treatment to eliminate suspended solids and organic matter using filtration. These samples were then conveyed to the Pakistan Council of Research in Water Resources (PCRWR) Laboratory in Badin for detailed quantitative examination.

2.3. Quality control and quality assurance

To ensure the reliability and accuracy of the results, strict quality control and quality assurance measures were implemented throughout the study. All sampling equipment was cleaned and calibrated before use. In the laboratory, method blanks, certified reference materials, and internal standards were used to monitor analytical performance. All analyses were performed in triplicate, and the relative standard deviation was maintained below 5 %. The ion balance error was calculated

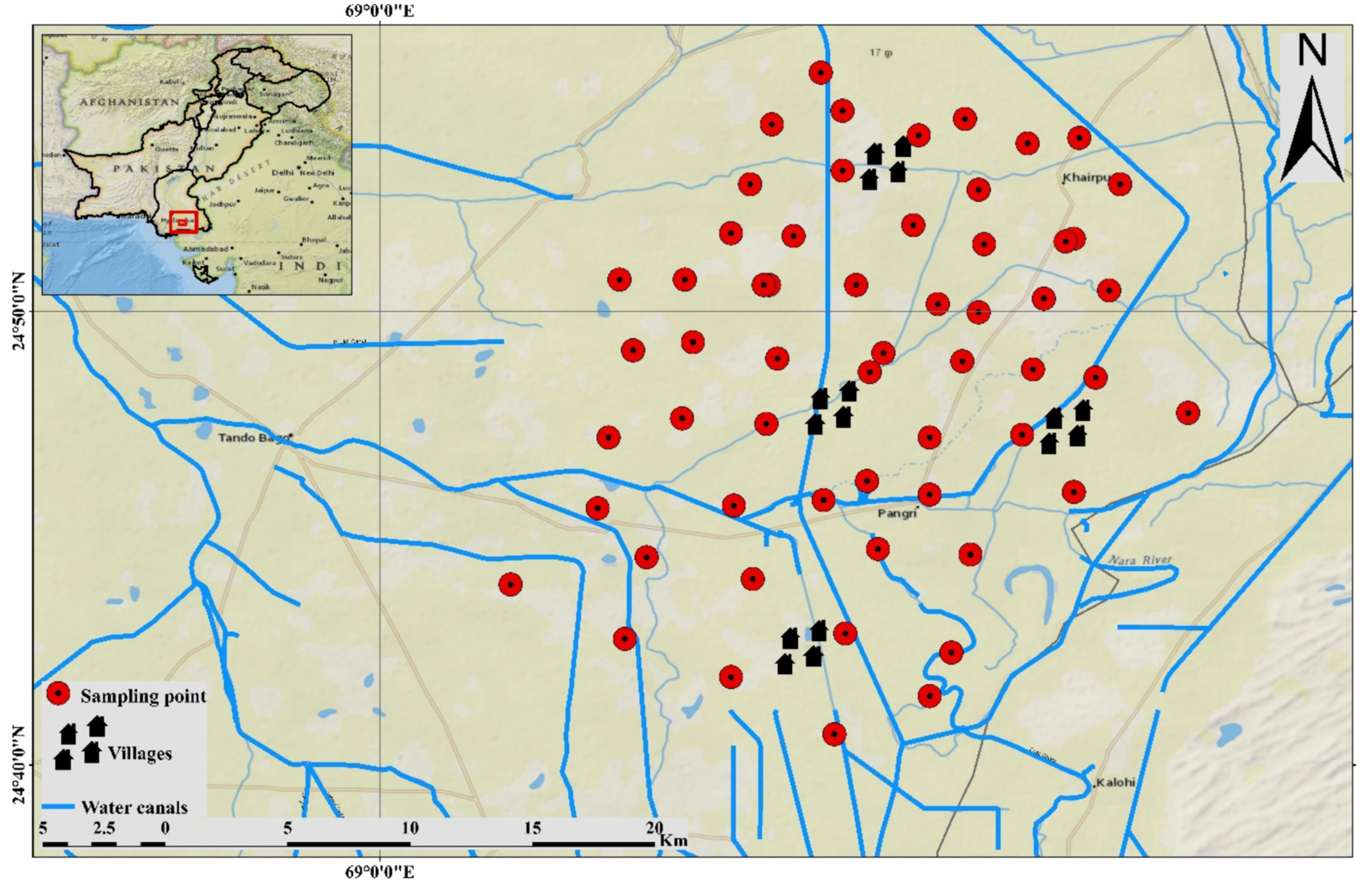


Fig. 1. Groundwater sampling locations in Tando Bago sub-district, Badin district, Sindh, Pakistan.

for each sample and only samples with an error of less than ±5 % were accepted for further analysis. Additionally, inter-laboratory comparison tests were conducted with a certified environmental testing laboratory to validate our results.

2.4. Pollution index (PI)

The PI was employed to assess groundwater contamination, which primarily relies on the concentration of elements compared to reference concentrations. The PI calculation employs the following formula: Eq. (1) (Masood et al., 2022; Nephalama and Muzerengi, 2016).

$$PI = {}^{C_F}\!/_{S_F} \tag{1}$$

Wherein "C_F" is the concentration of fluoride (mg.L^{-1}) in each sample, and "S_L" indicates fluoride standard limit of 1.5 mg.L^{-1} in the drinking water (WHO, 2011).

2.5. Fluoride pollution index (FPI)

The FPI was determined by aggregating the weighted values of specific groundwater parameters: fluoride concentration, bicarbonate concentration, sodium-to-calcium ratio, and pH. The FPI values are interpreted as follows: 1 to 2 represent low pollution, 2 to 3 signify medium pollution, and 3 to 4 indicate high pollution. Eq. (2) was implied to calculate the FPI (Haji et al., 2021).

$$FPI = {}^{W_F + W_{HCO_3} + W_{Na/Ca} + W_{pH}}\!/_{N} \tag{2}$$

The W_F, W_{HCO3}, $W_{Na/Ca}$, and W_{pH} are the assigned weight to the fluoride, bicarbonate, ratio between sodium and calcium, and pH, as presented in Table 3. Whereas N represents the total number of groundwater parameters.

2.6. Human health risk assessment (HHRA)

To assess the potential health risks associated with fluoride exposure, the chronic daily intake (CDI) and hazard quotients (HQ) were calculated using Eq. (3) and Eq. (4), for non-carcinogenic health risk assessment (Jat Baloch et al., 2022a; Jat Baloch et al., 2022b; USEPA, 2005).

$$CDI = {}^{C_F \times IR}\!/_{BW} \tag{3}$$

$$HQ = {}^{CDI}\!/_{R_F D} \tag{4}$$

The risk exposure factors for fluoride concentration (CF) differ among various population groups, with each group having specific values for daily water consumption (IR) and body weight (BW). For male infants, the IR is 0.08 L/day with a BW of 7.7 kg, while male children have an IR of 1.2 L/day and a BW of 16.4 kg. Male teenagers exhibit an IR of 2 L/day and a BW of 35.4 kg, whereas male adults have an IR of 3.1 L/day and a BW of 66 kg. In comparison, female infants have an IR of 0.08 L/day and a BW of 7.4 kg, with female children showing an IR of 1.2 L/day and a BW of 16 kg. Female teenagers consume 2 L/day of water, with a BW of 33.8 kg, and female adults have an IR of 2.1 L/day and a BW of 59 kg. Pregnant women have a daily water consumption of 2.4 L/day with a BW of 59 kg, while breastfeeding women consume 3.1 L/day of water, also with a BW of 59 kg. Across all these groups, the oral reference dose (RfD) for fluoride remains consistently set at 0.06 mg/kg/day (Aziz et al., 2012; Ghani et al., 2022; Iqbal et al., 2023a; Iqbal et al., 2021; Iqbal et al., 2023b; Jat Baloch et al., 2021; Ullah et al., 2022b).

2.7. Statistical analysis and mapping

Statistical analyses and visualizations were performed using SPSS and JASP software. These analyses included calculating standard indices, such as mean, standard deviation, and range, for the various parameters. Additionally, spatial distribution maps were created using ArcMap 10.4 software.

3. Results and discussion

3.1. Effect of TDS, turbidity, and iron

Total Dissolved Solids (TDS), turbidity, and iron are critical groundwater quality parameters that significantly influence the suitability of the groundwater, as shown in the spatial distribution of these parameters in Fig. 2.

Elevated TDS levels, ranging from 630 mg.L^{-1} to 2944 mg.L^{-1} with an average of 1533 mg.L^{-1}, can have detrimental effects on the organoleptic properties of water, such as taste and odor, and can also impact the chemical stability of water, leading to scaling and corrosion in water distribution systems (Salari, 2024). These effects can result in reduced consumer acceptance, increased maintenance costs, and potential health risks associated with the leaching of metals from corroded pipes. The (WHO, 2011) guidelines suggest a TDS concentration below 1000 mg.L^{-1} to ensure palatability and minimize health concerns (Derso Mengesha et al., 2018), but 42 % of the samples in this study exceed this limit. The high TDS levels can be attributed to both natural factors, such as rock weathering and mineral dissolution, and anthropogenic activities, including industrial effluents and agricultural runoff (Sassane and Touati, 2024; Yao et al., 2024). These sources can introduce a variety of dissolved inorganic salts and organic matter into the groundwater, contributing to the elevated TDS concentrations (Thirumoorthy et al., 2024).

Turbidity, a measure of the degree of cloudiness or murkiness caused by suspended particles like clay, silt, organic matter, and microorganisms (da Silva et al., 2024; Qian et al., 2024), exhibits a wide range of values in this study, from 0.75 to 361 NTU with an average of 23.2 NTU. High turbidity levels can have significant implications for public health and water treatment processes. Suspended particles can provide a favorable environment for the growth and proliferation of pathogenic organisms by shielding them from disinfectants and serving as a nutrient source (Stevenson and Bravo, 2019; Szpak et al., 2020). This can increase the risk of waterborne diseases and compromise the effectiveness of water treatment processes, necessitating higher doses of disinfectants and more advanced treatment techniques. Moreover,

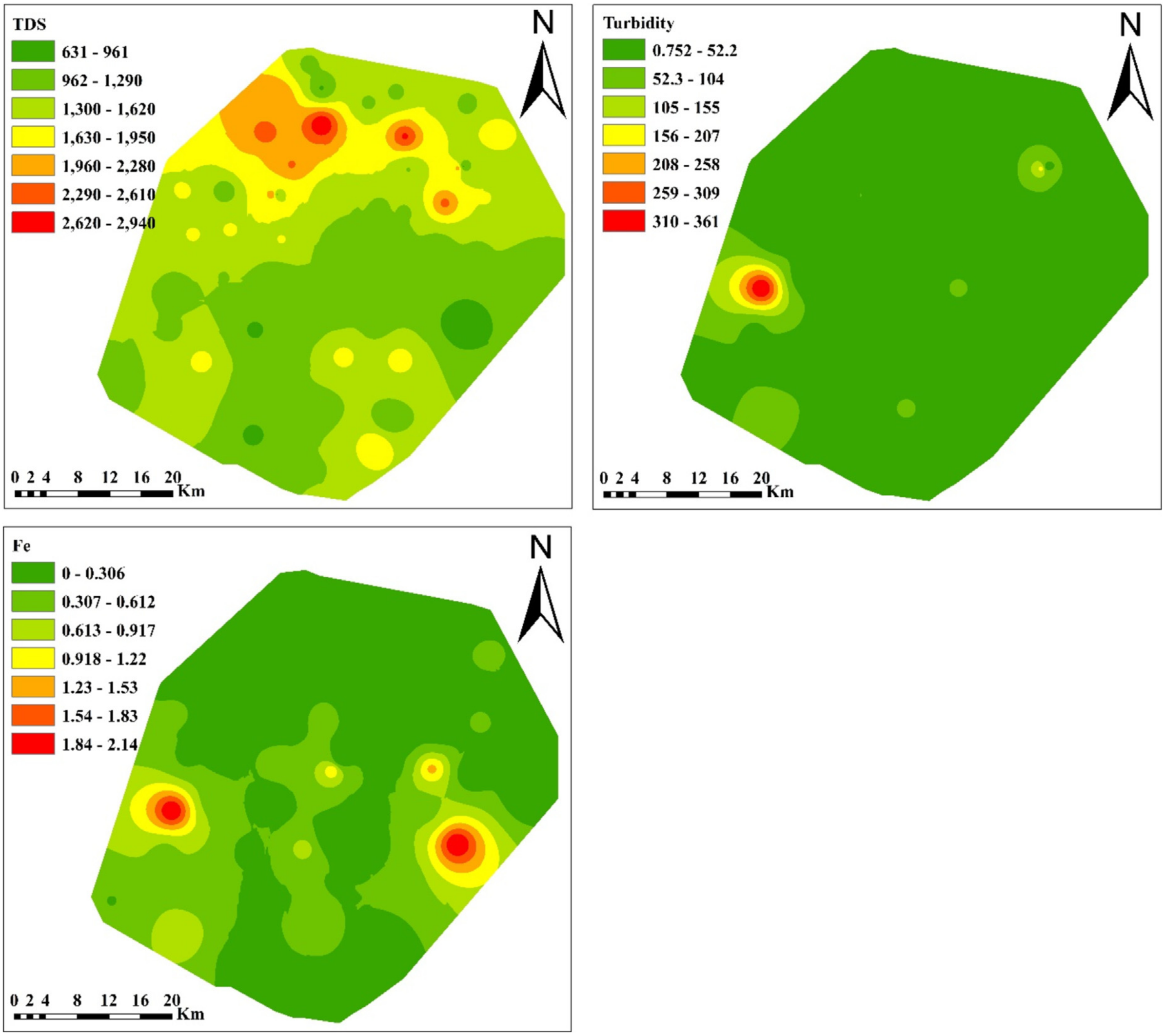


Fig. 2. Spatial distribution of TDS, Turbidity, and Iron concentrations across groundwater sampling locations.

elevated turbidity can diminish the aesthetic appeal of water, causing visible cloudiness and reducing consumer satisfaction (Tomperi et al., 2022). The (WHO, 2011) guidelines mention that turbidity should not exceed 5 NTU for drinking water to ensure its safety and suitability for consumption, but approximately 18 % of the analyzed samples surpass this threshold. Factors contributing to increased turbidity levels include soil erosion, surface runoff, and inadequate or inefficient water treatment processes (Abirhire et al., 2020). These factors can introduce suspended particles into the groundwater, leading to the observed high turbidity values.

Iron, a naturally occurring element in groundwater, can have significant effects on water quality when present in elevated concentrations. The analyzed data reveals iron concentrations ranging from 0.001 to 2.14 mg.L^{-1}, with an average value of 0.32 mg.L^{-1}. High iron levels can cause discoloration of the water, giving it a reddish-brown appearance and staining laundry and plumbing fixtures (Hu et al., 2018; Lytle et al., 2020). This can lead to aesthetic issues and reduced consumer acceptance of the water. Additionally, elevated iron concentrations can impart a metallic or bitter taste to the water, further affecting its palatability (Mirlohi, 2022; Rahman et al., 2020). The presence of iron can also facilitate the growth of iron bacteria, which form slimy coatings in pipes and can cause clogging, reduced water flow, and unpleasant odors (Hu et al., 2018; Qiu et al., 2018). These bacteria may also create favorable conditions for the growth of other microorganisms, potentially posing health risks. The (WHO, 2011) recommend a maximum iron concentration of 0.3 mg.L^{-1} for drinking water and this study contains 31 % of the samples exceed this limit.

3.2. Groundwater pollution indicator

The pollution index (PI) is an effective tool for assessing the toxicity level of drinking groundwater (Masood et al., 2022; Nephalama and Muzerengi, 2016). The value of PI below 1 indicates no pollution, while a value above 1 suggests a certain level of contamination. In this study, the PI of drinking groundwater samples from Tando Bago ranged from 0.15 to 4.53, with a mean of 1.28 and a standard deviation of 1.01 Table 1 and Fig. 3. The analysis revealed that 30 samples (53 %) had PI values above 1, indicating high fluoride contamination, while the remaining 27 samples (47 %) had PI values below 1, suggesting less contamination or fluoride levels within the permissible limit. These findings highlight the significant groundwater contamination in the study area. However, it is crucial to consider that the pollution index may vary depending on factors such as location, water source, and industrial and agricultural practices in the surrounding area. Therefore, while the PI serves as a useful indicator of groundwater quality, a comprehensive assessment should consider the specific environmental conditions and potential sources of contamination to develop effective management strategies and ensure safe drinking water for the population.

3.3. Fluoride pollution indices

The fluoride contamination in the Tando Bago showed that 47 % of the samples had fluoride concentrations exceeding the permissible limit of 1.5 mg.L^{-1} set by the (WHO, 2011). The average fluoride concentration was 1.92 mg.L^{-1}, with a range of 0.23 to 6.8 mg.L^{-1} and a standard deviation of 1.61 mg.L^{-1}. Additionally, 7 % of the samples were in the marginal range from 1.40 to 1.47 mg.L^{-1}, while the remaining 46 % were below the safe limit. The spatial distribution of fluoride contamination, as shown in Fig. 1 and compared to the (Talpur et al., 2020) study and the Fluoride Risk Index (FRI) in Table 2, revealed that the northern and southern parts of the study area have a high, very high, and extremely high risk of fluoride contamination. Whereas the central part has very low, low, and high levels of fluoride risk (Haji et al., 2021). To provide a more comprehensive evaluation, the Fluoride Pollution Index (FPI) was applied Table 3. The FPI ranged from 1.4 to 2.8, with an average of 2.28. The results showed that 64 % of the samples fell in the medium range, while the remaining 36 % were in the low range. None of the samples were classified as high in the FPI ranking.

Table 1
The measure of the pollution index.

Pollution index (PI)			
PI Range	Class	No of samples	% of samples
PI <1	No pollution	27	47
PI >1	Pollution	30	53

The FRI, FPI, and spatial distribution map collectively provide strong evidence of fluoride pollution in the groundwater of the Tando Bago subdistrict. Excessive fluoride in drinking water can have adverse effects on human health, as fluoride is a naturally occurring chemical element in the earth's crust, present in many minerals and rocks, and can leach into groundwater sources (Iqbal et al., 2023b; Talpur et al., 2020). Given the potential health risks associated with fluoride contamination, it is crucial to monitor groundwater quality regularly and implement appropriate management strategies to ensure safe drinking water for the population in the affected areas.

3.4. Human health risk assessment (HHRA)

3.4.1. Chronic daily intake (CDI)

The CDI of fluoride was estimated for different age groups of males and females, as shown in Fig. 4. The average CDI (mg/kg/day) for the male groups was as follows: infants = 0.02, children = 0.14, teenagers = 0.10, and adults = 0.09. For the female groups, the average CDI was infants = 0.02, children = 0.14, teenagers = 0.11, adults = 0.06, pregnant women = 0.07, and breastfeeding women = 0.10. The overall male (M) and female (F) CDI vulnerability trend line shows the following order of exposure: F-children > M-children > F-teenagers > M-teenagers > Breastfeeding women > M-adult > Pregnant women > F-adult > F-infant > M-infant. This trend indicates the daily exposure to fluoride-contaminated drinking water for different age and gender groups. Children appear to have the highest exposure to fluoride, while infants have the lowest exposure. Teenagers have the second-highest level of exposure, followed by breastfeeding women, adult males, pregnant women, and adult females, all of which are in the mid-range of daily exposure. These findings highlight the importance of considering age and gender when assessing the potential health risks associated with fluoride exposure through drinking water. Children and teenagers may be more vulnerable to the adverse effects of fluoride due to their higher exposure levels and the critical stages of growth and development they are undergoing.

3.4.2. Hazard quotient (HQ)

The quantitative outcomes and spatial distribution of HQ among males and females in different age groups as shown in Fig. 5, Fig. 6, and Fig. 7. The HQ classifications, such as HQ < 1, suggest a safe level with no health risk, whereas HQ ≥ 1 implies potential chances of fluoride-induced health risk (Nizam et al., 2022; Taiwo et al., 2023). In male population average HQ > 1 resulted infant = 1.75 %, children = 63.13 %, teenager = 59.64 %, and adult = 54.38 %, respectively. Similarly in female population infant = 1.75 %, children = 64.91 %, teenagers = 61.40 %, adult = 42.10, pregnant women = 47.36 %, and breastfeeding women = 54.38 %, respectively. Groundwater samples that resulted in HQ > 1 were mostly located in the northern and southern zones of the fluoride endemic study area. These zones are considered to have the potential skeleton and dental fluorosis risk among the local population, whereas the central part is under the safe limit. The HQ trendline indicates potential risks to human health as follows: F-children > M-children > F-teenagers > M-teenagers > Breastfeeding women > M-adult > Pregnant women > F-adult > F-infant > M-infant.

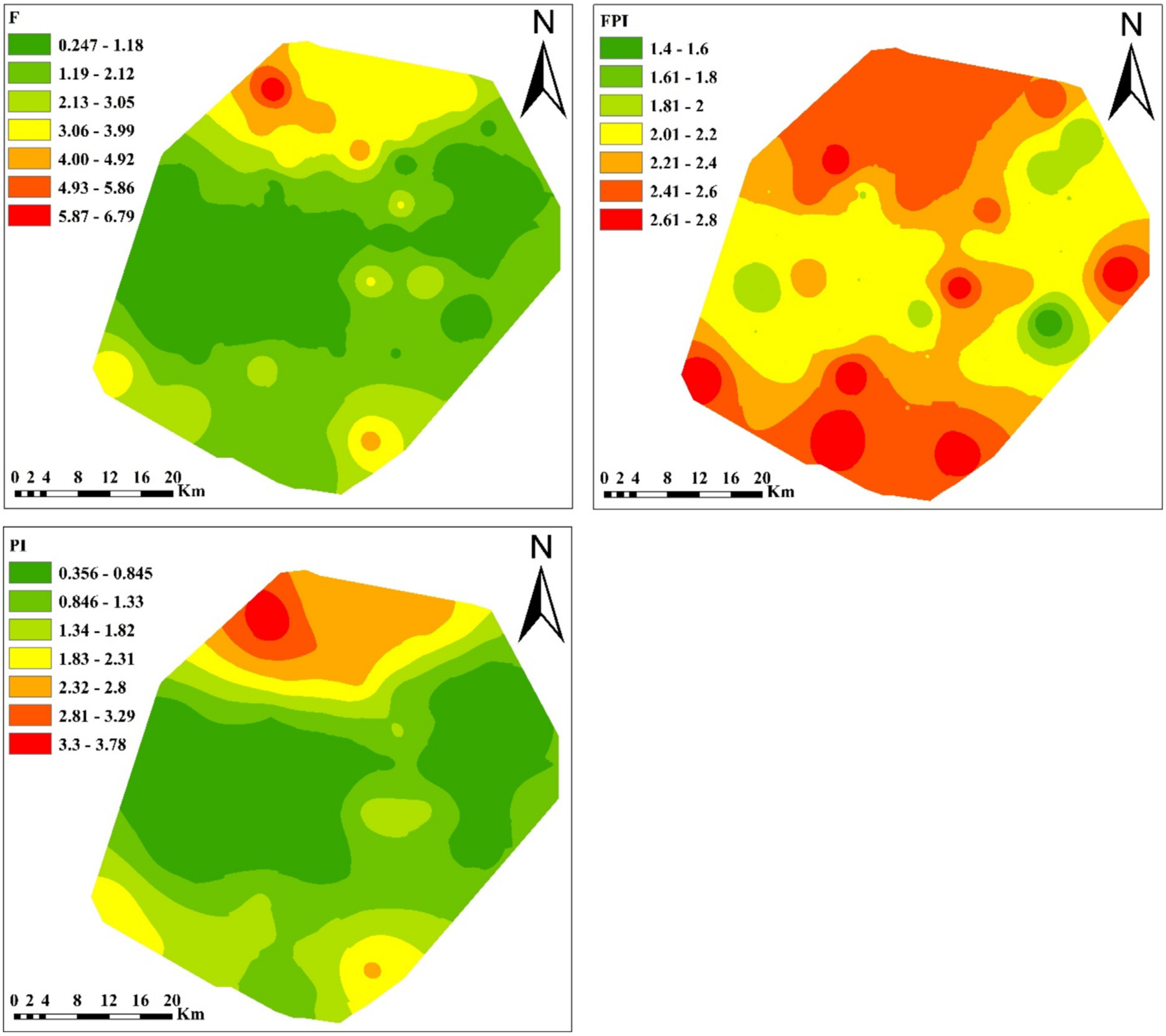


Fig. 3. Spatial distribution of fluoride, FPI, and PI in groundwater samples from Tando Bago.

An investigation conducted in Showt city, West Azerbaijan, Iran, assessed the potential health risks associated with fluoride exposure through drinking water. The study resulted in HQ for different age groups as HQ > 1 for 54.44 % of children, 31.82 % of teenagers, and 22.73 % of adults (Yousefi et al., 2019). Another investigation was conducted by (Chen et al., 2017) on fluoride health risk assessment of infants and children groups in Northwest China. They found infants were the most vulnerable group with HQ > 1 of 72 % and children 60 % of total samples. (Brahman et al., 2014) Studied in Nagarparker, Sindh, Pakistan. They classified the population into three groups, including 7 to 15 years, 16 to 25 years, and 26 to 50 years. Results indicated that younger age groups were at higher risk of fluorosis than the other groups. Fluoride human health risk in Khushab, Punjab, Pakistan, reported by (Iqbal et al., 2023b). They quantified non-carcinogenic health risk assessment, and HQ valued that adults and children are at high risk of skeleton fluorosis, whereas potential issues of dental fluorosis in infants. Moreover, above the permissible limit, fluoride leads to spinal disorders, and continual exposure to damages boons and teeth (Yousefi et al., 2018).

Health risk in the category for the female group, including pregnant and breastfeeding women, represented in Fig. 5 and Fig. 6. In 47 % of samples with an average HQ = 1.31 resulted for the pregnant women, and 54 % of samples with an average HQ = 1.69 for breastfeeding women; these are alarming indications. During pregnancy, high fluoride intake can result in maternal anemia, leading to embryonic outcomes,

Table 2
The measure of the fluoride risk index (FRI).

Fluoride risk index (FRI)			
Fluoride Rang	Risk class	No of samples	% of samples
0.23–0.45	Very low	5	8.77
0.5–0.93	Low	17	29.82
1.04–1.47	Medium	8	14.04
1.61–1.95	High	6	10.53
1.04–1.47	Very high	3	5.26
1.47 >	Extremely High	18	31.58

Table 3
The measure of the fluoride pollution index (FPI).

Fluoride pollution index (FPI)			
FPI Rang	Class	No of samples	% of samples
1–2	Low	21	36
2–3	Medium	37	64
3–4	High	0	0

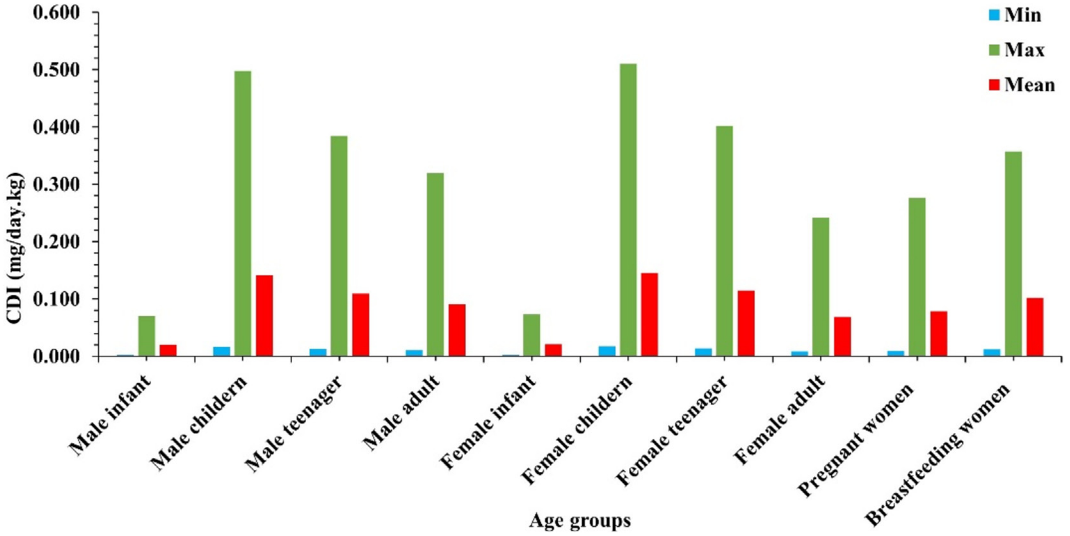


Fig. 4. CDI of fluoride across different age groups for males and females.

such as miscarriages, congenital malformations, intra-uterine death, and abortions (Goyal et al., 2020). Additionally, high fluoride intake during pregnancy may impact the developing fetus' brain development, potentially leading to a lower IQ of the baby (Li et al., 2008). An investigation was conducted on breastfeeding duration and fluoridated water intake (Ha et al., 2019). They divided children into groups of breastfeeding duration, such as 0 < 1 month, 1 to 6 months, 6 to 24 months, and > 24 months. The outcome of this study indicates that early exposure to high fluoride among children through breastfeeding resulted in dental caries at the early age of 5 to 6 years.

3.5. Prolong implications of fluoride exposure

Long-term fluoride exposure through drinking groundwater leads to chronic health conditions: weight loss, liver damage, imbalanced blood pressure, respiratory failure, paralysis, and cachexia. Similarly, chronic fluoride exposure can negatively impact male fertility and reproductive ability (Ortiz-Perez et al., 2003). A study by Freni (1994) reported a decreased birth rate in 30 regions of the US, which was directly proportional to the level of fluoride contamination in drinking water (Freni, 1994). Fluoride intake levels between 2 and 4 mg/L can affect children's visuospatial abilities, including skills like mental rotation, spatial reasoning, visual memory, and spatial visualization. These abilities are important for everyday tasks like solving puzzles, reading maps, and understanding geometry. They are also closely connected to cognitive functions like attention, working memory, and problem-solving (Aravind et al., 2016; Nizam et al., 2022; Saxena et al., 2012; Wang et al., 2007). Moreover, neurotoxicity and osteosarcoma (bone cancer) were also reported in children compared to other age groups; however, such cases are uncommon, requiring more research (Nizam et al., 2022; Shashi and Bhardwaj, 2011).

3.6. Recommendations

To improve the quality of drinking groundwater and mitigate the health risks associated with fluoride contamination in the Tando Bago subdistrict of Badin district, implementing advanced water treatment technologies is recommended. Reverse Osmosis (RO) systems can effectively remove dissolved solids, including fluoride ions, from groundwater. These should be installed at centralized water treatment facilities or

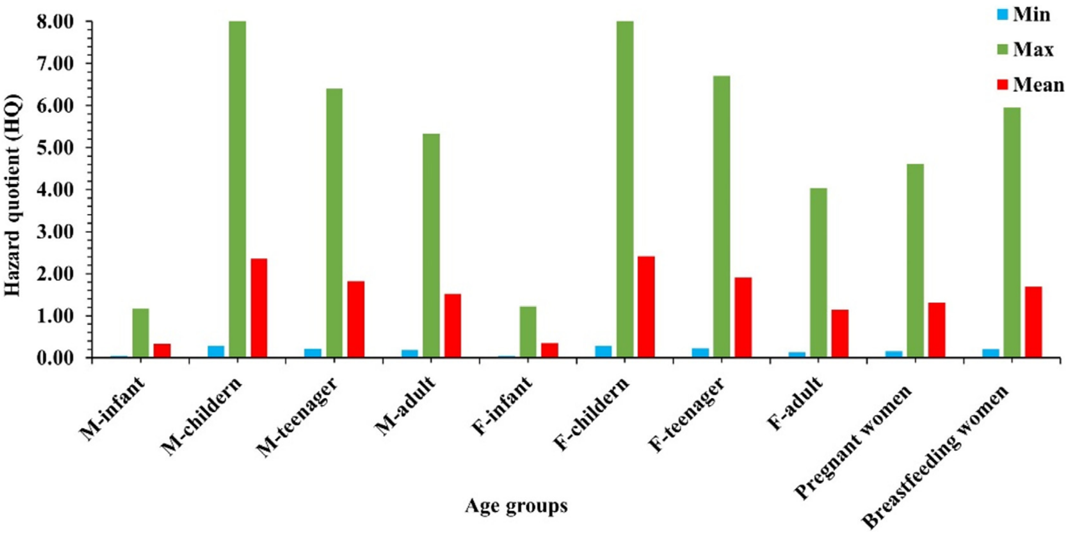


Fig. 5. HQ values for fluoride exposure across different age groups of males and females.

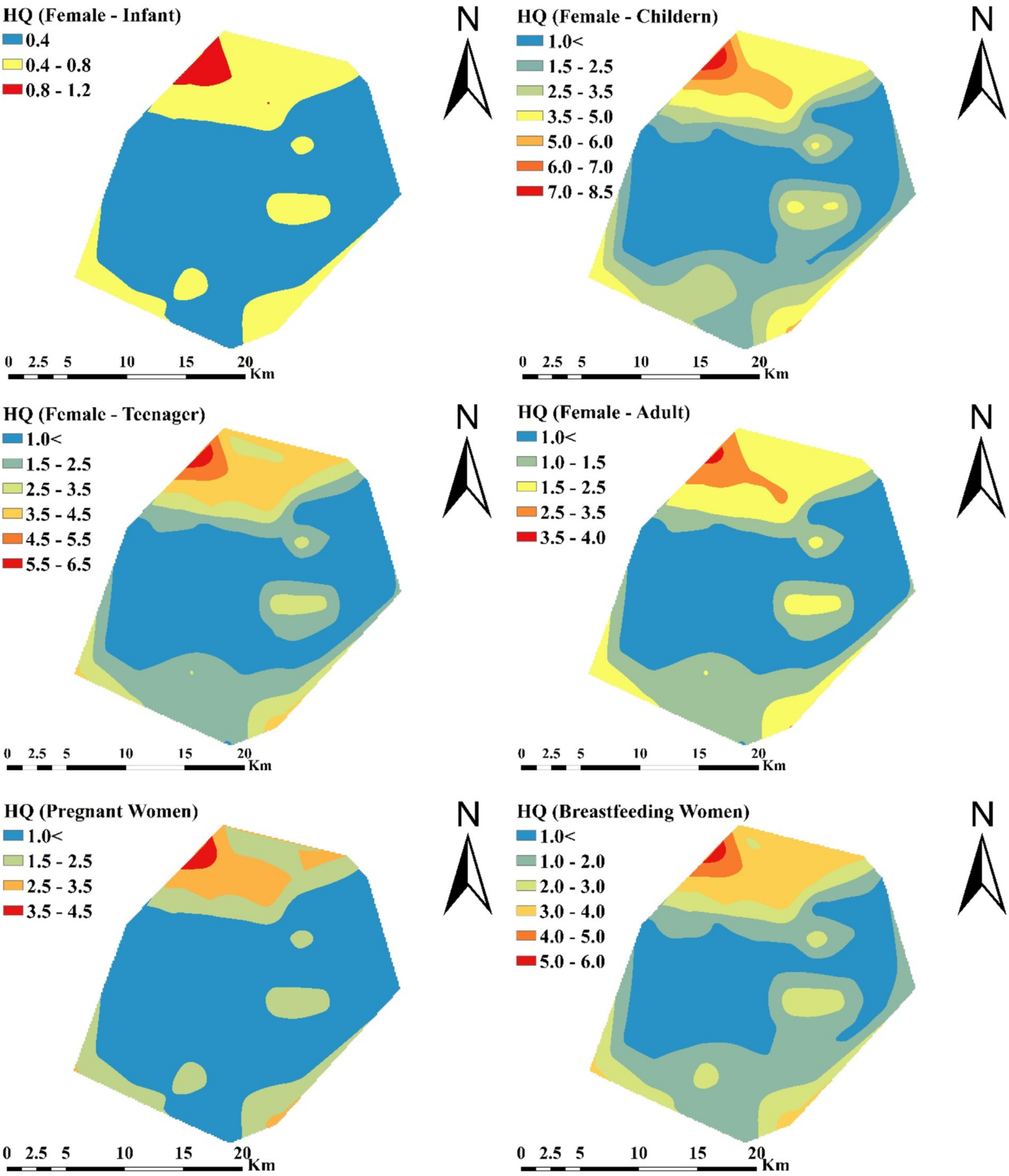


Fig. 6. Spatial distribution of HQ values for different age groups of females.

community-level water purification plants to provide safe drinking water to the affected population. Additionally, the cost-effective Activated Alumina Adsorption method, which involves passing water through a bed of activated alumina that selectively adsorbs fluoride ions with the adsorbent regenerated periodically, can be employed. Another efficient and environmentally friendly approach is Electrocoagulation, a process that uses electrical currents to coagulate and remove fluoride ions from water, implementable at various scales.

Concurrently, public awareness and education campaigns should be developed to disseminate information on the health risks associated with fluoride exposure and the importance of consuming safe drinking water. Training local health workers, schoolteachers, and community leaders to deliver awareness programs and promote healthy water consumption practices is crucial. Utilizing various media channels, such as radio, television, and social media, can effectively reinforce the message and reach a wider audience.

Moreover, establishing a comprehensive groundwater quality monitoring program is essential to regularly track fluoride levels and other contaminants. Conducting periodical health surveys can assess the prevalence of fluoride-related health effects in the population and evaluate the effectiveness of interventions. Employing Geographic Information Systems (GIS) can map the spatial distribution of fluoride contamination, identifying high-risk areas for targeted interventions.

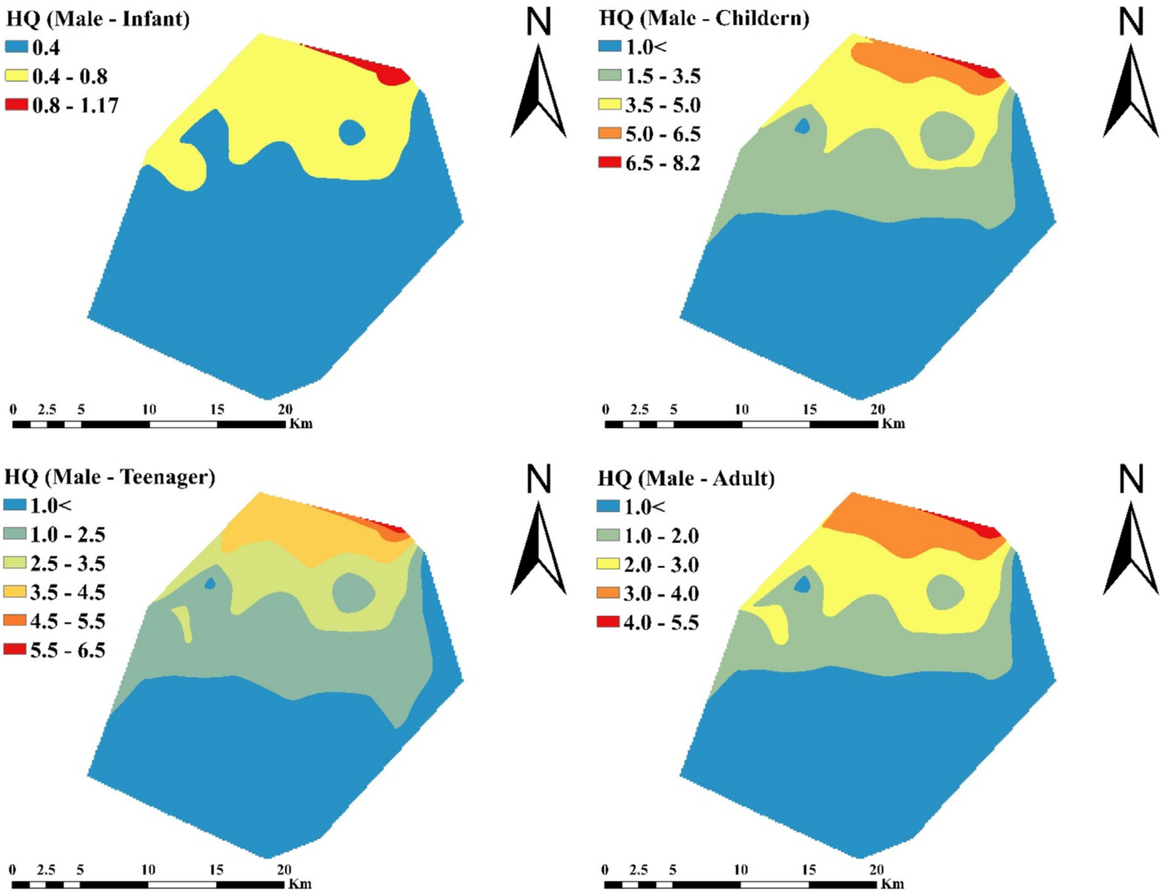


Fig. 7. Spatial distribution of HQ values for different age groups of males.

Fostering collaboration between government agencies, non-governmental organizations (NGOs), and local communities can pool resources and expertise for effective implementation of interventions. Engaging with research institutions and universities can further studies on fluoride contamination and develop innovative solutions tailored to the local context. Seeking funding and technical support from international organizations and donor agencies can aid in scaling up successful interventions and ensuring their sustainability.

By adopting a multi-faceted approach that combines technological solutions, public awareness, monitoring, and collaborations, the quality of drinking groundwater can be significantly improved, and the health risks associated with fluoride contamination can be effectively mitigated in the Tando Bago subdistrict.

4. Conclusion

This study provides a comprehensive assessment of fluoride contamination in the groundwater of Tando Bago subdistrict, Badin district, Pakistan, and its associated health risks. Key findings include:

- 47 % of groundwater samples exceeded the WHO fluoride limit of 1.5 mg/L, with a mean concentration of 1.92 mg/L.
- Spatial analysis using the Fluoride Risk Index (FRI) identified high to extremely high-risk zones in the northern and southern areas of the study region.
- Health risk assessment revealed children ($HQ > 1$ for 63–65 %) and teenagers ($HQ > 1$ for 60–62 %) as the most vulnerable groups, with females at slightly higher risk.
- Elevated levels of TDS, turbidity, and iron were also observed, further compromising groundwater quality.

These results highlight significant public health concern, particularly the risk of dental and skeletal fluorosis among the local population. The study underscores the urgent need for:

- Implementation of advanced water treatment technologies, such as reverse osmosis or activated alumina adsorption, to reduce fluoride levels in drinking water.
- Development of a comprehensive groundwater quality monitoring program to track fluoride and other contaminants over time.
- Public awareness campaigns to educate the local population about the health risks associated with fluoride exposure and the importance of safe drinking water.
- Collaboration between government agencies, NGOs, and research institutions to develop and implement sustainable solutions for safe water provision.

Future research should focus on evaluating the effectiveness of various fluoride removal techniques in the local context and assessing the long-term health impacts of chronic fluoride exposure in the affected population. This study serves as a crucial basis for informed decision-making and policy development to address the critical issue of fluoride contamination in the Tando Bago subdistrict and similar affected areas.

CRediT authorship contribution statement

Shakeel Ahmed Talpur: Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Muhammad Rashad:** Investigation, Writing – review & editing. **Aziz Ahmed:** Visualization, Validation, Software. **Gianluigi Rosatelli:** Writing – review & editing. **Muhammad Yousuf Jat Baloch:** Writing – review & editing, Writing – original draft. **Aqib Hassan Ali Khan:** Writing – review & editing, Writing – original draft, Visualization, Validation. **Hafeez Ahmed Talpur:** Writing – review & editing, Software, Methodology, Investigation. **Javed Iqbal:** Validation, Writing – original draft.

Declaration of competing interest

The authors declared that they have no direct or indirect competing interests.

References

Abirhire, O., Davies, J.-M., Guo, X., Hudson, J., 2020. Understanding the factors associated with long-term reconstructed turbidity in Lake Diefenbaker from Landsat-imagery. Sci. Total Environ. 724, 138222.

Ahmed, A., Noonari, T., Magsi, H., Mahar, A., 2013. Risk assessment of total and faecal coliform bacteria from drinking water supply of Badin city, Pakistan. J. Environ. Professi. Sri Lanka 2 (1), 52–64.

Aravind, A., Dhanya, R., Narayan, A., Sam, G., Adarsh, V., Kiran, M., 2016. Effect of fluoridated water on intelligence in 10-12-year-old school children. J. Int. Soc. Prevent. Communit. Dentistr. 6 (Suppl. 3), S237.

Arcentales-Ríos, R., Carrión-Méndez, A., Cipriani-Ávila, I., Acosta, S., Capparelli, M., Moulatlet, G., Pinos-Vélez, V., 2022. Assessment of metals, emerging contaminants, and physicochemical characteristics in the drinking water and wastewater of Cuenca, Ecuador. J. Trace Element. Minera. 2, 100030.

Ayoob, S., Gupta, A.K., 2006. Fluoride in drinking water: a review on the status and stress effects. Crit. Rev. Environ. Sci. Technol. 36 (6), 433–487.

Aziz, S., Ain, W., Majeed, R., Khan, M.A., Qayum, I., Ahmed, I., Hosain, K., 2012. Growth centile charts (anthropometric measurement) of Pakistani pediatric population. JPMA-J. Pakistan Med. Assoc. 62 (4), 367.

Baloch, M.Y.J., Talpur, S.A., Talpur, H.A., Iqbal, J., Mangi, S.H., Memon, S., 2020. Effects of arsenic toxicity on the environment and its remediation techniques: A review. J. Water Environ. Technol. 18 (5), 275–289.

Baloch, M.Y.J., Su, C., Talpur, S.A., Iqbal, J., Bajwa, K., 2022. Arsenic removal from groundwater using Iron pyrite: influences factors and removal mechanism. J. Earth Sci. 34 (3), 857–867.

Bassin, E.B., Wypij, D., Davis, R.B., Mittleman, M.A., 2006. Age-specific fluoride exposure in drinking water and osteosarcoma (United States). Cancer Causes Control 17, 421–428.

Brahman, K.D., Kazi, T.G., Baig, J.A., Afridi, H.I., Khan, A., Arain, S.S., Arain, M.B., 2014. Fluoride and arsenic exposure through water and grain crops in Nagarparkar, Pakistan. Chemosphere 100, 182–189.

Brindha, K., Rajesh, R., Murugan, R., Elango, L., 2011. Fluoride contamination in groundwater in parts of Nalgonda District, Andhra Pradesh, India. Environ. Monit. Assess. 172, 481–492.

Chen, J., Wu, H., Qian, H., Gao, Y., 2017. Assessing nitrate and fluoride contaminants in drinking water and their health risk of rural residents living in a semiarid region of Northwest China. Expo. Health 9, 183–195.

da Silva, E.P., Simões, T.R., Antoniosi Filho, N.R., Pereira, J., Formiga, K.T.M., 2024. Effect of rainfall characteristics on the transport of trace metals in suspended particles during rainfall events. J. Hydrol. 634, 131062.

Derso Mengesha, S., Weldetinsae, A., Tesfaye, K., Taye, G., 2018. Organoleptic and palatability properties of drinking water sources and its health implications in Ethiopia: a retrospective study during 2010-2016. Environ. Health Eng. Manag. J. 5 (4), 221–229.

Freni, S.C., 1994. Exposure to high fluoride concentrations in drinking water is associated with decreased birth rates. J. Toxicol. Environ. Health 42 (1), 109–121.

Gelberg, K.H., Fitzgerald, E.F., Hwang, S., Dubrow, R., 1995. Fluoride exposure and childhood osteosarcoma: a case-control study. Am. J. Public Health 85 (12), 1678–1683.

Ghani, J., Ullah, Z., Nawab, J., Iqbal, J., Waqas, M., Ali, A., Almutairi, M.H., Peluso, I., Mohamed, H.R., Shah, M., 2022. Hydrogeochemical characterization, and suitability assessment of drinking groundwater: application of geostatistical approach and geographic information system. Front. Environ. Sci. 10, 874464.

Goyal, L.D., Bakshi, D.K., Arora, J.K., Manchanda, A., Singh, P., 2020. Assessment of fluoride levels during pregnancy and its association with early adverse pregnancy outcomes. J. Family Med. Prim. Care 9 (6), 2693.

Ha, D., Spencer, A., Peres, K., Rugg-Gunn, A., Scott, J., Do, L., 2019. Fluoridated water modifies the effect of breastfeeding on dental caries. J. Dent. Res. 98 (7), 755–762.

Haji, M., Karuppannan, S., Qin, D., Shube, H., Kawo, N.S.J.A.o.e.c. and Toxicology, 2021. Potential human health risks due to groundwater fluoride contamination: A case study using multi-techniques approaches (GWQI, FPI, GIS, HHRA) in Bilate River basin of southern Main Ethiopian rift, Ethiopia. Arch. Environ. Contaminat. Toxicol. 80 (1), 277–293.

Hu, J., Dong, H., Xu, Q., Ling, W., Qu, J., Qiang, Z., 2018. Impacts of water quality on the corrosion of cast iron pipes for water distribution and proposed source water switch strategy. Water Res. 129, 428–435.

Iqbal, J., Su, C., Rashid, A., Yang, N., Baloch, M.Y.J., Talpur, S.A., Ullah, Z., Rahman, G., Rahman, N.U., Sajjad, M.M., 2021. Hydrogeochemical assessment of groundwater and suitability analysis for domestic and agricultural utility in southern Punjab, Pakistan. Water 13 (24), 3589.

Iqbal, J., Amin, G., Su, C., Haroon, E., Baloch, M.Y.J., 2023a. Assessment of landcover impacts on the groundwater quality using hydrogeochemical and geospatial techniques. Environ. Sci. Pollut. Res. 31, 40303–40323.

Iqbal, J., Su, C., Wang, M., Abbas, H., Baloch, M.Y.J., Ghani, J., Ullah, Z., Huq, M., 2023b. Groundwater fluoride and nitrate contamination and associated human health risk assessment in South Punjab, Pakistan. Environ. Sci. Pollut. Res. 30, 61606–61625.

Jat Baloch, M.Y., Zhang, W., Chai, J., Li, S., Alqurashi, M., Rehman, G., Tariq, A., Talpur, S.A., Iqbal, J., Munir, M., 2021. Shallow groundwater quality assessment and its suitability analysis for drinking and irrigation purposes. Water 13 (23), 3361.

Jat Baloch, M.Y., Zhang, W., Shoumik, B.A.A., Nigar, A., Elhassan, A.A., Elshekh, A.E., Bashir, M.O., Mohamed Salih Ebrahim, A.F., Adam Mohamed, K.A., Iqbal, J., 2022a. Hydrogeochemical mechanism associated with land use land cover indices using geospatial, remote sensing techniques, and health risks model. Sustainability 14 (24), 16768.

Jat Baloch, M.Y., Zhang, W., Zhang, D., Al Shoumik, B.A., Iqbal, J., Li, S., Chai, J., Farooq, M.A., Parkash, A., 2022b. Evolution mechanism of arsenic enrichment in groundwater and associated health risks in southern Punjab, Pakistan. Int. J. Environ. Res. Public Health 19 (20), 13325.

Kapani, K., Charantimath, N.V., Chikkanarayanaswamy, P., Jayaramaiah, U., 2019. Assessing the Water Quality of Vatadahosahalli Lake in Chikkaballapura District, Karnataka. India. HydroResearch 7, 326–336.

Keramati, H., Miri, A., Baghaei, M., Rahimizadeh, A., Ghorbani, R., Fakhri, Y., Bay, A., Moradi, M., Bahmani, Z., Ghaderpoori, M., 2019. Fluoride in Iranian drinking water resources: a systematic review, meta-analysis and non-carcinogenic risk assessment. Biol. Trace Elem. Res. 188, 261–273.

Li, J., Yao, L., Shao, Q.-L., Wu, C.-Y., 2008. Effects of high fluoride level on neonatal neurobehavioral development. Fluoride 41 (2), 165–170.

Liu, X., Li, Y., Chen, Z., Yang, H., Wang, S., Tang, Z., Wang, X., 2023. Recent Progress of COFs Membranes: Design, Synthesis and Application in Water Treatment. Eco-Environment & Health 2 (3).

Lytle, D.A., Tang, M., Francis, A.T., O'Donnell, A.J., Newton, J.L., 2020. The effect of chloride, sulfate and dissolved inorganic carbon on iron release from cast iron. Water Res. 183, 116037.

Masood, N., Hudson-Edwards, K.A., Farooqi, A.J.E.G., Health, 2022. Groundwater nitrate and fluoride profiles, sources and health risk assessment in the coal mining areas of salt range, Punjab Pakistan. Environ. Geochem. Health 44 (3), 715–728.

Mekal, A.D., El-Shazly, M.M., Ragab, M., Marzouk, E.R., 2023. Comparison of modern and 40-year-old drinking water pipeline in northern Sinai region, Egypt: characteristics and health risk assessment. J. Trace Element. Minera. 5, 100078.

Mirlohi, S., 2022. Characterization of metallic off-flavors in drinking water: health, consumption, and sensory perception. Int. J. Environ. Res. Public Health 19 (24), 16829.

More, S., Dhakate, R., Ratnalu, G.V., Machender, G., 2021. Hydrogeochemistry and health risk assessment of groundwater and surface water in fluoride affected area of Yadadri-Bhuvanagiri District, Telangana state, India. Environ. Earth Sci. 80, 1–18.

Mukherjee, I., Singh, U.K., 2018. Groundwater fluoride contamination, probable release, and containment mechanisms: a review on Indian context. Environ. Geochem. Health 40 (6), 2259–2301.

Nephalama, A., Muzerengi, C., 2016. Assessment of the influence of coal mining on groundwater quality: case of Masisi Village in the Limpopo Province of South Africa. Proceedings of the Freiberg/Germany, Mining Meets Water—Conflicts Solutions, Leipzig, Germany, pp. 11–15.

Nizam, S., Virk, H.S., Sen, I.S., 2022. High levels of fluoride in groundwater from northern parts of indo-Gangetic plains reveals detrimental fluorosis health risks. Environ. Adva. 8, 100200.

Ortiz-Perez, D., Rodrı́guez-Martı́nez M., Martı́nez, F, Borja-Aburto, V.C.H., Castelo, J., Grimaldo, J.I., de la Cruz, E., Carrizales, L., Dı́az-Barriga, F., 2003. Fluoride-induced disruption of reproductive hormones in men. Environ. Res. 93 (1), 20–30.

Qian, J., Hu, T., Xiong, H., Cao, X., Liu, F., Gosnell, K.J., Xie, M., Chen, R., Tan, Q.-G., 2024. Turbid waters and clearer standards: refining water quality criteria for coastal environments by encompassing metal bioavailability from suspended particles. Environ. Sci. Technol. 58 (12), 5244–5254.

Qiu, W., Li, W., He, J., Zhao, H., Liu, X., Yuan, Y., 2018. Variations regularity of microorganisms and corrosion of cast iron in water distribution system. J. Environ. Sci. 74, 177–185.

Rahman, S., Lee, P., Ahmed, F., 2020. Development and standardization of taste-rating of the water sample as a semi-quantitative assessment of iron content in groundwater. Groundw. Sustain. Dev. 11, 100455.

Rashid, A., Guan, D.-X., Farooqi, A., Khan, S., Zahir, S., Jehan, S., Khattak, S.A., Khan, M.S., Khan, R., 2018. Fluoride prevalence in groundwater around a fluorite mining area in the flood plain of the river swat, Pakistan. Sci. Total Environ. 635, 203–215.

Rashid, A., Farooqi, A., Gao, X., Zahir, S., Noor, S., Khattak, J.A., 2020. Geochemical modeling, source apportionment, health risk exposure and control of higher fluoride in groundwater of sub-district Dargai, Pakistan. Chemosphere 243, 125409.

Salari, M., 2024. Investigating groundwater quality using water quality indicators for drinking, agriculture and industry (case study: shiraz plain). J. Environ. Scie. Stud. 8 (4), 7574–7586.

Salve, P., Maurya, A., Kumbhare, P., Ramteke, D., Wate, S., 2008. Assessment of groundwater quality with respect to fluoride. Bull. Environ. Contam. Toxicol. 81, 289–293.

Sassane, A., Touati, M., 2024. Metallic groundwater contamination assessment using the heavy metal pollution index: a case study of the Guelma plain alluvial groundwater, northeast of Algeria. Sustain. Water Res. Manag. 10, 30.

Saxena, S., Sahay, A., Goel, P., 2012. Effect of fluoride exposure on the intelligence of school children in Madhya Pradesh, India. J. Neurosci. Rural Pract. 3 (02), 144–149.

Shashi, A., Bhardwaj, M., 2011. Study on blood biochemical diagnostic indices for hepatic function biomarkers in endemic skeletal fluorosis. Biol. Trace Elem. Res. 143 (2), 803–814.

Srinivasamoorthy, K., Vijayaraghavan, K., Vasanthavigar, M., Sarma, S., Chidambaram, S., Anandhan, P., Manivannan, R., 2012. Assessment of groundwater quality with special emphasis on fluoride contamination in crystalline bed rock aquifers of Mettur region, Tamilnadu, India. Arab. J. Geosci. 5 (1), 83–94.

Stevenson, M., Bravo, C., 2019. Advanced turbidity prediction for operational water supply planning. Decis. Support. Syst. 119, 72–84.

Szpak, D., Tchórzewska-Cieślak, B., Pietrucha-Urbanik, K., 2020. Analysis of the turbidity of raw water in the context of water-supply safety. Desalinat. Water Treatm. 186, 281–289.

Taiwo, A.M., Hassan, T., Adeoye, I.A., Adekoya, G.A., Tayo, O.E., Ogunsola, D.O., Babawale, M.K., Isichei, O.T., Olayinka, S.O., 2023. Assessment of levels and health risk of potentially toxic elements (PTEs) in selected sachet water packaged from groundwater resources in Ogun state, Nigeria. J. Trace Element. Minera. 5, 100087.

Talpur, S.A., Noonari, T.M., Rashid, A., Ahmed, A., Jat Baloch, M.Y., Talpur, H.A., Soomro, M.H., 2020. Hydrogeochemical signatures and suitability assessment of groundwater with elevated fluoride in unconfined aquifers Badin district, Sindh, Pakistan. SN Appl. Sci. 2, 1–15.

Talpur, H.A., Talpur, S.A., Mahar, A., Rosatelli, G., Baloch, M.Y.J., Ahmed, A., Khan, A.H.A., 2024a. Investigating drinking water quality, microbial pollution, and potential health risks in selected schools of Badin city, Pakistan. HydroResearch 7, 248–256.

Talpur, S.A., Baloch, M.Y.J., Su, C., Iqbal, J., Ahmed, A., Talpur, H.A., 2024b. Application of synthetic Iron Oxyhydroxide with influencing factors for removal of as (V) and as (III) from groundwater. J. Earth Sci. 35 (3), 998–1009.

Thapa, R., Gupta, S., Kaur, H., Baski, R., 2019. Assessment of groundwater quality scenario in respect of fluoride and nitrate contamination in and around Gharbar village, Jharkhand, India. HydroResearch 2, 60–68.

Thirumoorthy, P., Murugasamy, M.V., Dhanasekaran, J., Sasikumar, K., Periyasamy, M., Selvam, J., 2024. Assessment of groundwater quality in Perundurai region of South India using water quality index and statistical modelling. Groundw. Sustain. Dev. 25, 101104.

Tomperi, J., Isokangas, A., Tuuttila, T., Paavola, M., 2022. Functionality of turbidity measurement under changing water quality and environmental conditions. Environ. Technol. 43 (7), 1093–1101.

Ullah, Z., Rashid, A., Ghani, J., Nawab, J., Zeng, X.-C., Shah, M., Alrefaei, A.F., Kamel, M., Aleya, L., Abdel-Daim, M.M., Iqbal, J., 2022a. Groundwater contamination through potentially harmful metals and its implications in groundwater management. Front. Environ. Sci. 10, 1021596.

Ullah, Z., Xu, Y., Zeng, X.-C., Rashid, A., Ali, A., Iqbal, J., Almutairi, M.H., Aleya, L., Abdel-Daim, M.M., Shah, M., 2022b. Non-carcinogenic health risk evaluation of elevated fluoride in groundwater and its suitability assessment for drinking purposes based on water quality index. Int. J. Environ. Res. Public Health 19 (15), 9071.

Ullah, Z., Rashid, A., Nawab, J., Bacha, A.-U.-R., Ghani, J., Iqbal, J., Zhu, Z., Alrefaei, A.F., Almutairi, M.H., 2023. Fluoride contamination in groundwater of community tube wells, source distribution, associated health risk exposure, and suitability analysis for drinking from arid zone. Water 15 (21), 3740.

USEPA, 2005. Guidelines for carcinogen risk assessment. Risk Assessment Forum;. US Environmental Protection Agency Washington, DC, USA (EPA/630/P-03 F).

Wang, S.-X., Wang, Z.-H., Cheng, X.-T., Li, J., Sang, Z.-P., Zhang, X.-D., Han, L.-L., Qiao, X.-Y., Wu, Z.-M., Wang, Z.-Q., 2007. Arsenic and fluoride exposure in drinking water: children's IQ and growth in Shanyin county, Shanxi province, China. Environ. Health Perspect. 115 (4), 643–647.

WHO, 2011. Guidelines for drinking-water quality. WHO Chron. 38 (4), 104–108.

Yao, Y., Tu, C., Hu, G., Zhang, Y., Cao, H., Wang, W., Wang, W., 2024. Groundwater Hydrochemistry and Recharge Process Impacted by Human Activities in an Oasis–Desert in Central Asia. Water 16 (5), 763.

Yousefi, M., Ghoochani, M., Mahvi, A.H., 2018. Health risk assessment to fluoride in drinking water of rural residents living in the Poldasht city, northwest of Iran. Ecotoxicol. Environ. Saf. 148, 426–430.

Yousefi, M., Ghalehaskar, S., Asghari, F.B., Ghaderpoury, A., Dehghani, M.H., Ghaderpoori, M., Mohammadi, A.A., 2019. Distribution of fluoride contamination in drinking water resources and health risk assessment using geographic information system, Northwest Iran. Regul. Toxicol. Pharmacol. 107, 104408.

Zango, M.S., Pelig-Ba, K.B., Anim-Gyampo, M., Gibrilla, A., Sunkari, E.D., 2021. Hydrogeochemical and isotopic controls on the source of fluoride in groundwater within the Vea catchment, northeastern Ghana. Groundw. Sustain. Dev. 12, 100526.

Zhang, X., Razanajatovo, M.R., Du, X., Wang, S., Feng, L., Wan, S., Chen, N., Zhang, Q., 2023. Well-designed protein amyloid nanofibrils composites as versatile and sustainable materials for aquatic environment remediation: A review. Eco-Environ. & Health. 2 (4), 264–277.

Zheng, H., Qu, C., Zhang, J., Talpur, S.A., Ding, Y., Xing, X., Qi, S., 2019. Polycyclic aromatic hydrocarbons (PAHs) in agricultural soils from Ningde, China: levels, sources, and human health risk assessment. Environ. Geochem. Health 41, 907–919.

Zhu, M., Wang, J., Yang, X., Zhang, Y., Zhang, L., Ren, H., Wu, B., Ye, L., 2022. A review of the application of machine learning in water quality evaluation. Eco-Environ. & Health. 1 (2), 107–116.