Asian Journal of Chemistry; Vol. 38, No. 1 (2026), 123-132

ASIAN JOURNAL OF CHEMISTRY

https://doi.org/10.14233/ajchem.2026.34804

Groundwater Fluoride Contamination in Balochistan, Pakistan: Health Risk and Regional Variability Analysis using HQ and NPI Indices

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Received: 1 October 2025 *Accepted*: 12 November 2025 *Published online*: 31 December 2025 AJC-22230

Groundwater fluoride contamination in Balochistan, Pakistan, poses significant public health and socio-economic challenges. This study comprehensively assessed groundwater quality across 7 districts, including Quetta, Loralai, Sibi, Kachi Bolan, Sohbatpur, Jafarabad and Naseerabad, through 825 samples collected during 2022 and 2023. Parameters analyzed included fluoride (F^-), total dissolved solids (TDS), electrical conductivity (EC) and pH. Advanced indices, including hazard quotient (HQ), fluoride concentration (C_F), pollution index (PI_F) and Nemerow Pollution Index (NPI), were used to evaluate risks for male and female population groups. The highest F^- contamination was observed in Sibi (58% unsafe samples), followed by Loralai (20.2%), with contamination severity ranked as Sibi > Loralai > Sohbatpur > Kachi Bolan > Quetta > Jafarabad > Naseerabad. HQ analysis revealed children are significantly more vulnerable, with the highest HQ for children observed in Sohbatpur (mean: 1.128). The C_F analysis showed minimal risk for infants (< 1 year) but higher exposure for children (1-8 years), particularly in Sibi (mean: 0.112 mg/L). The NPI findings classified Nasirabad as minimal risk (NPI: 0.859), while Sibi, Sohbatpur, Kachi Bolan and Loralai posed high risks (NPI: 1.33-1.50), whereas EC and TDS variability highlighted groundwater quality differences, with high salinity and TDS concentrations in Sohbatpur and Jafarabad indicating unsuitability for drinking.

Keywords: Groundwater, Toxicity, Hazard quotient, Nemerow Pollution Index, Children's vulnerability, Balochistan, Pakistan.

INTRODUCTION

Fluoride (F^-) contamination of groundwater is a global issue, affecting millions across diverse geographies, including regions of India, East Africa and China, where natural geological factors and human activities exacerbate the problem [1,2]. This global challenge underscores the critical need to address F^- related health risks through sustainable interventions, particularly in arid and F^- rich regions like Balochistan, Pakistan. Groundwater F^- contamination in Balochistan, poses a significant challenge with serious implications for public health and socio-economic stability. Over the decades, various studies have highlighted elevated F^- concentrations in the region, particularly in Quetta, Sibi and Kachi Bolan districts, where levels often exceed the WHO permissible limit of 1.5 mg/L [3,4]. This contamination arises from a complex interplay of natural geological factors and anthropogenic activities, mirroring similar challenges faced by fluoride affected regions worldwide.

Fluoride enrichment in parts of Balochistan can be linked to the presence of fluorite-bearing sedimentary formations such as those reported from Loralai district where weathering and dissolution of minerals like fluorite and fluorapatite commonly release F^- into groundwater [5,6]. Groundwater flowing through these formations dissolves these minerals, releasing F^- into the water supply, arid climate further exacerbates the issue. High evaporation rates concentrate F^- levels in shallow aquifers, a phenomenon also observed in arid regions like Rajasthan, India and parts of the Middle East [7,8]. Geothermal activity, present in some areas of Balochistan, further contributes by introducing naturally high F^- levels from thermal springs, similar to patterns observed in the East African Rift Valley [2]. Mining and mineral extraction, have also been linked to elevated F^- levels, as reported for Sibi district where both F^- and arsenic contamination have been reported [4]. The over extraction of groundwater lowers the water table, enhancing the dissolution of F^- rich minerals and worsening contamination levels [9,10]. Dental and skeletal fluorosis in Balochistan province are widespread in areas where untreated groundwater serves as the primary drinking water source. Beyond the visible effects, there is growing evidence linking high F^- exposure to cognitive impairments in children. Studies have highlighted potential neurotoxic effects, raising concerns about similar impacts on children in Balochistan's affected areas [11,12].

The fluoride burden in Balochistan province aligns with global challenges, underscore the universal nature of the problem, where socio-economic disparities and dependence on untreated groundwater exacerbate health risks [13]. Understanding and addressing fluoride problems in Balochistan within this global context highlights the shared responsibility of mitigating its effects and ensuring access to safe drinking water [8,14]. The present study underscores the urgent need for comprehensive groundwater quality assessment in Balochistan to address fluoride contamination, a significant public health and socioeconomic challenge.

EXPERIMENTAL

Geographic, geological and climatic overview: Balochistan is the largest province of Pakistan, which features diverse terrains, including mountains, plateaus, valleys and plains [15]. The districts of Quetta, Loralai, Sibi, Kachi Bolan, Sohbatpur, Jafarabad and Nasirabad exemplify this diversity [16]. Quetta, encircled by the Toba Kakar and Chiltan ranges, combines rugged landscapes with fertile valleys [17]. Loralai transitions between hills and plains, while Sibi links highlands to the Indus plains, featuring flat terrain bordered by low hills. Kachi Bolan's arid landscapes include the historic Bolan Pass [18]. The fertile plains of Sohbatpur, Jafarabad and Nasirabad, sustained by the Pat Feeder Canal and Indus River, are pivotal for agriculture [19,20].

Geologically the study area is a part of 1250 km long and 180 km wide Kirther Sulaiman Foldbelt. Its western part is bounded by Chaman Fault. The rocks exposed in the area ranges from Triassic to Quaternary age (Fig. 1a). The southern side of the study area including Jafarabad, sohbatpur, Nasirabad and lower parts of Sibi are mainly covered with Quaternary sediments (Fig. 1c). Aquifers in these districts are mainly hosted in Holocene and Pleistocene medium to coarse grained sediments. The Quetta and Loralai districts mainly contain rocks of Mesozoic. The Mesozoic sequence comprised of Wulgai formation (mudstone, shale, limestone) of Triassic age Shirinab formation (limestone, sandstone, shale) of Jurassic age [21]. The Cretaceous Sembar, Goru and Parh Formations mainly contain black shale, sandstone and pelagic limestone. The western part is also characterized by Cretac-ous ophiolitic sequence, mainly contains mafic/ultramafic rocks, dolerite dykes, sepentinite and variable quantity of fluorite, barite, magnesite, barite and chromite deposits at several places [15].

The Mesozoic sequence unconformably overlain by Eocene Ghazij formation (shale, claystone and sandstone) and Oligocene Nisai Formation (limestone, shale, sandstone, conglomerate) in the region [15]. The karst limestone and conglomerate mainly act as aquifers in the Quetta region. Due to low annual precipitation rate groundwater (GW) recharge is limited. The western region aquifers are recharged through Nari and Moro River while in south eastern areas, aquifers are recharged through Indus and Gaj Rivers. The water table ranges from 1-80 m. The annual evapotranspiration rate is 2015 Mm^3 which is 38% of total recharge, therefore, GW resources are at risk due to extreme climate and over-extraction. About 90% of water is supplied through GW, which is used for domestic and irrigation purpose [22].

Loralai is mineral-rich with Jurassic limestone, while Sibi contains Quaternary alluvial deposits [23]. Climate varies significantly. Quetta experiences semi-arid conditions with snowfall; Loralai has extreme seasonal variations [17]. Sibi records Pakistan's highest temperatures, while Kachi Bolan remains arid [16]. The plains of Sohbatpur, Jafarabad and Nasirabad face monsoondriven rainfall and seasonal flooding [19].

Study area: The study area includes seven districts of Balochistan, Pakistan, with diverse landscapes. Quetta (30.1798ºN, 66.9750ºE) lies amid the Toba Kakar and Chiltan ranges near the Afghan border. Loralai (30.3705ºN, 68.5972ºE) features hills and plains, while Sibi (29.5423ºN, 67.8763ºE) connects highlands to the Indus plains. Kachi Bolan (29.4936ºN, 67.6218ºE) includes the historic Bolan Pass. Sohbatpur (28.5195ºN, 68.5437ºE), Jafarabad (28.2827ºN, 68.2833ºE) and Nasirabad (27.7388ºN, 68.1991ºE) consist of fertile, irrigated plains shaped by the Indus River and Pat Feeder Canal (Fig. 1b-c).

Sample collection: A total of 825 GW samples were collected from seven districts. Sampling occurred during August-October 2022, except in Quetta and Sibi, where it took place in October-November 2023. In Quetta, 152 samples were obtained from tube wells (TW) at depths of 550-1,100 feet across 28 wards, primarily for human consumption. In Loralai, GW samples were collected from TW ranging from 30 to 1,000 feet deep, dug wells (20-100 feet) and from the Karez system. In Sibi, 50 samples were taken from the city, sourced from GW and streams. In Kachi Bolan, 58 samples were collected from shallow bore wells (30-55 feet) manually operated hand pumps (HP) used primarily for drinking. Similarly, 158 samples were collected in Sohbatpur from shallow bore wells (25-60 feet). In Jafarabad, 178 samples were collected from sub-districts including Jafarabad, Dera Allahyar (Jhatpat) and Osta Muhammad, mostly from shallow HP bores (20-60 feet). In Naseerabad, 16 samples were taken from shallow HP bore wells (20-50 feet) bore wells after discarding standing water, in pre acid-soaked 500-1,000 mL polystyrene bottles rinsed with deionized water. Analysis was conducted at the Water Quality Testing Laboratory, Pakistan Council of Research in Water Resources (PCRWR), Karachi.

Analysis of water samples: Water samples were analyzed for key parameters; electrical conductivity (EC) and total dissolved solids (TDS) were measured with the HQ14d HACH meter, while pH levels were determined using the HQ11d HACH meter. Fluoride (F^-) concentrations were analyzed with a HACH colorimeter.

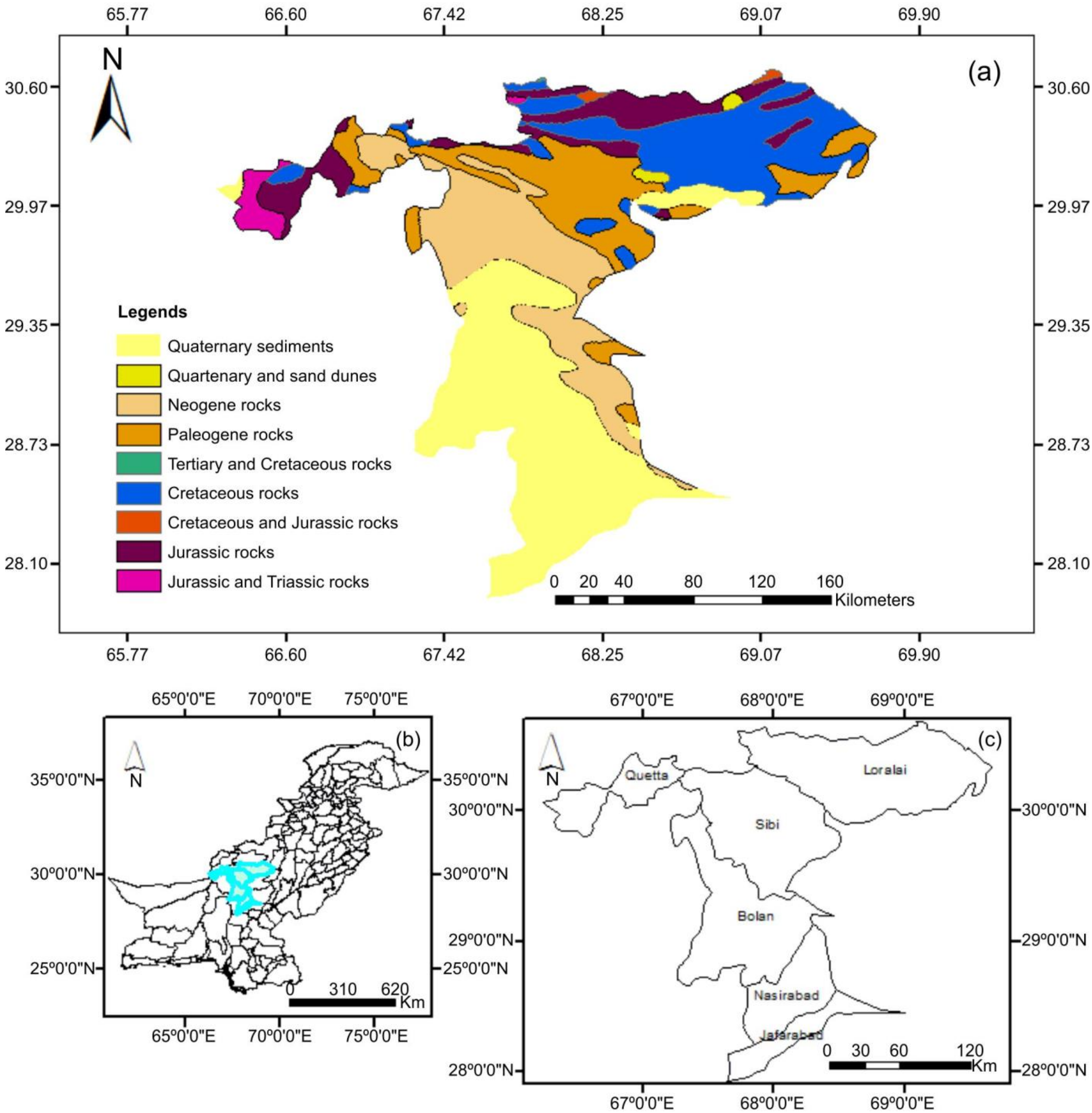

Fig. 1. (a) Geological map of the study area (b,c) maps showing the location of districts, from where the water samples were collected

Analysis of data: The analytical data was utilized to calculate various indices based on the following equations.

Chronic daily intake (CDI) is calculated to estimate the average daily exposure to a contaminant over a long period, aiding in the assessment of potential health risks [24]. CDI was calculated using equation:

$$CDI = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad (1)$$

where; C = fluoride concentration in consumed water (mg/L), IR = water ingestion rate (L/day), EF = exposure frequency (days/year), ED = exposure duration (years), BW = body weight (Kg), AT = average time (days).

Hazard quotient (HQ) is a key metric in risk assessment, used to evaluate non-carcinogenic health risks from chemical or contaminant exposure. HQ < 1 = indicates no significant risk of adverse health effect, while; HQ ≥ 1 indicates potential risk for adverse health effects [24], determined by:

$$HQ = \frac{CDI}{RfD} \quad (2)$$

where, CDI= chronic daily intake (mg/kg/day), RfD = reference dose for fluoride (mg/kg/day), HQ < 1 = indicates no significant risk of adverse health effect, while; HQ ≥ 1 indicates potential risk for adverse health effects [25,26].

Pollution index (PI) is a dimensionless ratio that compares the concentration of a pollutant to its permissible limit, reflecting the degree of pollution [27]. The PI for fluoride for each sample was calculated using formula:

$$PI_F = \frac{\text{Measured fluoride concentration}}{\text{Standard fluoride limit}} \quad (3)$$

Nemerow Pollution Index (NPI) assesses water quality by combining the maximum and average pollution indices to reflect both extreme and mean pollution levels. $NPI_F > 1$ indicates F^- pollution exceeding acceptable limits, $NPI_F \leq 1$ indicates F^- within safe limits [27]. NPI_F calculated using equation:

$$NPI = \sqrt{\frac{1}{2}(C^2_{mean} + C^2_{max})} \quad (4)$$

where, C^2_{max} = maximum pollution index for F^-, C^2_{mean} = average pollution index for F^-.

Fluoride range and risk classification: F^- range based risk classifications are commonly utilized to evaluate the potential health risks associated with varying F^- concentrations in water. These classifications are grounded in international guidelines and supported by extensive scientific research on F^- toxicity and deficiency. The F^- range and classification followed as a maximum F^- limit of 1.5 mg/L [26], in drinking water for public health protection. However, prolonged exposure to levels above 5 mg/L significantly increases the risk of severe skeletal fluorosis and irreversible skeletal damage [28].

Geochemical controls on GW F^- levels: High F^- levels in GW across Sibi, Loralai, Sohbatpur and Jaffarabad in Balochistan are driven by geochemical, climatic and anthropogenic factors. The dissolution of F^- bearing minerals, such as fluorite (CaF_2), apatite and biotite, prevalent in the region's igneous and metamorphic rocks, is a primary source of fluoride [29]. It has been reported that the solubility of F^- varies with the soil type as well as pH and has the tendency to be higher in the alkaline pH, leading to higher bio-availability. The pH of groundwater plays an important role for the mobilization/immobilization of F^- in groundwater [30]. Fluoride ions are adsorbed on the surface of clays in acidic pH, while alkaline pH promotes desorption of F^- ions in the groundwater [31]. In the study area, it seems that F^- ions are released from fluorite, biotite and aptite under the influence of alkaline pH. In the southern part of study area mostly aquifers are hosted in Holocene and Pleistocene sediments, which were deposited by weathering of adjacent ophiolitic and volcanic rocks [30]. These clastic sediments contain higher F^- concentrations, due to their rapid burial and presservation and favourable hydrogeochemical conditions of aquifer led to the release of F^- in the groundwater.

Balochistan's arid and semi-arid climate, together with local soil and lithology, tends to concentrate F^- in shallow aquifers, particularly in semi-arid zones of the province [32]. Ca^{2+} depletion due to calcite precipitation reduces F^- binding, leading to elevated F^- levels, a common phenomenon in Balochistan's aquifers [29].

RESULTS AND DISCUSSION

Physico-chemical parameters: In present study EC, pH and TDS levels in groundwater across the districts were also evaluated. In Quetta, EC ranged from 340 to 1,629 µS/cm, with a mean value of 637.32 ± 214.40 µS/cm, indicating moderate salinity levels (Table-1). This aligns with earlier findings by Umer *et al.* [33], who reported EC values ranging from 300 to 1,700 µS/cm in the same region. The pH levels varied from 6.93 to 8.31 (mean 7.67 ± 0.24) (Table-1), consistent with neutral to slightly alkaline water previously observed [34]. TDS ranged from 204 to 977 mg/L, with a mean of 383 ± 128.50 mg/L, indicating most samples fall within WHO's permissible limit of 1,000 mg/L. These results align with previous regional studies reporting TDS values between 200 and 1,000 mg/L [35,36]. In Loralai, EC ranged from 503 to 8,270 µS/cm, with a mean of 1,407.02 ± 786.71 µS/cm, reflecting higher variability compared to previous reports [37], which documented a range of 500 to 7,500 µS/cm. The pH levels (6.8 to 8.6; mean 7.67 ± 0.22) were comparable to prior studies showing similar neutrality. TDS levels (302-4,962 mg/L; mean 844.21 ± 472.03 mg/L) (Table-1), revealed moderate to high mineral content, in line with earlier observations [32,38]. For Sibi, EC values ranged from 921 to 2,740 µS/cm, with a mean of 1,097.21 ± 268.95 µS/cm, indicating moderate salinity, consistent with data reported EC values between 900 to 2,800 µS/cm [39]. The pH (7.61-8.28; mean 7.99 ± 0.14) remained slightly alkaline, as documented in previously. TDS values (552.6-1,644 mg/L; mean 658.33 ± 161.37 mg/L) showed moderate mineral content, similar to earlier studies [39]. In Kachi Bolan, EC values ranged 485 to 3,590 µS/cm (mean 1,055.98 ± 184.51 µS/cm), aligning with reported findings [40].

The pH levels (6.82-8.39; mean 7.87 ± 0.47) were slightly alkaline and consistent with prior studies. TDS levels (291-2,154 mg/L; mean 633.60 ± 110.55 mg/L) (Table-1), were mostly within permissible limits, similar to previous reports [32]. In Sohbatpur, EC exhibited significant variability, ranging from 336 to 11,790 µS/cm (mean 5,623.88 ± 5,187.69 µS/cm), with extreme salinity in some areas. Previous studies [41] also documented high EC variability, reflecting the similar concerns. The pH values ranged from 6.52 to 8.06 (mean 7.58 ± 0.31), consistent with earlier findings. TDS values (202-7,074 mg/L; mean 2,223.02 ± 3,112.84 mg/L) (Table-1), revealed substantial mineral content, comparable to prior reports [32]. In Jafarabad, EC ranged from 321 to 20,290 µS/cm (mean 1,857.15 ± 2,692.70 µS/cm), with wide variability consistent with previous reported EC values from 300 to 19,000 µS/cm [32,42]. The pH values (6.55-8.24; mean 7.55 ± 0.23) were within the safe range, similar to previous studies. TDS values (193-12,174 mg/L; mean 1,098.68 ± 1,619.60 mg/L) (Table-1), indicated potential unsuitability for drinking water in certain areas, as reported in earlier assessments [43]. In Naseerabad, EC ranged from 427 to 5,230 µS/cm (mean 2,222.56 ± 1,389.38 µS/cm). Karim *et al.* [43] and Tahir & Rasheed [36] documented the similar EC ranges. The pH values (7.04-8.34; mean 7.50 ± 0.28) were slightly alkaline, consistent with earlier findings. TDS levels (256-3,138 mg/L; mean 1,334.31 ± 834.11 mg/L) (Table-1), showed moderate

TABLE-1
VALUES OF CHEMICAL PARAMETERS OF GROUNDWATER SAMPLES IN BALOCHISTAN PROVINCE, PAKISTAN

District	EC (µS/cm)		pH		TDS (mg/L)		F^- (mg/L)	
	Range	Mean (± SD)	Range	Mean (± SD)	Range	Mean (± SD)	Range	Mean (± SD)
Quetta (152)	340-1629	637.32 (214.40)	6.93-8.31	7.67 (0.24)	204-977	383 (128.50)	0.18-2.38	0.942 (0.522)
Loralai (213)	503-8270	1407.02 (786.71)	6.8-8.6	7.67 (0.22)	302-4962	844.21 (472.03)	0.19-2.72	1.208 (0.511)
Sibi (50)	921-2740	1097.21 (268.95)	7.61-8.28	7.99 (0.14)	552.6-1644	658.33 (161.37)	1.32-2.61	1.532 (0.172)
K. Bolan (58)	485-3590	1055.98 (184.51)	6.82-8.39	7.87 (0.47)	291-2154	633.60 (110.55)	0.35-2.57	1.178 (0.434)
Sohbatpur (158)	336-11790	5623.88 (5187.69)	6.52-8.06	7.58 (0.31)	202-7074	2223.02 (3112.84)	0.14-3.01	1.015 (0.774)
Jafarabad (178)	321-20290	1857.15 (2692.7)	6.55-8.24	7.55 (0.23)	193-12174	1098.68 (1619.6)	0.23-2.46	0.683 (0.333)
Naseerabad (16)	427-5230	2222.56 (1389.38)	7.04-8.34	7.50 (0.28)	256-3138	1334.31 (834.11)	0.36-1.55	0.956 (0.363)

to high mineral content, aligning with findings by Chandio *et al*. [43] and Tahir & Rasheed [36].

Fluoride quantification: According to the WHO, the maximum permissible limit for F^- in drinking water is 1.5 mg/L. In Quetta, F^- concentrations were ranged from 0.18 to 2.38 mg/L, with a mean value of 0.942 ± 0.522 mg/L, measured across 152 water samples (Table-1). Among these, 23 samples (15.1%) exceeded the safe drinking water limit. These findings are consistent with earlier studies [36,39,43], which reports F^- levels ranging from 0.15 to 2.5 mg/L in the same area. In Loralai, F^- levels ranged from 0.19 to 2.72 mg/L, with an average concentration of 1.208 ± 0.511 mg/L in 213 water samples (Table-1), where 20.2% of the samples surpassed the permissible limit (Fig. 2). Another study documented F^- concentrations from 0.2 to 2.8 mg/L, corroborating the elevated F^- levels in certain areas [40]. In Sibi, F^- concentrations varied from 1.32 to 2.61 mg/L, with a mean value of 1.532 ± 0.172 mg/L across 50 samples (Table-1). Notably, 58% of the samples exceeded the safe limit, aligning with the findings by Afzal *et al.* [44], who recorded F^- levels between 1.3 and 2.5 mg/L. In Kachi Bolan, F^- levels in the present study ranged from 0.35 to 2.57 mg/L, with a mean concentration of 1.178 ± 0.434 mg/L in 58 samples, with 15.5% of samples exceeding the permissible limit (Fig. 2). Previous reports [36,39,43] indicated comparable F^- concentrations. In Sohbatpur, F^- concentrations ranged from 0.14 to 3.01 mg/L, with a mean of 1.015 ± 0.774 mg/L in 158 samples, where 16.5% exceeded safe limits (Fig. 2). Earlier investigations also reported F^- levels in the range of 0.2 to 3.0 mg/L, reflecting similar contamination hotspots [36,39,43]. In Jafarabad, F^- levels were recorded between 0.23 and 2.46 mg/L, with an average con-centration of 0.683 ± 0.333 mg/L from 178 samples (Table-1) and only 4.5% of the samples exceeded the permissible limit (Fig. 2). Historical data [37] reported F^- concentrations bet-ween 0.3 and 2.5 mg/L, suggesting an improvement in water quality in some areas. In Naseerabad, F^- concentrations ranged from 0.36 to 1.55 mg/L, with a mean of 0.956 ± 0.363 mg/L in 16 samples, none of which exceeded the WHO limit. This aligns with previous findings in the area [36,43], which reported F^- levels to be well within the safe range.

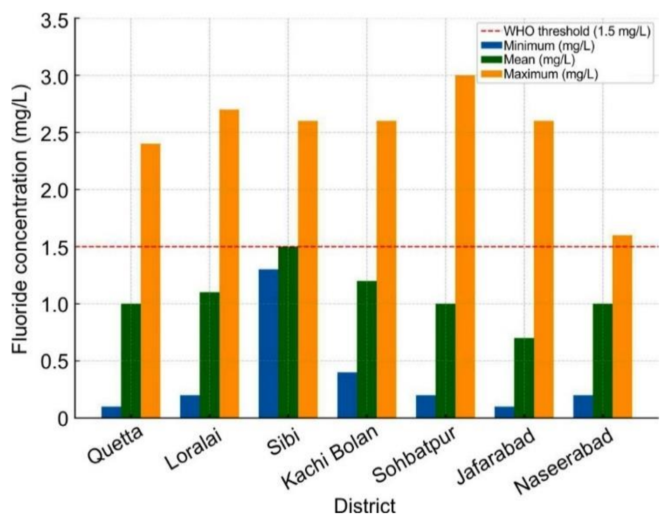

Fig. 2. Comparative analysis of fluoride levels in groundwater across Balochistan districts

Analysis of fluoride hazard quotient (HQ): The analysis of fluoride HQ in Balochistan highlights significant variations, emphasizing the need for region-specific interventions. In Quetta, HQ values for adults range from 0.086-1.133 (mean 0.449 ± 0.248), while children show higher values of 0.200-2.644 (mean 1.047 ± 0.578), underscoring their vulnerability to GW contaminants [26]. Similarly, Loralai records elevated HQs, with adults between 0.271-1.233 (mean 0.664 ± 0.244) and children from 0.633–2.878 (mean 1.549 ± 0.568) (Table-2). Sibi presents the highest mean HQs, with adult values of 0.629-1.243 (mean 0.730 ± 0.082) and children at 1.467-2.900 (mean 1.702 ± 0.191), signaling critical health risks [26]. In Kachi Bolan, adults display HQs of 0.167-1.224 (mean 0.561 ± 0.206) compared to children's range of 0.389–2.856 (mean 1.308 ± 0.482) (Table-2). Sohbatpur reveals significant variability, with adult HQs spanning 0.067-1.433 (mean 0.483 ± 0.369) and children's values reaching 0.156-3.344 (mean 1.128 ± 0.861), reflecting localized contamination hotspots [26]. Lower HQs are observed in Jafarabad and Naseerabad, with adult HQs of 0.110-1.171 (mean 0.329 ± 0.158) and 0.172-0.738 (mean 0.455 ± 0.173), respectively (Table-2).

TABLE-2
HAZARD QUOTIENT (HQ) DATA FOR GROUNDWATER SAMPLES COLLECTED IN BALOCHISTAN DISTRICT, PAKISTAN

District	Adult		Children	
	HQ:min-max	HQ:mean (± SD)	HQ:min-max	HQ:mean (± SD)
Quetta	0.086-1.133	0.449 (0.248)	0.200 (2.644)	1.047 (0.578)
Loralai	0.271-1.233	0.664 (0.244)	0.633-2.878	1.549 (0.568)
Sibi	0.629-1.243	0.730 (0.082)	1.467-2.900	1.702 (0.191)
Kachi Bolan	0.167-1.224	0.561 (0.206)	0.389-2.856	1.308 (0.482)
Sohbatpur	0.067-1.433	0.483(0.369)	0.156-3.344	1.128 (0.861)
Jafarabad	0.110-1.171	0.329(0.158)	0.256-2.733	0.768 (0.370)
Naseerabad	0.172-0.738	0.455 (0.173)	0.400-1.722	1.063 (0.403)

TABLE-3
DISTRICT-WISE DISPARITIES IN HAZARD QUOTIENT (HQ) FOR ADULTS AND CHILDREN ACROSS THE DISTRICTS OF PAKISTAN

District	HQ adult			HQ children			HQ adult range	HQ children range	HQ adults to children ratio
	Min	Max	Mean	Min	Max	Mean			
Quetta	0.086	1.133	0.449	0.200	2.644	1.047	1.047	2.444	0.428844317
Loralai	0.271	1.233	0.664	0.633	2.878	1.549	0.962	2.245	0.428663654
Sibi	0.629	1.243	0.730	1.467	2.900	1.702	0.614	1.433	0.428907168
Kachi Bolan	0.167	1.224	0.561	0.389	2.856	1.308	1.057	2.467	0.428899083
Sohbatpur	0.067	1.433	0.483	0.156	3.344	1.128	1.366	3.188	0.428191489
Jafarabad	0.110	1.171	0.329	0.256	2.733	0.768	1.061	2.477	0.428385417
Naseerabad	0.172	0.738	0.455	0.400	1.722	1.063	0.566	1.322	0.428033866

Children in these districts also exhibit comparatively lower ranges, with Jafarabad at 0.256-2.733 (mean 0.768 ± 0.370) and Naseerabad at 0.400-1.722 (mean 1.063 ± 0.403) (Table-2). These HQ findings are consistent with reported F^- levels in groundwater across Balochistan province. According to studies, F^- concentrations frequently exceed the WHO's recommended limit of 1.5 mg/L for drinking water, particularly in districts like Sibi, Loralai and Sohbatpur [26]. Sibi reports F^- levels as high as 3.5 mg/L, correlating with the highest HQ values for children and adults. Similarly, F^- concentrations in Loralai and Sohbatpur often surpass 2.5 mg/L, mirroring their elevated HQs and highlighting significant health risks [34]. In contrast, Jafarabad and Naseerabad exhibit F^- concentrations mostly below 1.5 mg/L, corresponding to their relatively lower HQs, suggesting safer conditions.

The alignment between F^- levels and HQ data emphasize the disproportionate impact on children, as their higher water intake relative to body weight increases vulnerability to F^- exposure [26]. These findings align with global insights into F^- exposure, emphasizing the importance of maintaining HQs within recommended thresholds to prevent adverse health outcomes, particularly for children [26]. The scatter plot serves as a powerful tool for visualizing district-wise HQ disparities, revealing higher HQ values in children compared to adults, emphasizing their greater vulnerability to GW contaminants. Sibi and Loralai exhibit significantly elevated HQ values, indicating high health risks, while Jafarabad and Quetta show comparatively lower values, suggesting safer conditions.

HQ disparities analysis: The district-wise HQ disparities analysis highlights significant variations in HQ values across 7 districts, revealing critical insights into groundwater safety. Children consistently exhibit higher mean HQ values than adults, with Sibi showing the highest mean HQ for children at 1.702, compared to 0.730 for adults. Similarly, Loralai records mean HQ values of 1.549 for children and 0.664 for adults, underscoring the heightened vulnerability of younger populations. The analysis also reveals notable variability in HQ ranges. Sohbatpur stands out with the widest range for children (0.156-3.344), reflecting localized hotspots of contamination. For adults, districts like Sohbatpur and Kachi Bolan exhibit HQ ranges exceeding 1.0, signaling diverse exposure levels within these districts. In contrast, Quetta and Jafarabad show relatively lower mean HQ values (1.047 and 0.768 for children, respectively) and narrower ranges, suggesting comparatively safer conditions. The adult-to-child HQ ratios remain consistent across districts, averaging approximately 0.43, reinforcing the disproportionate impact on children (Table-3).

Fluoride concentration (C_F) assessment among male population groups: The assessment of C_F risk exposure in male population groups highlights variations in groundwater associated health risks. The risk exposure factors for C_F differ among various population groups, with each group having specific values for daily water consumption (IR) and body weight (BW). Male infants (< 1 year) across all districts exhibited relatively low C_F levels, with ranges such as 0.002-0.025 mg/L in Quetta, 0.002–0.028 mg/L in Loralai (Table-4) and 0.003-0.027 mg/L in Kachi Bolan, with mean values consistently below 0.025 mg/L. This suggests minimal risk for this vulnerable group. Male children (1-8 years) displayed broader C_F ranges, indicating higher exposure. For instance, C_F levels were between 0.013-0.174 mg/L in Quetta (mean 0.069 ± 0.038 SD) and 0.014-0.199 mg/L in Loralai (mean 0.088 ± 0.038 SD) (Table-4), with Sibi recording some of the highest exposure (0.097-0.191 mg/L, mean 0.112 ± 0.013 SD). Kachi Bolan and Sohbatpur districts also exhibited considerable exposure, with ranges up to 0.188 mg/L and 0.220 mg/L, respectively. Teenagers (9-18 years) experienced intermediate exposure levels, with C_F ranges such as 0.010–0.134 mg/L in Quetta (mean 0.053 ± 0.029 SD) and 0.011-0.154 mg/L in Loralai (mean 0.068 ± 0.029 SD) (Table-4).

TABLE-4
FLUORIDE CONCENTRATION (C_F) RISK EXPOSURE FOR DIFFERENT MALE POPULATION GROUPS ACROSS THE DISTRICTS IN BALOCHISTAN, PAKISTAN

District	Male infant			Male children			Male teenager			Male adult		
	Min	max	Mean (± SD)	Min	max	Mean (± SD)	Min	max	Mean (± SD)	Min	max	Mean (± SD)
Quetta	0.002	0.025	0.025 (0.005)	0.013	0.174	0.069 (0.038)	0.010	0.134	0.053 (0.029)	0.008	0.112	0.044 (0.025)
Loralai	0.002	0.028	0.013 (0.005)	0.014	0.199	0.088 (0.038)	0.011	0.154	0.068 (0.029)	0.009	0.128	0.057 (0.024)
Sibi	0.014	0.027	0.016 (0.002)	0.097	0.191	0.112 (0.013)	0.075	0.147	0.087 (0.010)	0.062	0.123	0.072 (0.008)
Kachi Bolan	0.003	0.027	0.012 (0.005)	0.026	0.188	0.086 (0.032)	0.020	0.145	0.067 (0.025)	0.016	0.121	0.055 (0.020)
Sohbatpur	0.001	0.031	0.011 (0.008)	0.010	0.220	0.074 (0.057)	0.008	0.170	0.057 (0.044)	0.007	0.141	0.048 (0.036)
Jafarabad	0.002	0.026	0.007 (0.003)	0.017	0.180	0.050 (0.024)	0.013	0.139	0.039 (0.019)	0.011	0.116	0.032 (0.016)
Naseerabad	0.004	0.016	0.010 (0.004)	0.026	0.113	0.070 (0.027)	0.020	0.088	0.054 (0.021)	0.017	0.073	0.045 (0.017)

Sibi stood out with C_F levels of 0.075-0.147 mg/L (mean 0.087 ± 0.010 SD), while Kachi Bolan and Sohbatpur recorded ranges extending up to 0.145 mg/L and 0.170 mg/L, respectively. Male adults (18-60 years) generally showed lower C_F levels compared to children and teenagers, with ranges such as 0.008-0.112 mg/L in Quetta (mean 0.044 ± 0.025 SD) and 0.009-0.128 mg/L in Loralai (mean 0.057 ± 0.024 SD). However, Sibi again reported higher exposure levels (0.062-0.123 mg/L, mean 0.072 ± 0.008 SD) (Table-4). In Kachi Bolan and Sohbatpur areas, C_F ranged up to 0.121 mg/L and 0.141 mg/L, respectively. Jafarabad and Naseerabad recorded the lowest C_F levels across all age groups, with mean values for male adults not exceeding 0.045 mg/L. The C_F exposure analysis reveals Sibi poses the highest risk across all male population groups, with consistently elevated C_F values, while Jafarabad exhibits the lowest risk levels. The overall C_F exposure risk order is Sibi > Loralai > Kachi Bolan > Sohbatpur > Quetta > Naseerabad > Jafarabad, highlighting significant inter-district variability (Fig. 3).

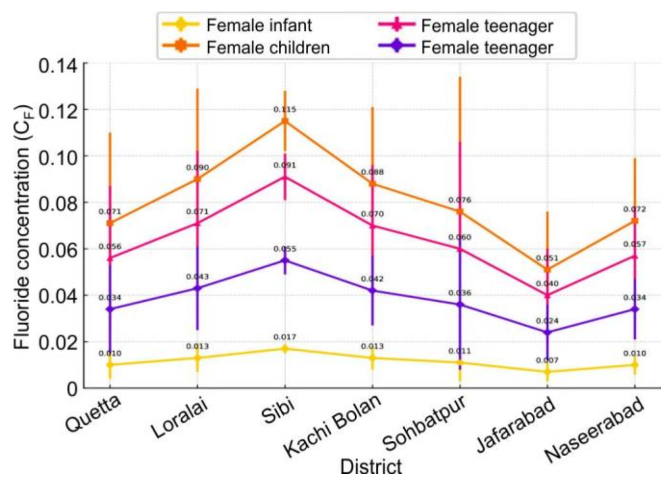

Fig. 3. Fluoride concentration (C_F) risk exposure in various male population groups across the districts

Fluoride exposure and safety across male population age groups: The evaluation of fluoride exposure across different male population age groups highlights varying degrees of safety and risk. For infants (< 1 year), all 825 samples (100%) fell within the safe fluoride intake range of 0.01-0.05 mg/kg/day (Table-5), indicating no immediate risk for this vulnerable group. Among children aged 1-8 years, who have a safe intake range of 0.05-0.1 mg/kg/day, 624 samples (75.6%) were classified as safe, while 201 samples (24.4%)

TABLE-5
ASSESSMENT OF FLUORIDE EXPOSURE AND SAFETY ACROSS MALE (M) POPULATION AGE GROUPS ACROSS THE DISTRICTS (INSIDE PARENTHESES MAXIMUM SAFE F^- INTAKE mg/kg/day)

District	M infant (0.01-0.005)		M children (0.05-0.1)		M teenager (0.05-0.1)		M adult (0.05-0.1)	
	Number of water samples							
	Safe	Unsafe	Safe	Unsafe	Safe	Unsafe	Safe	Unsafe
Quetta	152	0	121	31	138	14	145	7
Loralai	213	0	153	60	180	33	196	17
Sibi	50	0	1	49	48	2	49	1
K. Bolan	58	0	43	15	52	6	56	2
Sohbatpur	158	0	121	37	126	32	133	25
Jafarabad	178	0	170	8	174	4	177	1
Naseerabad	16	0	15	1	16	0	16	0
Total	825	0	624	201	734	91	772	53
Percentage	100	0	75.6	24.4	89	11	93.6	6.4

exceeded the maximum safe limits (Table-5), making this group the most vulnerable to potential overexposure. For teenagers (9-18 years) with the same safe intake range as children, 734 samples (89%) were within safe limits, while 91 samples (11%) exceeded safe thresholds. Among adult males (18-60 years), 772 samples (93.6%) were deemed safe, with only 53 samples (6.4%) falling into the unsafe category (Fig. 4). Sibi presented the highest number of unsafe samples across the children and teenage age groups. Conversely, Jafarabad and Naseerabad exhibited the lowest levels of fluoride exposure risk.

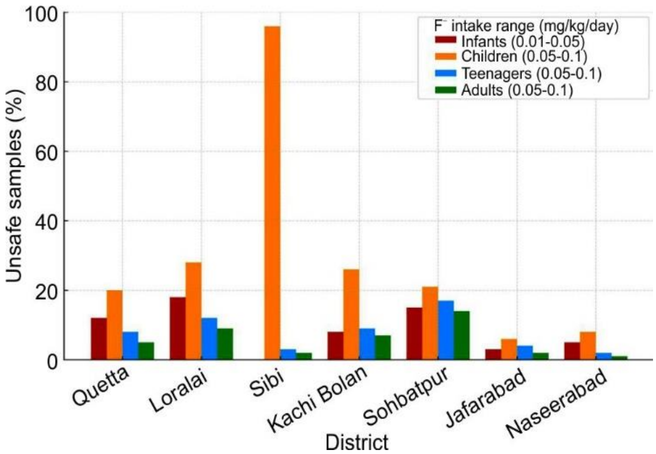

Fig. 4. Analysis of fluoride exposure across the districts for male population groups

Fluoride concentration (C_F) assessment among female population groups: The analysis of C_F in different female population groups across the districts reveals significant variations in exposure levels. Among female infants (< 1 year), C_F levels ranged from 0.002-0.033 mg/L, with mean values varying from 0.007 ± 0.004 SD in Jafarabad to 0.017 ± 0.002 SD in Sibi. For female children (1-8 years), C_F levels spanned 0.011-0.226 mg/L, with the highest mean observed in Sibi (0.115 ± 0.013 SD) and the lowest in Jafarabad (0.051 ± 0.025 SD). Teenagers (9-18 years) exhibited C_F levels ranging from 0.008-0.178 mg/L, with mean values between 0.040 ± 0.020 SD in Jafarabad and 0.091 ± 0.010 SD in Sibi. Among female adults (18-60 years), C_F levels ranged from 0.005-0.107 mg/L, with mean values between 0.024 ± 0.012 SD in Jafarabad and 0.055 ± 0.006 SD in Sibi (Table-6). Pregnant and lactating women demonstrated distinct exposure patterns. Pregnant women showed C_F levels from 0.006-0.122 mg/L, with the highest mean in Sibi (0.062 ± 0.007 SD). Lactating women recorded levels from 0.007-0.158 mg/L, with mean values ranging from 0.036 ± 0.017 SD in Jafarabad to 0.080 ± 0.009 SD in Sibi. Overall, Sibi District consistently exhibited higher C_F levels across most groups, signaling greater F^- exposure risks. In contrast, Jafarabad and Naseerabad recorded lower mean values, indicating comparatively safer exposure levels (Fig. 5).

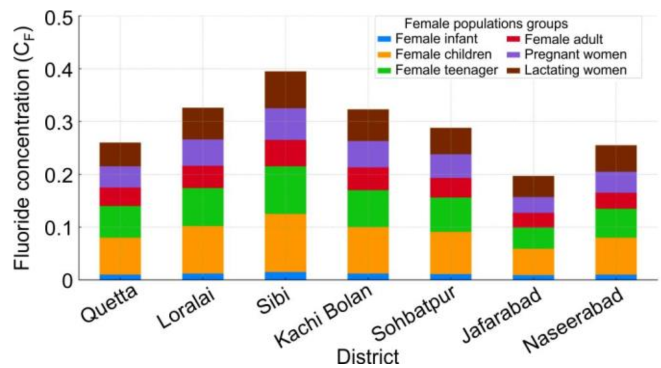

Fig. 5. Fluoride concentration (C_F) risk exposure in various female population groups across the districts

Fluoride exposure and safety across female population age groups: The assessment of fluoride exposure and safety across female population age groups provides critical insights into health risks relative to established maximum safe F^- intake levels (mg/kg/day). Female infants (< 1 year) exhibited no unsafe samples, with all 825 samples (100%) falling within the safe range of 0.01-0.05 mg/kg/day (Table-7). This indicates that this group is currently not at risk from F^- exposure. For female children (1-8 years), 607 samples (73.6%) were deemed safe, while 218 samples (26.4%) exceeded the safe intake

TABLE-6
FLUORIDE CONCENTRATION (C_F) RISK EXPOSURE FOR DIFFERENT FEMALE POPULATION GROUPS ACROSS THE DISTRICTS IN BALOCHISTAN, PAKISTATAN

District	Female infant			Female children			Female teenager			Female adult		
	Min	Max	Mean (± SD)	Min	Max	Mean (± SD)	Min	Max	Mean (± SD)	Min	Max	Mean (± SD)
Quetta	0.002	0.026	0.010 (0.006)	0.014	0.179	0.071 (0.039)	0.011	0.141	0.056 (0.031)	0.006	0.085	0.034 (0.019)
Loralai	0.002	0.029	0.013 (0.006)	0.014	0.204	0.090 (0.039)	0.011	0.161	0.071 (0.031)	0.007	0.097	0.043 (0.018)
Sibi	0.014	0.028	0.017 (0.002)	0.099	0.196	0.115 (0.013)	0.078	0.154	0.091 (0.010)	0.047	0.093	0.055 (0.006)
Kachi Bolan	0.004	0.028	0.013 (0.005)	0.026	0.193	0.088 (0.033	0.021	0.152	0.070 (0.026)	0.012	0.091	0.042 (0.015)
Sohbatpur	0.002	0.033	0.011 (0.008)	0.011	0.226	0.076 (0.058)	0.008	0.178	0.060 (0.046)	0.005	0.107	0.036 (0.028)
Jafarabad	0.003	0.027	0.007 (0.004)	0.017	0.185	0.051 (0.025)	0.014	0.146	0.040 (0.020)	0.008	0.088	0.024 (0.012)
Naseerabad	0.004	0.017	0.010 (0.004)	0.027	0.116	0.072 (0.027)	0.021	0.092	0.057 (0.021)	0.013	0.055	0.034 (0.013)

TABLE-7
ASSESSMENT OF FLUORIDE EXPOSURE AND SAFETY ACROSS FEMALE (F) POPULATION AGE GROUPS ACROSS THE DISTRICTS (INSIDE PARENTHESES MAXIMUM SAFE F^- INTAKE mg/kg/day)

District	F infant (0.01-0.005)		F children (0.05-0.1)		F teenager (0.05-0.1)		F adult (0.05-0.1)		Preg. woman (0.05-0.1)		Lact. woman (0.05-0.1)	
	Number of water samples											
	Safe	Unsafe	Safe	Unsafe	Safe	Unsafe	Safe	Unsafe	Safe	Unsafe	Safe	Unsafe
Quetta	152	0	116	36	136	16	152	0	152	0	140	12
Loralai	213	0	145	68	174	39	213	0	210	3	184	29
Sibi	50	0	1	49	47	3	50	0	49	1	49	1
K.Bolan	58	0	42	16	44	6	58	0	57	1	54	4
Sohbatpur	158	0	120	38	125	33	154	4	143	15	126	32
Jafarabad	178	0	168	10	174	4	178	0	178	0	176	2
Naseerabad	16	0	15	1	16	0	16	0	16	0	16	0
Total	825	0	607	218	716	101	821	4	805	20	745	80
Percentage	100	0	73.6	26.4	86.8	12.2	99.5	0.5	97.6	2.4	90.3	9.7

threshold of 0.05-0.1 mg/kg/day. Female teenagers (9-18 years) showed a higher proportion of safe samples, with 716 (86.8%) falling within the safety limits and 101 samples (12.2%) categorized as unsafe (Table-7).

Among female adults (18-60 years), 821 samples (99.5%) were within the safe range, with only 4 samples (0.5%) exceeding the threshold (Table-7). Similarly, pregnant and lactating women displayed high safety levels, with 805 samples (97.6%) and 745 samples (90.3%) within safe intake levels, respectively. However, 20 samples (2.4%) for pregnant women and 80 samples (9.7%) for lactating women were unsafe, indicating minor risks in these groups. District-wise, Sibi exhibited the highest percentage of unsafe samples across multiple groups, particularly among children and teenagers, while Jafarabad and Naseerabad demonstrated the lowest exposure risks (Fig. 6).

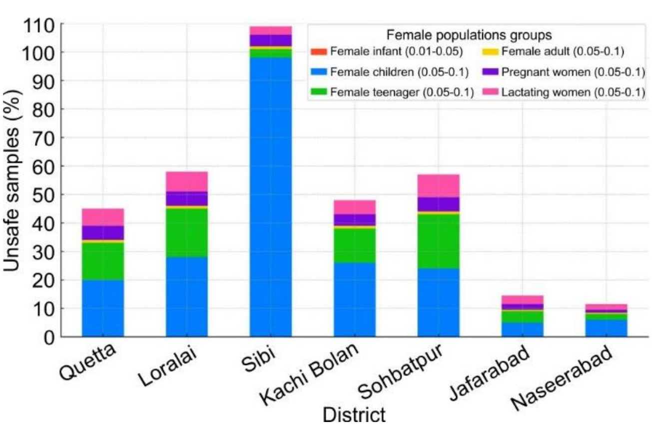

Fig. 6. Assessment of fluoride exposure across the districts for female population groups

Nemerow Pollution Index (NPI): In Nasirabad district, NPI is approximately 0.859, indicating that F^- concentrations in GW are within the permissible limit. This reflects minimal risk of F^- contamination, suggesting acceptable water quality under current conditions for the population [3]. In Sibi, the NPI of 1.43 signifies that F^- concentrations exceed the permissible limit, posing a significant health risk. In Jaffarabad district, the NPI is 1.20, exceeding the permissible threshold, despite a mean F^- concentration of 0.69 mg/L being below the limit. The maximum concentration (2.46 mg/L) suggests localized hotspots requiring targeted interventions. Similarly, Sohbatpur district's NPI of 1.50, driven by a maximum concentration of 3.01 mg/L, indicates moderate to significant health risks. Localized hotspots demand immediate attention to prevent long-term health impacts, particularly for children, who are more susceptible to F^- toxicity due to their lower body weight and higher intake relative to body size [28]. In Kachi Bolan, the NPI of 1.33 highlights the influence of a high maximum concentration (2.57 mg/L). In Loralai, NPI of 1.40 reflects moderate risk. A maximum F^- concentration of 2.72 mg/L reinforces the need for targeted interventions to mitigate long-term health risks. In Quetta district, the NPI of 1.21 suggests F^- concentrations nearing the critical threshold, primarily due to a high concentration. Overall the NPI risk levels revealed that Naseerabad exhibits a minimal risk with an NPI of 0.859, Sibi, Sohbatpur, Kachi Bolan and Loralai show high risk (NPI: 1.33-1.50), signifying unsafe F^- levels and potential health hazards. Jaffarabad and Quetta present a medium risk with NPI values of 1.20 and 1.21, respectively, approaching critical thresholds (Fig. 7).

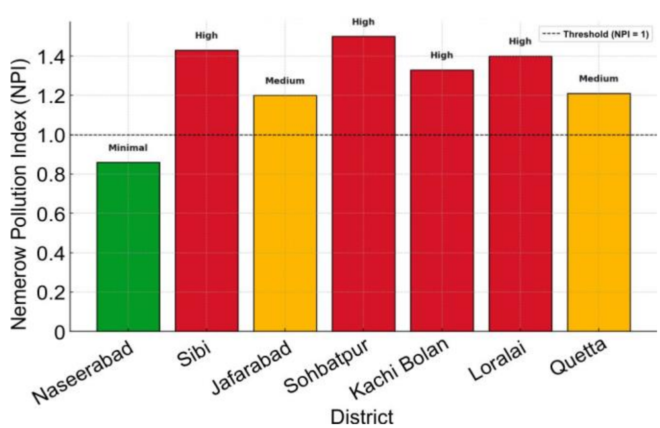

Fig. 7. Displays the Nemerow Pollution Index (NPI) and risk assessment across the districts in Balochistan

Conclusion

Fluoride (F^-) concentrations exceeded the WHO limit (1.5 mg/L) in Balochistan, with the highest contamination in Sibi (58% unsafe samples), followed by Loralai (20.2%), Sohbatpur (16.5%), Kachi Bolan (15.5%), Quetta (15.1%), Jafarabad (4.5%) and none in Naseerabad of Balochistan, Pakistan. Hazard quotient (HQ) analysis indicated children are significantly more vulnerable than adults, with the highest HQ observed in Sohbatpur (mean HQ children: 1.128), followed by Sibi (1.702) and Loralai (1.549). The C_F analysis revealed minimal risk for male infants (< 1 year), with mean C_F values below 0.025 mg/L across all districts. Male children (1-8 years) showed higher exposure, particularly in Sibi (mean: 0.112 mg/L). Teenagers (9-18 years) experienced intermediate exposure, while male adults generally exhibited lower C_F levels, except in Sibi (mean: 0.072 mg/L). Female populations showed similar trends, with infants having minimal exposure (mean C_F: 0.007-0.017 mg/L), while female children and teenagers had higher exposure, notably in Sibi. Among teenagers, females had a slightly higher proportion of unsafe samples (12.2%) compared to males (11%). The Nemerow Pollution Index (NPI) identified Nasirabad as minimal risk (NPI: 0.859), while high-risk districts included Sibi, Sohbatpur, Kachi Bolan and Loralai (NPI: 1.33-1.50). Medium risks were reported in Jafarabad (1.20) and Quetta (1.21). Significant variability in EC (340-20,290 µS/cm) and TDS (202-12,174 mg/L) levels highlights differences in groundwater quality. High salinity and TDS concentrations in Sohbatpur and Jafarabad indicate potential unsuitability for drinking water. District-specific interventions are essential, focusing on high-risk areas like Sibi and Loralai areas. Children require urgent attention due to their heightened vulnerability to F^- toxicity. Strategies should prioritize improving water quality and raising community awareness.

ACKNOWLEDGEMENTS

The authors sincerely acknowledge and extended their gratitude to the United Nations Children's Fund (UNICEF), through its Pakistan offices in Islamabad, Karachi and Quetta, for providing invaluable technical support and assistance in field activity monitoring and groundwater quality assessment in Balochistan province of Pakistan.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

The authors declare that no AI tools were used in the preparation or writing of this research/review article.

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