



Comprehensive Assessment of Fluoride Content in Groundwater and Its Health Implications in the Sauran District, Kazakhstan

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Abstract

This study evaluated fluoride concentrations in drinking water from 63 sources across 38 settlements in the Sauran District of southern Kazakhstan and assessed related health risks. Fluoride levels ranged from 0.01 to 1.10 mg L⁻¹; 90.5% of sources contained <0.7 mg L⁻¹, and 38.1% contained <0.3 mg L⁻¹. Optimal concentrations (0.7–1.1 mg L⁻¹) were found in only six sources, some of which were unsuitable for drinking due to high mineralisation. Although the overall water quality was satisfactory, widespread fluoride deficiency indicated limited nutritional value. Hazard Quotient (HQ) values did not exceed 0.33 for children and 0.24 for adults, showing no toxicity risk but suggesting insufficient fluoride intake and an increased likelihood of dental caries, particularly among children. Fluoride measurements in seven widely consumed tea brands showed that tea provides a partial supplementary source of fluoride, but not enough to compensate for deficiency in drinking water. The results indicate that fluoride inadequacy is a regional concern despite generally acceptable water quality. Ensuring optimal fluoride levels should therefore be considered in local drinking-water management and public-health planning.

Keywords: Fluoride; Groundwater quality; Health risk; Nutritional quality index; Southern Kazakhstan; Tea consumption.

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1. Introduction

In recent decades, numerous studies have highlighted the critical importance of trace elements in drinking water, including iodine, bromine, selenium, fluorine, silicon, zinc, molybdenum, cobalt, and others, which are essential for the proper functioning of the human body. Alongside mineral composition and microbiological safety, the presence of these elements in optimal concentrations plays a decisive role in determining the overall quality and health benefits of drinking water. Despite the recognized importance of water quality, access to safe drinking water remains a major global challenge. According to the United Nations (UN), nearly 30% of the world's population still lacks access to drinking water that meets established safety standards.^[1] This issue is becoming increasingly severe due to a combination of factors, including population growth, climate change, and the rising discharge of

domestic and industrial waste into water sources. These wastes often contain a mixture of both traditional contaminants (e.g., heavy metals, nitrates) and emerging pollutants, such as pharmaceuticals, microplastics, and persistent organic compounds.^[2,3]

Fluoride is a common trace element present in both surface and groundwater, and it can exert significant effects on human health. Fluoride in natural waters primarily accumulates through the geological weathering of fluoride-bearing minerals, as well as from anthropogenic sources, including industrial activities.^[4,5] The concentration and mobility of fluoride ions in natural waters are influenced by environmental factors such as pH, temperature, the presence of complexing ions (e.g., Al³⁺ and Fe³⁺) and precipitating ions (e.g., Ca²⁺, Mg²⁺, Ba²⁺), adsorption and desorption processes, precipitation levels, and other factors.^[4,6]

Although fluoride levels in drinking water are strictly regulated in many countries, concentrations can vary widely—from mere fractions of a milligram to several tens of milligrams per liter. To safeguard public health, the World Health Organization (WHO) recommends limiting fluoride concentration in drinking water to 1.5 mg L⁻¹. Fluoride levels in surface water are generally low, often not exceeding 0.3 mg L⁻¹. A study of 33 surface water bodies in the Thrace region of Turkey revealed fluoride deficiencies below 0.5 mg L⁻¹, which

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may pose risks to dental health.^[7] However, numerous exceptions occur due to local geology and anthropogenic contamination, such as discharges from industries producing phosphate fertilisers, aluminium, steel, glass and ceramics, semiconductors, herbicides, and insecticides.^[8] Groundwater often contains significantly higher fluoride concentrations, particularly in arid and semi-arid regions, where levels may exceed 30 mg L⁻¹.^[9,10] In the Eastern Province of Saudi Arabia, elevated geogenic fluoride concentrations were observed in coastal aquifers, posing health risks especially for children consuming such water.^[11] Similarly, a study of 107 groundwater sources in eastern Ghana revealed high geogenic fluoride levels, with hazard index (HI) values reaching up to 17.4 in some locations.^[12] In Pakistan, specifically in Swat District,^[13] Sindh Province,^[14] and Khyber District,^[15] fluoride concentrations in groundwater used for drinking were found to significantly exceed WHO guidelines, as evidenced by hazard index values greater than 1.

Fluoride is an essential trace element for the human body, as at optimal concentrations it contributes to the formation and preservation of mineralised dental tissues, supports bone growth and health—which is particularly important for the growth and physical development of children—and helps maintain bone strength in the elderly. A deficiency of this trace element in the diet leads to dental caries and osteoporosis. In addition, fluoride exhibits a strong bactericidal effect, which contributes to the maintenance of healthy oral microflora.^[16] There is also evidence of fluoride's involvement in the activity of certain enzymes affecting protein synthesis and in the metabolism of carbohydrates and lipids.^[17,18] Fluoride has a narrow range of optimal concentrations, and a distinguishing feature is that it can exert toxic effects at higher levels. When the concentration of fluoride in water exceeds the WHO recommended threshold, the primary risk is an increase in dental fluorosis.

According to the WHO, excessive fluoride concentrations in drinking water constitute a significant public health concern in numerous countries, particularly in regions with naturally elevated groundwater fluoride levels. While precise estimates of affected populations vary, it is widely acknowledged that tens of millions of individuals worldwide are affected by various forms of fluorosis.^[19] For example, in India, extensive areas of high fluoride in groundwater have been identified in 19 of the 28 states, and more than 60–70 million people are at risk of developing dental and skeletal fluorosis.^[6,20] Similarly, approximately 80 million people inhabiting the East African Rift Valley across nine African countries are at risk.^[21] Overall,

the issue of fluoride concentrations in drinking water significantly exceeding WHO guidelines remains pertinent for countries such as Canada, Argentina, Germany, Finland, Estonia, China, Pakistan, Iran, Sri Lanka, Kenya, Tanzania, Ghana, Bangladesh, and many others.^[9] Fluoride concentrations exceeding 3–4 mg L⁻¹ in drinking water can result in a more severe condition, skeletal fluorosis, which manifests as bone and joint damage.^[22] Long-term consumption of water with high fluoride concentrations, particularly from an early age, can lead to complications beyond fluorosis, including nervous system damage,^[23] cognitive impairment in children,^[24] and genitourinary and thyroid disorders.^[18] The beneficial and adverse effects of fluoride on the human body remain insufficiently studied and warrant further clinical investigation.

The daily fluoride requirement for adults is 3–4 mg day⁻¹, whereas children should receive 1–2 mg day⁻¹. An intake of 0.05 mg kg⁻¹ body weight is considered adequate.^[25] The majority of fluoride is obtained from water through drinking and cooking (more than 75%), as fluoride ingested via water is almost completely absorbed.^[26] Fluoride intake from food is less substantial, particularly when the food has a high calcium content.^[27] Moreover, the fluoride content of most foods is relatively low, typically ranging from 0.05 to 0.5 mg kg⁻¹.^[28] The highest concentrations of fluoride are found in seafood, especially marine fish.^[29] Certain tea varieties may contain considerably higher amounts of fluoride, ranging from 100 to 500 mg kg⁻¹ dry weight, particularly when cultivated in regions of India and other countries with elevated levels of mobile fluoride in soils and irrigation water.^[30,31]

The Republic of Kazakhstan, located in Central Asia and the ninth largest country in the world by area, has limited water resources, which are also unevenly distributed. There is a shortage of quality drinking water in Kazakhstan, and the Government of the Republic pays particular attention to this issue. In the open scientific literature, studies on the fluoride content of drinking water in Kazakhstan are scarce and, moreover, cover only certain regions of the country. Adenova *et al.*^[32] conducted a detailed study of more than 200 water-bearing flowing wells in three districts of the Jambul Region of Kazakhstan, which are used by rural residents of these districts for drinking and irrigation. The study found that in the examined water sources, fluoride ions were present in the dry season at concentrations ranging from 0.38 to 4.0 mg L⁻¹, with an average of 1.2 mg L⁻¹, whereas in the wet season the fluoride content increased markedly, ranging from 1.80 to 12.0 mg L⁻¹, with an average of 1.84 mg L⁻¹. As observed, the fluoride concentrations in the studied wells span a relatively wide range; however, based on the mean concentrations, it can be concluded that most sources exhibit elevated fluoride levels. Another study^[33] also reported elevated fluoride ion content in groundwater in some areas of the Jambul Region (Thalas-Assin interfluvium), reaching 4.5–12.2 mg L⁻¹, and attributed this to anthropogenic pollution, such as phosphate mining and fertiliser production.

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Recent hydrological studies have also emphasized that the water regime of rivers in arid regions of Kazakhstan is strongly influenced not only by meteorological conditions but also by the characteristics of the underlying surface and human activity. In the Ile–Balkhash basin, one of the most densely populated and industrially developed regions of Kazakhstan, a significant increase in water discharge has been observed since the 1970s, leading to rising water levels in Lake Balkhash. These changes are linked to both economic development and climate variability, underscoring the importance of sustainable water management and the implementation of modern water-saving irrigation systems in the region.^[34]

In Kazakhstan, regular environmental monitoring is conducted by the Republican State Enterprise Kazhydromet (RSE Kazhydromet), a major scientific and production organisation established under the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan. According to data presented in the annual bulletin of RSE Kazhydromet,^[35] certain regions of Kazakhstan exhibit elevated fluoride concentrations in natural waters. In northern Kazakhstan, in the Akmola Region, there is a system of 12 freshwater lakes with surface areas ranging from 1 to 26 km², in which elevated geogenic fluoride concentrations, ranging from 6.2 to 9.1 mg L⁻¹, were recorded. At the same time, the local population uses water from some of these lakes for drinking and irrigation. Balkhash Lake, the second largest body of water in Kazakhstan after the Caspian Sea and the 14th largest lake in the world, has also shown elevated fluoride concentrations of up to 3 mg L⁻¹ at certain monitoring stations, according to RSE Kazhydromet. In Alakol Lake (2,650 km²) and Zhalanashkol Lake (37.6 km²), located in eastern Kazakhstan, fluoride concentrations ranged from 1.7 to 2.4 mg L⁻¹. In one of the major rivers, the Yesil River, fluoride concentrations reached 4.5 mg L⁻¹. However, the highest fluoride concentration in the natural waters of Kazakhstan was observed in the small Akbulak River in the Akmola Region, where it reached 18 mg L⁻¹.

In Kazakhstan, information on the fluoride content of drinking water in the scientific literature is limited. Some of the following information was obtained from both scientific articles and official websites of Public Water Utilities (PWUs) and Municipal Sanitary and Epidemiological Stations (MSEs). Unfortunately, not all PWUs and MSEs responsible for monitoring the quality of drinking water conduct tests for fluoride content. A review of available materials indicates that in most cities and towns of Kazakhstan, drinking water contains fluoride ions below the optimal concentrations recommended by the WHO (<0.7 mg L⁻¹). Cities where the fluoride content in drinking water is below these optimal concentrations include, for example, Shymkent, Taldykurgan, Aktobe,^[36] Zaisan,^[37] Lisakovsk, Pavlodar,^[38] Semey,^[39] Kyzyl-Orda,^[40] Ust-Kamenogorsk, and others. This situation increases the risk of dental caries among the populations of the aforementioned cities. Dental caries is a common disease in Kazakhstan. According to the United

Kazakhstan Dental Association, an average of 76 per cent of children in the country are affected by dental caries.^[41] Kazakhstan has one of the highest Decayed, Missing, and Filled Teeth (DMFT) indices among 12-year-old children, at 4.0, whereas in some developed European countries it is only 0.5.^[42] However, despite very low fluoride concentrations in certain cities, drinking water fluoridation is not practised in Kazakhstan. In contrast, cities with optimal fluoride concentrations in drinking water include Aktau, Karaganda,^[43] and Kokshetau.^[44] Elevated fluoride concentrations exceeding the WHO guidelines and the drinking water quality standards of Kazakhstan have been recorded in Shuchinsk and in small villages of the Akmola Region supplied with water from Shortandy Lake, where fluoride concentrations reach 4 mg L⁻¹ and higher.^[45]

In recent years, the search for cost-effective and sustainable materials for water purification has intensified globally. Particular attention has been given to bio-waste-derived adsorbents that can effectively remove various contaminants from water. For instance, eggshell-based sorbents have demonstrated high adsorption capacities for removing azo dyes in both batch and continuous modes, following the Sips isotherm and pseudo-first-order kinetics, and showing endothermic and spontaneous adsorption behavior.^[46] Such approaches illustrate the potential of eco-friendly and inexpensive materials for water treatment and could be further explored for the removal of ions such as fluoride from drinking water.

This study examines the fluoride ion content in drinking water from settlements in the Sauran district, southern Kazakhstan. The scarcity of information on this topic in the open literature likely reflects a lack of prior research in this region. The objectives of this study were as follows: The objectives of this study are as follows: (1) to determine fluoride concentrations and associated major ions in drinking water from various sources in the Sauran district; (2) to assess the spatial distribution of fluoride and identify areas at potential health risk; (3) to evaluate non-carcinogenic health risks of fluoride intake for children and adults, including contribution from locally consumed tea; and (4) to provide a basis for regional water management strategies and inform public health measures aimed at ensuring optimal fluoride levels.

The methods of water quality indexing and health risk assessment applied in this study comply with international standards and are widely employed in global water supply research. Their effectiveness has been demonstrated across diverse hydrogeological settings, encompassing both fluoride-deficient and fluoride-rich regions.^[11] This ensures the comparability of results and permits the integration of the obtained data into the international framework for evaluating drinking water safety. The findings may inform the development of regional water supply programmes, substantiate the need for centralised fluoridation, or guide decisions regarding the replacement of water sources.

Furthermore, the results will contribute to the hydrochemical database of southern Kazakhstan and may serve as a reference for comparative studies both within Kazakhstan and in international research contexts.

In order to establish a conceptual foundation for the study, the following sections offer an overview of the geological and hydrogeological framework of the Sauran district. This framework governs the occurrence and mobility of fluoride in local water resources. A detailed description of the sampling methods, analytical techniques, water quality indices and risk-assessment approaches is then provided. The purpose of this description is to comprehensively evaluate fluoride contamination and its potential health impacts.

2. Materials and methods

2.1 Study area

2.1.1 Geographic location and climate

The study area is located in southern Kazakhstan within the Turkistan Region and comprises two cities—Turkistan (225,700 inhabitants) and Kentau (74,700 inhabitants)—as well as 36 rural settlements, the largest of which are Eski-Ikan (14,294 inhabitants) and Karnak (10,246 inhabitants). The population of the remaining settlements does not exceed 5,000. The northeastern part of the study area lies at the foothills of the southern macro-slope of the Karatau Range, while the remainder is situated on an ancient alluvial plain of the Syr Darya River. The climate is continental and semi-arid, characterised by long, hot, and dry summers, and short, mild winters. Annual precipitation does not exceed 250 mm, and the mean annual temperature ranges from 12 to 13 °C.

2.1.2 Geology and geomorphology

The study area is situated within a tectonically stable zone, composed predominantly of sedimentary rocks of Cretaceous and Quaternary age. The geological section consists of interbedded sandstones, clays, and loess deposits. The principal sedimentary rocks include limestones, sandstones, siltstones, and dolomites. The presence of fluoride-bearing minerals in Cretaceous deposits may contribute to elevated fluoride concentrations in groundwater. The foothill relief is hilly, dissected by valleys of small mountain rivers, and features well-developed terraces. Soils in this zone are classified as light mountain sierozems.^[47] The southwestern part of the area exhibits a flat relief with winding depressions of ancient riverbeds and comprises weakly stratified clay and loamy Quaternary alluvial deposits. The soils are predominantly meadow-grey, with localised salinization.^[48]

2.1.3 Hydrology and hydrogeology

The region's hydrological regime exhibits seasonal variability, with peak water discharge occurring during spring snowmelt and minimum levels in late summer. Mountain streams and ephemeral rivers provide limited recharge due to low infiltration and high evaporation.^[49] Groundwater occurs under various hydrogeological conditions, ranging from

shallow unconfined aquifers to deeper confined systems, and serves as the primary source of drinking water for both urban and rural populations. Water is abstracted from wells, typically 50 to 900 meters deep, and distributed via pipelines. Aquifers comprise sands and sandstones interbedded with clay layers.^[50] The area also contains artesian wells tapping deep horizons. Additionally, shallow private wells are used, although many are unsuitable for drinking due to high mineralisation. Shallow aquifers are particularly vulnerable to contamination because of their high permeability and limited protective cover.

2.1.4 Economy and land use

The local economy is based on agriculture, livestock grazing, and small-scale manufacturing. Kentau retains remnants of its mining legacy, whereas Turkistan has developed into a regional hub for tourism and services. Natural vegetation consists of steppe grasses and sparse shrubs, while land use is largely oriented towards irrigated farming. Crops such as cotton and vegetables are cultivated using both groundwater and surface water. Human activities, including intensive farming and livestock grazing, may contribute to diffuse pollution and affect groundwater quality through leaching of agrochemicals and organic matter. No industrial facilities in the study area act as significant sources of fluoride contamination.

2.2 Water sample collection

A total of 63 water samples were collected from 38 settlements, including two cities (Turkistan and Kentau) and 36 villages. Samples were obtained from water supply networks fed by municipal deep wells (depth 50–900 m), as well as from private shallow wells equipped with electric pumps (depth 3–17 m). The study area and sampling locations are shown in Fig. 1. Table 1 presents the names of the settlements, their assigned identification numbers, and the type of water supply source. Water sampling was conducted in September and October 2024, in accordance with the state standard GOST 24481-80. Plastic containers with a volume of 1.0 L were used for sampling. Each sample was collected after allowing the water to run for at least fifteen minutes with the tap fully open. Prior to sampling, the container was rinsed at least twice with the water to be analysed. Following collection, the samples were labelled and transported to the laboratory for further analysis of TDS, fluoride, calcium, magnesium, sodium, and hydrogen carbonate.

2.3 Analytical methods

2.3.1 Physicochemical analysis of water

Water samples were neither preserved nor frozen, and analyses were performed on the same day. A cooler with refrigerants was used for transportation. pH measurements were performed in situ using a HANNA HI98128 portable pH metre. TDS in water were determined using a SevenCompact S230 stationary conductometer with an InLab 731-ISM sensor (Mettler Toledo). Calcium and magnesium contents were

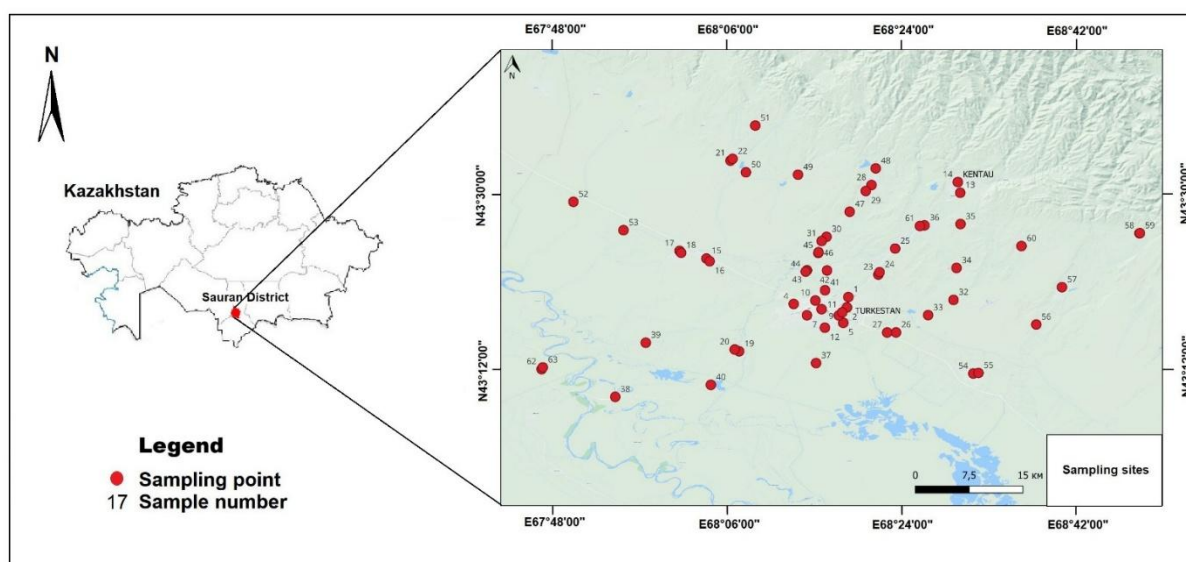


Fig. 1: Location map of the water sampling sites in the sauran district.

Table 1: Water sampling locations and descriptions of water source types.

Sample No.	Locality	Water source	Sample No.	Locality	Water source
1	Turkestan city	Tap water	33	Bershintobe vill.	Tap water
2	Turkestan city	Tap water	34	Koskorgan vill.	Tap water
3	Turkestan city	Private well	35	Kotyrbulak vill.	Tap water
4	Turkestan city	Tap water	36	Kusshyata vill.	Private well
5	Turkestan city	Private well	37	Shoitobe vill.	Tap water
6	Turkestan city	Tap water	38	Jalanthos vill.	Tap water
7	Turkestan city	Tap water	39	Nurtas vill.	Tap water
8	Turkestan city	Private well	40	S. Kozhanov vill.	Tap water
9	Turkestan city	Tap water	41	Birlik vill.	Private well
10	Turkestan city	Tap water	42	Karashyk vill.	Tap water
11	Turkestan city	Tap water	43	Kumtiym vill.	Tap water
12	Turkestan city	Tap water	44	Kumtiym vill.	Private well
13	Kentau town	Tap water	45	Shipan vill.	Private well
14	Kentau town	Tap water	46	Shipan vill.	Tap water
15	Kosmezgil vill.	Tap water	47	Shekerbulak vill.	Tap water
16	Kosmezgil vill.	Private well	48	Shashtobe vill.	Tap water
17	Shornak vill.	Tap water	49	Sert vill.	Tap water
18	Shornak vill.	Private well	50	Ulgili vill.	Tap water
19	Teke vill.	Tap water	51	Abay vill.	Private well
20	Teke vill.	Artesian well	52	Eski Sauran vill.	Private well
21	Babaikorgan vill.	Private well	53	Sauran vill.	Tap water
22	Babaikorgan vill.	Private well	54	Eski Ikan vill.	Private well
23	Shobanak vill.	Private well	55	Eski Ikan vill.	Tap water
24	Shobanak vill.	Tap water	56	Aktobe vill.	Artesian well
25	Urangai vill.	Private well	57	Zhana Ikan vill.	Tap water
26	Yntymak vill.	Tap water	58	Oyik vill.	Tap water
27	Yntymak vill.	Private well	59	Oyik vill.	Private well
28	Karnak vill.	Private well	60	Shoktas vill.	Tap water
29	Karnak vill.	Private well	61	Bostandyk vill.	Tap water
30	Zhuinek vill.	Private well	62	Koktobe vill.	Artesian well
31	Zhuinek vill.	Tap water	63	Koktobe vill.	Private well
32	Shaga vill.	Tap water			

determined by titrimetric method with EDTA reagent, in accordance with standard GOST 23268.5-78. Hydrogen carbonate content was determined by the acidimetric titration method following standard GOST 31957-2012. Sodium content was measured using an FP6450 flame photometer according to RD 52.24.391-2008. Fluoride concentration was determined by a photometric method based on the formation of a ternary complex of alizarin-complexon, lanthanum (III), and fluoride in the presence of acetone (standard RD 52.24.533-2017). The detection limit of fluoride was 0.006 mg L⁻¹.

2.3.2 Fluoride determination in brewed tea

The fluoride ion content in tea samples was determined by the potentiometric method in accordance with GOST 4386-89. The analysis was performed using an ITAN ionometer equipped with an ELIS-131F fluoride-selective electrode. The detection limit for fluoride was 0.02 mg L⁻¹. For the procedure, 0.5 g of tea (previously dried at 105 °C) was infused with 100 mL of distilled water preheated to 100 °C. Extraction was conducted for 15 minutes, followed by filtration of the resulting tea infusion. After the filtrate had cooled to room temperature, the volume was adjusted to 100 mL with distilled water. The resulting tea infusion had a concentration of 0.5% w/v. A 20 mL aliquot was used for analysis. An acetate–citrate buffer solution (pH 5.0 ± 0.2) was employed as the indifferent electrolyte.

2.3.3 Precision and accuracy

The experiment was conducted using analytical-grade reagents and distilled water (conductivity <2 µS cm⁻¹). Instrument calibration was conducted on a daily basis using Certified Reference Materials (CRMs). Additionally, instrument calibration was performed whenever more than ten samples were analysed. Reliability was assessed via repeatability and trueness parameters, in accordance with standard protocols. The accuracy of fluoride determination was found to be no greater than 10% at the 95% confidence level. Each water sample was analysed in triplicate, and arithmetic means were employed if the criteria for repeatability were met. It is imperative to note that the relative standard deviations (RSD) for all the major parameters were maintained below 5% with a view to ensuring methodological reproducibility.

2.4 Calculation of water quality indices

2.4.1 Water quality index

The WQI is a widely used tool for assessing the overall quality of water by integrating multiple physicochemical parameters into a single numerical value.^[51] It is commonly calculated using the weighted arithmetic mean method, which assigns relative weights to selected water quality parameters based on their significance to human health and environmental impact. The WQI is computed using the following expressions Eq. (1-3):

$$Wi = \frac{wi}{\sum_{i=1}^n wi} \quad (1)$$

$$qi = \left(\frac{Ci}{Si} \right) \times 100 \quad (2)$$

$$WQI = \sum_{i=1}^n Wi \times qi \quad (3)$$

where w_i denotes the assigned weight of each parameter according to its relative significance to overall water quality. W_i refers to the relative weight, whereas q_i represents the quality rating associated with each of the n considered water quality parameters. C_i is the measured concentration of the substance in the water sample, and S_i corresponds to its permissible standard limit. The assigned weights, relative weights, and WHO guideline values used in the calculation are provided in Table 2. Based on the computed WQI values, water quality was classified according to the following thresholds: excellent ($WQI < 50$), good ($50 \leq WQI \leq 100$), poor ($100 < WQI \leq 200$), and very poor ($200 < WQI \leq 300$).^[52]

Table 2: Input data for WQI and DWNQI calculation.

Parameters	WQI		DWNQI		
	w_i	W_i	S_i	RDI_i	W_i
TDS	4	0.1905	1000	-	-
pH	3	0.1429	6.5–8.5	-	-
F ⁻	4	0.1905	1.2	3.5	0.5
Ca ²⁺	3	0.1429	100	1000	1.0
Mg ²⁺	3	0.1429	50	350	1.0
Na ⁺	3	0.1429	200	1500	0.5
HCO ₃ ⁻	1	0.0476	400	-	-
Σ (Total)	21	1.000	-	-	3.0

2.4.2 Drinking water nutritional quality index

The DWNQI reflects the extent to which drinking water contributes to meeting the Recommended Daily Intake (RDI) of essential micronutrients.^[53] In this study, the nutritional value of water was assessed based on the concentrations of F⁻, Ca²⁺, Mg²⁺, and Na⁺. The DWNQI was calculated using the following Eq. (4):

$$DWNQI = \sum_{i=1}^n \left(\frac{Ci \times IR}{RDI_i} \times Wi \right) \quad (4)$$

where C_i represents the concentration of element i in drinking water (mg L⁻¹); IR denotes the average daily water intake, set at 2 L day⁻¹; RDI_i refers to the recommended daily intake for element i (mg day⁻¹); w_i is a dimensionless weighting factor indicating the relative importance of element i in terms of human health; and n corresponds to the total number of elements evaluated in the index (in this case, $n = 4$). The values of RDI_i and w_i used in the calculation are presented in Table 2. The index is typically classified into categories that reflect the nutritional quality of drinking water: very poor (0–25), poor

(25–45), marginal (45–60), fair (60–70), good (70–80), and excellent (80–100).^[54]

2.4.3 Fluoride pollution index

To quantitatively assess fluoride contamination in groundwater, the FPI was employed. The FPI is calculated by incorporating key hydrochemical parameters that influence fluoride leaching and mobility, namely pH, Na/Ca, and HCO_3^- .^[55] These factors reflect geochemical conditions that promote the release of fluoride from minerals into groundwater. The FPI is computed using the following Eq. (5):

$$FPI = \frac{W_F + W_{\text{HCO}_3} + W_{\text{pH}} + W_{\frac{\text{Na}}{\text{Ca}}}}{N} \quad (5)$$

where W_F , W_{HCO_3} , W_{pH} , and $W_{\text{Na/Ca}}$ are the designated weights assigned according to the measured concentrations of the respective substances, with their specific values provided in.^[13] N denotes the total number of parameters considered (typically four). Groundwater samples were classified based on their FPI values into three contamination levels: low (1.0–2.0), moderate (2.0–3.0), and high fluoride pollution (3.0–4.0).

2.5 Human health risk assessment

2.5.1 Non-carcinogenic risk of fluoride in drinking water

The assessment of non-carcinogenic health risks associated with fluoride exposure through drinking water was performed using the HQ method. Calculations were conducted separately for children and adults to account for age-dependent variations in exposure and physiological parameters. The HQ was defined as the ratio of the CDI of fluoride to its reference dose (RfD), in accordance with guidelines established by the United States Environmental Protection Agency (USEPA).^[56] The CDI was calculated using the following Eq. (6):^[57]

$$CDI = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad (6)$$

where C is the fluoride concentration in water (mg L^{-1}), IR is the ingestion rate (L day^{-1}), EF is the exposure frequency (days year^{-1}), ED is the exposure duration (years), BW is the body weight (kg), and AT is the averaging time (days), typically equal to $ED \times 365$ for non-carcinogenic risk. For adults, the input values were set as follows: $IR = 2$, $BW = 70$, $ED = 30$; and for children: $IR = 1$, $BW = 25$, $ED = 6$. An EF of 365 days/year was assumed for both groups. Once the CDI was calculated, the HQ was derived using the Eq. (7):

$$HQ = \frac{CDI}{RfD} \quad (7)$$

where the RfD for fluoride is typically $0.06 \text{ mg kg}^{-1} \text{ day}^{-1}$.^[54] An HQ value below 1 suggests that the exposure is unlikely to result in adverse health effects, whereas an HQ above 1 indicates potential concern, warranting further evaluation. ($0.06 \text{ mg kg}^{-1} \text{ day}^{-1}$)

2.5.2 Non-carcinogenic risk of fluoride in brewed tea

In addition to direct consumption of drinking water, fluoride intake through tea was also considered in the exposure assessment. Given that tea can substantially contribute to overall fluoride exposure, particularly in populations with high tea consumption, a separate calculation was performed to account for this pathway. To improve the accuracy of the non-carcinogenic risk estimation associated with fluoride intake, the contribution from tea consumption was incorporated into the HQ calculation.

The fluoride concentration in tea was determined experimentally. Tea was infused using distilled water to eliminate external sources of fluoride. Consequently, the final fluoride concentration in the beverage comprised both the fluoride present in the water used for brewing and the fluoride extracted from the tea leaves. This measured concentration was then included in the exposure assessment. To account for both sources of intake, namely drinking water and tea, the total chronic daily intake (CDI_{total}) was calculated as the sum of fluoride intake from water and tea, using the following Eq. (8):

$$CDI_{\text{total}} = CDI + CDI_{\text{tea}} \quad (8)$$

For adults, the total daily fluid intake was assumed to consist of 1.0 L of drinking water and 1.0 L of tea. For children, the intake was estimated at 0.5 L of water and 0.5 L of tea per day. The resulting value of CDI_{total} was then used to calculate the adjusted hazard quotient for tea consumption (HQ_{tea}) as follows Eq. (9):

$$HQ_{\text{tea}} = \frac{CDI_{\text{total}}}{RfD} \quad (9)$$

By incorporating tea consumption into the risk assessment, this approach provides a more comprehensive estimate of total fluoride exposure and more accurately reflects real-life intake scenarios, particularly in populations where tea is a routine component of the daily diet.

2.6 Statistical analyses and spatial mapping

Statistical analysis of the results, calculation of water quality indices, and Pearson correlation analysis were performed using Microsoft Excel 2016. Spatial distribution maps were generated using the kriging interpolation method, which is widely applied in geostatistics to predict values at unsampled locations based on measured data points.^[58] The kriging algorithm accounts for both the distance and the degree of variation between known data points, providing statistically optimal and unbiased estimates. In this study, ordinary kriging was implemented in Python (version 3.x) using PyCharm 2025.1. Interpolation was performed on georeferenced water quality data, and the resulting continuous surfaces were visualised as spatial distribution maps with colour gradients representing varying levels of water quality.

3. Results

3.1 Physicochemical characteristics of groundwater

The results of the chemical analysis of water from 63 sources in the Sauran District are presented in Fig. 2. The pH of the waters studied ranged from 6.73 to 8.15, with a mean value of 7.44, which is within the permissible range according to Kazakhstan drinking water standards (6.5–8.5). The 25th and 75th percentiles were 7.23 and 7.67, respectively. The TDS content varied widely, ranging from 131 mg L⁻¹ to 2676 mg L⁻¹, with a mean value of 607 mg L⁻¹. The lowest TDS readings were observed in artesian wells, ranging from 277 to 422 mg L⁻¹ (mean 370 mg L⁻¹). Moderate TDS values were recorded in deep water wells with water intake depths up to 900 m, ranging from 131 to 1067 mg L⁻¹ (mean 404 mg L⁻¹). The highest TDS values were measured in shallow private wells (depths up to 17 m), ranging from 366 to 2676 mg L⁻¹ (mean 998 mg L⁻¹). The high mineralisation of water from private wells renders it unsuitable for drinking; it is primarily used for household purposes, such as garden irrigation and livestock watering. According to WHO and Kazakhstan drinking water standards, TDS should not exceed 1000 mg L⁻¹, whereas optimal TDS is recommended to be up to 500 mg L⁻¹ based on taste and potential long-term health effects. Of the 63 sources studied, eight sources (12.7 %) exceeded 1000 mg L⁻¹, and 23 sources (36.5 %) were between 500 and 1000 mg L⁻¹.

The hydrogen carbonate content ranged from 73.2 to 488.0 mg L⁻¹, with a mean value of 238.8 mg L⁻¹ (Fig. 2). An outlier

was detected at 488.0 mg L⁻¹ in a shallow private well (4 m depth) in Shipan village (Sample 45), which also exhibited a high TDS value of 2473 mg L⁻¹. The 25th and 75th percentiles were 183.0 and 274.5 mg L⁻¹, respectively. Average hydrogen carbonate concentrations were 188.6 mg L⁻¹ in artesian wells, 203.0 mg L⁻¹ in deep wells, and 308.6 mg L⁻¹ in shallow wells. Although hydrogen carbonate is not regulated in drinking water, it can influence water taste and scaling in heating devices.

Calcium concentrations ranged from 12.0 to 320.6 mg L⁻¹, with a mean of 73.6 mg L⁻¹ (Fig. 2). The calcium box plot shows six outliers corresponding to concentrations ranging from 151.7 to 320.6 mg L⁻¹, which were measured in shallow wells with an intake depth of up to 5 metres. The 25th and 75th percentiles were 41.3 and 82.4 mg L⁻¹, respectively. Mean calcium concentrations were 43.3 mg L⁻¹ in artesian wells, 48.2 mg L⁻¹ in deep wells, and 121.8 mg L⁻¹ in shallow wells. The magnesium concentration in the studied waters ranged from 6.3 to 164.0 mg L⁻¹, with a mean value of 34.4 mg L⁻¹. The magnesium box plot also reveals six outliers corresponding to concentrations between 77.4 and 164.0 mg L⁻¹. These concentrations were likewise measured in water from shallow wells characterised by high TDS values and elevated calcium content. The 25th and 75th percentiles for magnesium were 15.2 and 39.8 mg L⁻¹, respectively. The average Ca/Mg molar ratio was 1.70 in deep wells and 1.21 in shallow wells.

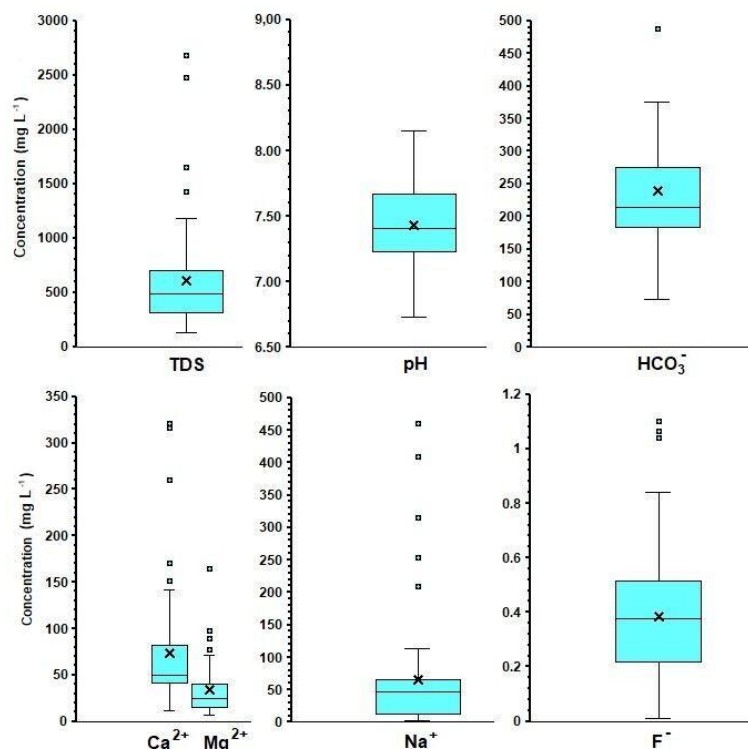


Fig. 2: Box plots of pH, fluoride, TDS, hydrogen carbonate, calcium, magnesium, and sodium concentrations in water sources of the Sauran District. Each box plot shows the median (horizontal line within the box), the mean (cross symbol), the lower and upper quartiles (25th and 75th percentiles), and outliers. The fig. 2 indicates that shallow wells characteristically exhibit higher levels of variability and elevated concentrations of TDS, hydrogen carbonate, calcium, magnesium, and sodium in comparison with deep and artesian wells.

Sodium concentrations varied from 3.2 to 460.9 mg L⁻¹ (mean 65.4 mg L⁻¹), with the interquartile range between 13.4 and 65.3 mg L⁻¹ (Fig. 2). Five outliers (208.6–460.9 mg L⁻¹) were observed. Average sodium concentrations were 40.9 mg L⁻¹ in deep wells, 44.9 mg L⁻¹ in artesian wells, and 110.5 mg L⁻¹ in shallow private wells.

3.2 Fluoride concentration

3.2.1 Groundwater

Analysis of groundwater sources (n = 63) showed that the concentration of fluoride ions in the water samples varied within a relatively wide range, from 0.01 to 1.10 mg L⁻¹, with a mean of 0.40 mg L⁻¹ and a standard deviation (SD) of ± 0.25 (Fig. 2). The box plot of fluoride concentrations reveals three outliers corresponding to the highest measured values: 1.04 mg L⁻¹ in shallow private well water in Yntymak village (TDS = 862 mg L⁻¹); 1.07 mg L⁻¹ in tap water in Ulgili village (TDS = 533 mg L⁻¹); and the maximum in this study, 1.10 mg L⁻¹ in tap water in Sert village (TDS = 505 mg L⁻¹). The interquartile range was limited to concentrations between 0.22 and 0.52 mg L⁻¹. The lowest fluoride concentration, 0.01 mg L⁻¹, was measured in tap water in the northern part of Turkestan city (TDS = 237 mg L⁻¹). In Turkestan, 12 water samples from different parts of the city were analysed, of which three were taken from private wells and the remaining nine from tap water supplied from deep municipal wells. The fluoride content of tap water in Turkestan ranged from 0.01 to 0.41 mg L⁻¹, with an average of 0.13 mg L⁻¹. The TDS of the nine aforementioned sources ranged from 205 to 428 mg L⁻¹, with an average of 273 mg L⁻¹. The fluoride content of water from private wells in the city was considerably higher, ranging from 0.17 to 0.57 mg L⁻¹, with an average of 0.38 mg L⁻¹. The TDS content of private wells was also elevated, averaging 1406 mg L⁻¹. The fluoride content of tap water in Kentau town was low, averaging only 0.03 mg L⁻¹ (mean TDS = 228 mg L⁻¹). Overall, the analysis of 63 water samples showed that the mean fluoride content of water from deep municipal wells was 0.32 mg L⁻¹ (SD = ± 0.26), from artesian wells 0.41 mg L⁻¹ (SD = ± 0.31), and from shallow private wells 0.49 mg L⁻¹ (SD = ± 0.20).

3.2.2 Brewed tea

To investigate fluoride content in tea beverages, seven brands of tea most popular in the study region were selected. The

sample included both black and green teas, with black tea being more commonly consumed among the local population. Consumers also predominantly favour loose-leaf and granulated tea, while tea bags are less popular. The average fluoride concentrations, obtained from two parallel determinations for each brand, are presented in Table 3.

The mean fluoride concentration in tea beverages was 0.86 mg L⁻¹, ranging from 0.38 to 1.36 mg L⁻¹. Fluoride content in green tea was slightly lower (0.68 mg L⁻¹) compared with black tea (0.93 mg L⁻¹). A study by Pattaravisitsate *et al.*^[59] similarly reported lower fluoride concentrations in green tea (1.45 mg L⁻¹) than in black tea (2.55 mg L⁻¹). Szmagara *et al.*^[60] also noted comparable fluoride levels in both tea types. It should be noted that the sample size for green tea in the present study was smaller than that for black tea. The average fluoride concentration (0.86 mg L⁻¹) found in tea beverages was subsequently used to assess potential health risks using the CDI and HQ methodologies. Previous studies reported average fluoride concentrations of 2.65 mg L⁻¹ (1% w/v),^[60] 2.53 mg L⁻¹ (2% w/v),^[59] 1.38 mg/L (0.5% w/v),^[61] and 2.38 mg/L (1% w/v).^[62] However, when adjusted to the brewing conditions of the present study (0.5% w/v), these values corresponded to 1.33 mg L⁻¹, 0.63 mg L⁻¹, 1.38 mg L⁻¹, and 1.19 mg L⁻¹, respectively, which are comparable with the results obtained here.

3.3 Correlation

The figure indicates that moderate to high fluoride contamination is predominantly concentrated in shallow wells in the central and north-western parts of the district, whereas deep aquifers generally exhibit low to moderate contamination. A correlation assessment was conducted to identify the factors governing fluoride variability in both groundwater and brewed tea. In the context of groundwater, a discernible correlation was observed between fluoride concentration and total dissolved solids (TDS). All samples with the highest fluoride levels (1.04–1.10 mg L⁻¹) were characterised by elevated mineralisation (TDS = 505–862 mg L⁻¹), whereas waters with extremely low fluoride content (<0.10 mg L⁻¹), primarily municipal tap water from Turkestan and Kentau, also exhibited the lowest TDS values (205–237 mg L⁻¹). This pattern indicates a moderate positive correlation between fluoride and TDS, implying that water circulating through highly mineralised aquifers or geochemically enriched strata

Table 3: Fluoride concentration in tea infusions from selected brands.

No.	Brand	Tea type	Country of origin	F ⁻ (mg L ⁻¹)	±SD (mg L ⁻¹)
1	Green No.95	green loose leaf	Uzbekistan	0.79	0.05
2	Bayce	green loose leaf	Turkey	0.56	0.07
3	Piala	black granulated	Kazakhstan	0.81	0.09
4	Shah	black granulated	Russia	1.36	0.10
5	Assam	black granulated	Kazakhstan	0.93	0.11
6	Champion	black loose leaf	Turkey	0.38	0.05
7	Tess	black loose leaf	Russia	1.18	0.05

accumulates both fluoride and dissolved salts.

This trend is further reinforced by the findings of the study's groundwater source analysis, which revealed that shallow private wells, characterised by increased water–rock interaction and longer residence time, exhibited the highest mean fluoride concentration (0.49 mg L^{-1}). This was followed by artesian wells, which had an average fluoride concentration of 0.41 mg L^{-1} . The deepest municipal wells, which are characterised by more stable hydrochemical conditions and lower mineralisation, exhibited the lowest fluoride levels (0.32 mg L^{-1}). The findings, when considered collectively, suggest that aquifer depth, lithology, and mineralization degree are key controls governing fluoride enrichment in the region.

In brewed tea, a distinct correlation was observed between fluoride content and the type of tea. The fluoride concentrations in black teas ($0.81\text{--}1.36 \text{ mg L}^{-1}$; mean 0.93 mg L^{-1}) were systematically higher than those in green teas ($0.56\text{--}0.79 \text{ mg L}^{-1}$; mean 0.68 mg L^{-1}). This discrepancy is attributable to the well-documented propensity of mature tea leaves, which are predominantly utilized in the production of black tea, to accumulate fluoride during the growth phase. The observed pattern is consistent with earlier reports and confirms that leaf maturity and processing method are the primary determinants of fluoride content in tea infusions. Despite the negligible levels of dissolved solids present in brewed tea, its fluoride concentration exhibits a pronounced compositional dependency. This phenomenon stands in contrast to that

observed in groundwater, where geochemical processes exert a predominant influence.

4. Discussion

4.1 Evaluation of fluoride in groundwater

In Kazakhstan, two standards regulate the maximum permissible concentration of fluoride in drinking water: 1.5 mg L^{-1} and 1.2 mg L^{-1} . The limit of 1.5 mg L^{-1} aligns with international recommendations, including the WHO guideline, and is widely accepted in many other countries. This threshold is considered appropriate for regions with a temperate and relatively cool climate.

The lower standard of 1.2 mg L^{-1} is applied in the arid and hot areas of Kazakhstan. In such regions, water intake is typically higher, which increases the risk of excessive fluoride accumulation in the body. For this reason, the stricter limit of 1.2 mg L^{-1} is regarded as a safer value to prevent potential adverse health effects. Accordingly, the southern part of Kazakhstan, characterised by a subtropical and arid climate, adopts the 1.2 mg L^{-1} standard.

Numerous studies examining the health effects of fluoride have led to the establishment of a conventional classification system. Fluoride levels below 0.3 mg L^{-1} are considered *very low*. Concentrations of $0.3\text{--}0.7 \text{ mg L}^{-1}$ are classified as *low*, whereas $0.7\text{--}1.1 \text{ mg L}^{-1}$ are regarded as *optimal* for human health.^[63,64]

The data on fluoride content in the analysed waters are

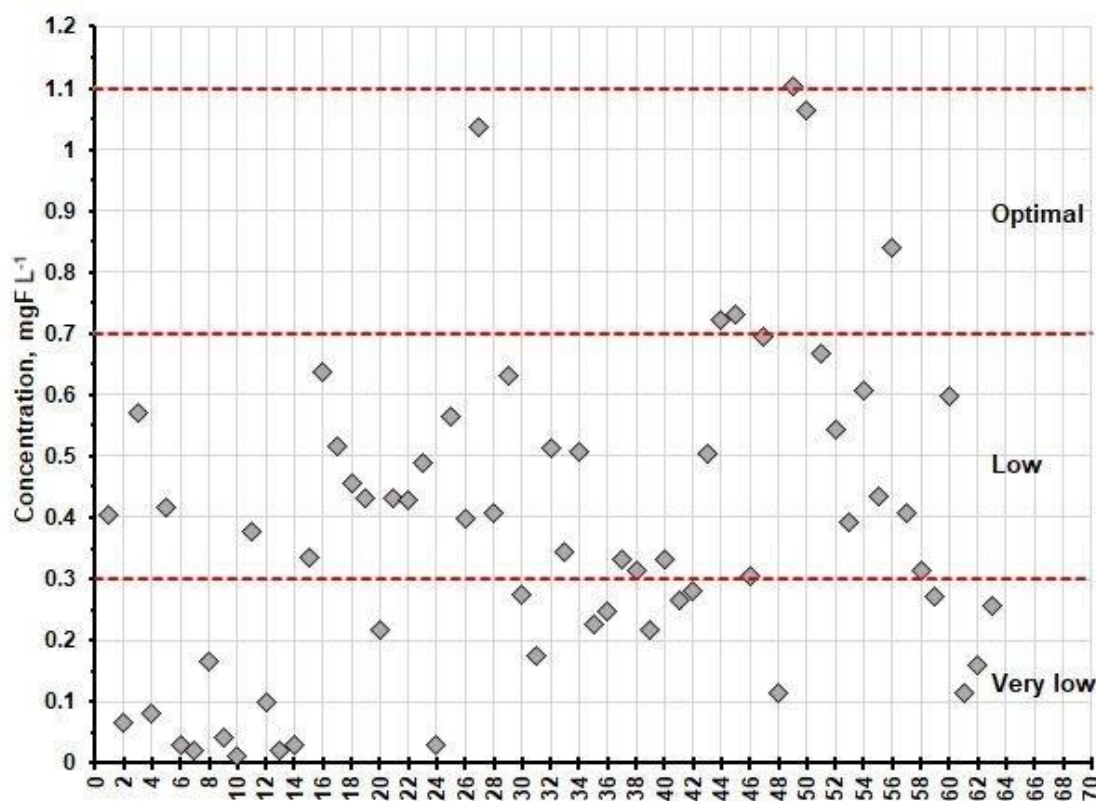


Fig. 3: Fluoride concentrations in the water sources of the Sauran District. The x-axis shows sample numbers. It is evident from the figure that the majority of sources display fluoride concentrations that are either very low or low, with only a limited number of sources exhibiting optimal levels.

summarised in Fig. 3. In this graph, fluoride concentration ranges are marked by horizontal lines corresponding to three conventional categories: 0–0.3 mg L⁻¹ (very low), 0.3–0.7 mg L⁻¹ (low), and 0.7–1.2 mg L⁻¹ (optimal). The numbers on the x-axis indicate the sample codes listed in Table 1. As shown in Fig. 3, most water sources contained either very low or low fluoride concentrations.

Very low concentrations (<0.3 mg L⁻¹) were identified in 24 sources (38.1%). These included eight sources in Turkestan city, two in Kentau town, and fourteen in twelve villages (Teke, Shobanak, Zhuinek, Kotyrbulak, Kusshyata, Nurtas, Birlik, Karashyk, Shashrobe, Oyik, Bostandyk, and Koktobe). Among these 24 sources, 17 were deep wells (mean 0.11 mg L⁻¹, SD ±0.09), two were artesian wells (mean 0.19 mg L⁻¹, SD ±0.03), and five were shallow private wells (mean 0.24 mg L⁻¹, SD ±0.04). Similar observations of very low fluoride levels have been reported in several regions of Poland^[65] and in the Suzhou urban area of China,^[66] where concentrations remained below 0.1 mg L⁻¹.

Low fluoride concentrations (0.3–0.7 mg L⁻¹) were recorded in 33 sources (52.4%). Four of them were located in Turkestan city, while the remaining 29 originated from 24 villages, including Kosmezgil, Shornak, Teke, Babaikorgan,

Shobanak, Urangai, Yntymak, Karnak, Shaga, Bershintobe, Koskorgan, Shoitobe, Jalandhos, S. Kozhanov, Kumtiym, Shipan, Shekerbulak, Abay, Eski Sauran, Sauran, Eski Ikan, Zhana Ikan, Oyik, and Shoktas. Nineteen of these sources were deep wells (mean 0.43 mg L⁻¹, SD ±0.10), while fourteen were shallow private wells (mean 0.51 mg L⁻¹, SD ±0.10).

Optimal fluoride concentrations (0.7–1.1 mg L⁻¹) were found in six sources. These included tap water from deep wells (up to 200 m) in Sert (1.10 mg L⁻¹) and Ulgili (1.07 mg L⁻¹), private wells in Yntymak (1.04 mg L⁻¹), Kumtiym (0.72 mg L⁻¹), and Shipan (0.73 mg L⁻¹), and a flowing artesian well (up to 700 m) in Aktobe village (0.84 mg L⁻¹). Despite optimal fluoride concentrations, private wells showed elevated TDS levels (862–2473 mg L⁻¹), which made the water unsuitable for drinking. In contrast, water from Sert, Ulgili, and Aktobe had acceptable TDS values (505, 532, and 277 mg L⁻¹, respectively), indicating that these sources meet drinking-water quality standards.

4.2 Evaluation of water quality

4.2.1 WQI

The WQI results are presented as a spatial distribution map generated using kriging interpolation (Fig. 4). Water from

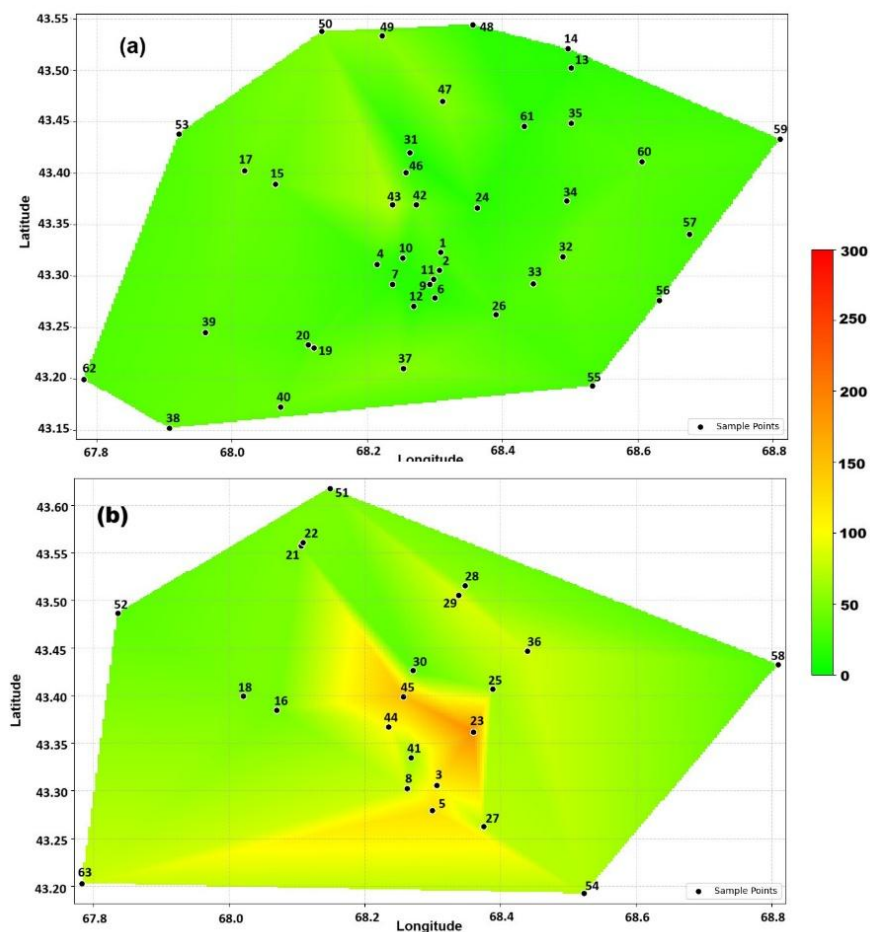


Fig. 4: Spatial distribution of the WQI in the Sauran District obtained by kriging: (a) deep aquifers and (b) shallow aquifers. The numbers on the map correspond to sample numbers. The figure indicates that water from deep aquifers is predominantly of excellent or good quality, whereas several shallow aquifer sources in the central district are inadequate and unsuitable for drinking.

deep aquifers was predominantly classified as ‘excellent’ (87.8%) and ‘good’ (12.2%). WQI values for these sources ranged from 11 to 69, with a mean of 31. Only one deep aquifer sample (Sample 43 from Kumtiym) slightly exceeded WHO guideline values for TDS ($q = 107$) and Na ($q = 104$) (Fig. 4a).

In contrast, water from shallow aquifers exhibited noticeably poorer quality (Fig. 4b). WQI values ranged from 33 to 189, with an average of 76. Among these sources, 36.4% were classified as ‘excellent’, 40.1% as ‘good’, and 22.7% as ‘poor’. Five sources (Samples 3, 5, 23, 44, and 45) were identified as unsuitable for drinking. These sources exceeded WHO recommendations for TDS ($q = 142$ – 268), Ca ($q = 106$ – 321), Mg ($q = 111$ – 328), and Na ($q = 54$ – 230). All of these poor-quality sources are located in the central part of the Sauran District and are considered unequivocally unfit for human consumption.

4.2.2 DWNQI

In this study, alongside WQI, the DWNQI was calculated to assess the nutritional value of drinking water. This assessment was based on the concentrations of Ca^{2+} , Mg^{2+} , F^- , and Na^+ . The results are presented as a spatial distribution in Fig. 5.

Water from deep aquifers was classified as ‘excellent’ and ‘good’ according to WQI (Fig. 5a). However, DWNQI values indicated extremely low nutritional value for these sources, ranging from 4 to 24, with an average of 11. Such water does not meet the daily human requirements for Ca^{2+} , Mg^{2+} , F^- , and Na^+ . Therefore, supplementation from alternative sources, such as mineral water or food, is necessary.

For shallow aquifer water, DWNQI values ranged from 11 to 68, with an average of 27 (Fig. 5b). Among these samples, 50% were classified as ‘very poor’, 40.9% as ‘poor’, and only two samples (5 and 23) were rated as marginal and fair, with DWNQI values of 45 and 68, respectively.

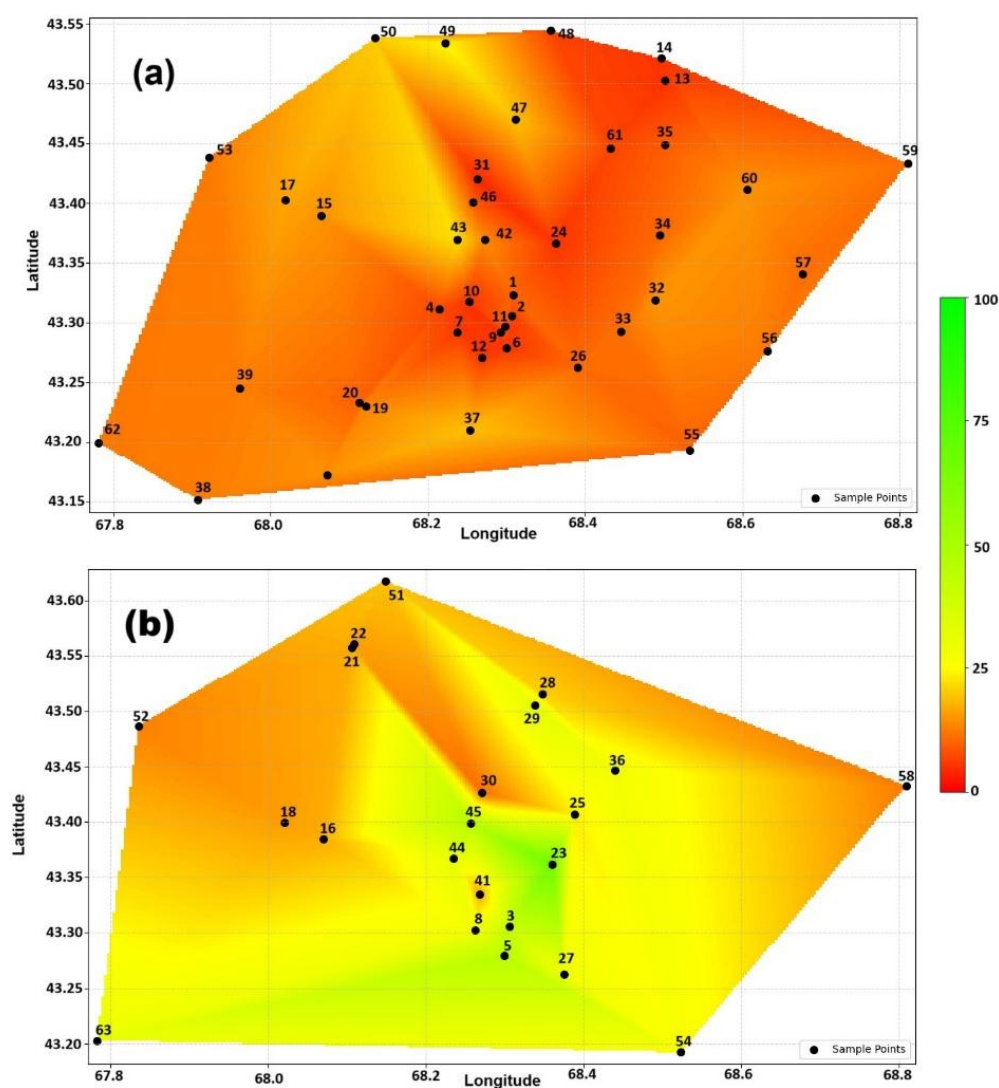


Fig. 5: Spatial distribution of the DWNQI in the Sauran District obtained by kriging: (a) deep aquifers and (b) shallow aquifers. The numbers on the map correspond to sample numbers. The figure indicates that, despite the acceptable WQI, the majority of deep and shallow aquifer waters exhibit a notably low nutritional value, with shallow sources in the central district demonstrating marginally higher mineral content that nevertheless falls short of the required level.

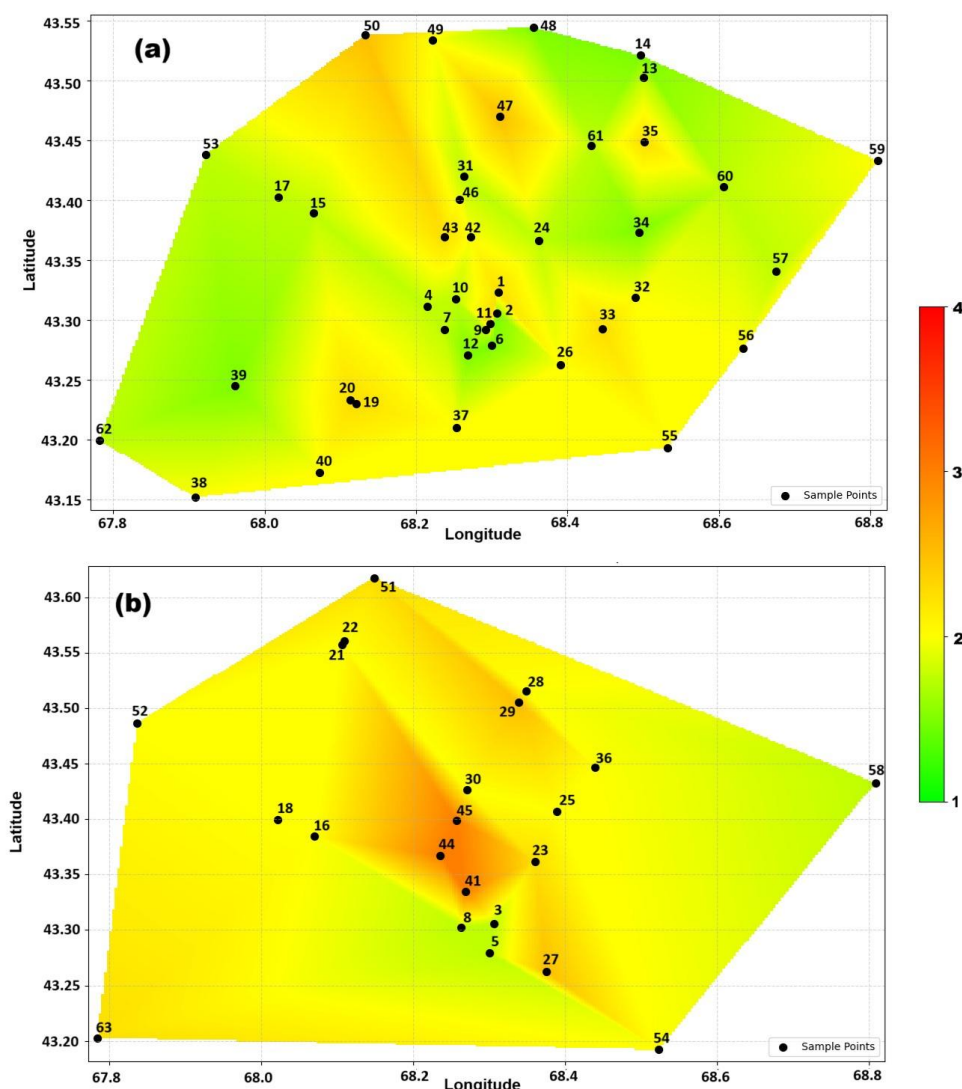


Fig. 6: Spatial distribution of the FPI in the Sauran District obtained by kriging: (a) deep aquifers and (b) shallow aquifers. The numbers on the map correspond to sample numbers. As demonstrated in Fig. 6, moderate to high fluoride contamination is predominantly concentrated in shallow wells within the central and north-western regions of the district. Conversely, deep aquifers characteristically manifest low to moderate contamination levels.

A similar trend was observed by Agbasi *et al.*,^[53] who reported low nutritional value in drinking water from suburban areas of south-eastern Nigeria, where over 73% of samples were categorized as poor based on DWNQI. These findings highlight the relevance of insufficient water mineralisation, particularly in the context of transitioning from traditional water quality assessment to comprehensive nutrient-based indicators.

4.2.3 Fluoride pollution index

To assess the level of fluoride contamination in groundwater, the FPI was applied. This index considers not only the concentration of F^- but also additional physicochemical parameters, including HCO_3^- content, pH, and the Na/Ca ratio. FPI serves both as a measure of contamination severity and as an indicator of potential risk resulting from geochemical conditions that promote fluoride enrichment.

In deep aquifers, 51% of sources were classified as having low fluoride contamination, while 49% were considered moderate. The spatial distribution map (Fig. 6a) shows that sources with moderate contamination are mainly concentrated in the north-western and southern regions of the study area. Analysis of average weighting factors revealed that pH (2.54) and HCO_3^- (2.49) contributed the most to the FPI. Alkaline conditions and elevated bicarbonate levels facilitate the dissolution of fluoride-bearing minerals. A Na/Ca ratio below 1 was observed in 58.5% of sources, whereas a ratio above 1 occurred in 36.6%. In two sources (Samples 38 and 43), the Na/Ca ratio exceeded 2. Elevated Na/Ca ratios may indicate ion exchange processes, where Na^+ replaces Ca^{2+} in clay minerals, enhancing fluoride leaching. The average contributions of Na/Ca and F^- to the FPI were 1.46 and 1.10, respectively.

Among shallow aquifer sources, low fluoride contamination

was observed in 18.2% of samples, and moderate contamination in 68.2% (Fig. 6b). Three sources (Samples 41, 44, and 45) reached FPI values of 3, corresponding to the high-risk category. These samples also exhibited high Na/Ca ratios (5.09, 2.97, and 2.35), which may suggest groundwater contamination from domestic wastewater. Comparison with data from the Isa Khel region in Pakistan,^[67] supports the relevance of these results. There, similarly high FPI values—up to 3.75—were reported, with 48.7% of groundwater samples classified as high fluoride contamination.

The FPI spatial distribution map (Fig. 6b) shows that elevated index values are concentrated in the central part of the study area, particularly around the suburbs of Turkestan city. In shallow aquifers, the main contributors to FPI were HCO_3^- (mean 3.55) and pH (mean 2.22). Contributions from Na/Ca and F^- were somewhat lower, averaging 1.59 and 1.32, respectively.

4.3 Fluoride human health risk assessment

4.3.1 Drinking water

The daily fluoride intake from deep aquifers varied considerably between children and adults, depending on the water source (Table 4). The average CDI values were $0.013 \text{ mg kg}^{-1} \text{ day}^{-1}$ for children and $0.009 \text{ mg kg}^{-1} \text{ day}^{-1}$ for adults. Non-carcinogenic risk also differed across sources but did not exceed 0.74 for children and 0.53 for adults. The highest HQ was observed in Sample 49, which contained 1.10 mg L^{-1} of fluoride. Relatively elevated HQ values (> 0.4) were also

recorded in Samples 50 and 56 for both age groups. On average, HQ values for children were approximately 40% higher than those for adults. Comparable findings have been reported in previous studies,^[57,68] which showed that the non-carcinogenic fluoride risk is higher for infants and children than for adults. Overall, given the low mean HQ values, which did not exceed 0.22, water from deep aquifers does not pose a non-carcinogenic risk from fluoride exposure for either age group. Similarly low HQ values, with a maximum of 0.20, were reported by^[69] in an assessment of groundwater quality in the Azad Jammu and Kashmir region of Pakistan.

For shallow aquifers, CDI values were substantially higher. Average CDI values were 52.1% higher for children and 34.0% higher for adults compared with deep aquifers, resulting in mean CDI values of $0.020 \text{ mg kg}^{-1} \text{ day}^{-1}$ and $0.014 \text{ mg kg}^{-1} \text{ day}^{-1}$, respectively. The highest HQ values were observed in Sample 27, with 0.69 for children and 0.49 for adults, corresponding to a fluoride concentration of 1.04 mg L^{-1} . Comparable HQ values, not exceeding 0.66 for children, were reported by Dehghani *et al.*^[70] in Fars Province, Iran. In the present study, the average HQ values for shallow aquifer sources were slightly higher than those for deep aquifers, but did not exceed 0.33. This indicates that non-carcinogenic health risks are absent for both children and adults. Based on these observations, HQ values within the range of 0.4–0.6 may be considered acceptable, as they roughly correspond to optimal fluoride concentrations in drinking water ($0.7\text{--}1.1 \text{ mg L}^{-1}$).

Table 4: Non-carcinogenic risk of fluoride exposure in drinking water for children and adults.

Water Source	CDI ($\text{mg kg}^{-1} \text{ day}^{-1}$)				HQ			
	Min	Max	Mean	$\pm\text{SD}$	Min	Max	Mean	$\pm\text{SD}$
Children								
Deep aquifers	4.0×10^{-4}	4.4×10^{-2}	1.3×10^{-2}	1.1×10^{-2}	6.7×10^{-3}	0.74	0.22	0.17
Shallow aquifers	6.7×10^{-3}	4.2×10^{-2}	2.0×10^{-2}	8.0×10^{-3}	0.11	0.69	0.33	0.13
Adults								
Deep aquifers	2.9×10^{-4}	3.2×10^{-2}	9.3×10^{-3}	7.5×10^{-3}	4.8×10^{-3}	0.53	0.15	0.12
Shallow aquifers	4.8×10^{-3}	3.0×10^{-2}	1.4×10^{-2}	5.7×10^{-3}	0.08	0.49	0.24	0.10

Table 5: Non-carcinogenic risk of fluoride exposure from tea infusions prepared with drinking water from different sources of the Sauran District.

Water Source	CDI _{tea} ($\text{mg kg}^{-1} \text{ day}^{-1}$)				HQ _{tea}			
	Min	Max	Mean	$\pm\text{SD}$	Min	Max	Mean	$\pm\text{SD}$
Children								
Deep-aquifers (tea infusion)	1.8×10^{-2}	6.1×10^{-2}	3.0×10^{-2}	1.1×10^{-2}	0.29	1.02	0.50	0.17
Shallow aquifers (tea infusion)	2.4×10^{-2}	5.9×10^{-2}	3.7×10^{-2}	8.0×10^{-3}	0.40	0.98	0.62	0.13
Adults								
Deep-aquifers (tea infusion)	1.3×10^{-2}	4.4×10^{-2}	2.2×10^{-2}	7.5×10^{-3}	0.21	0.73	0.36	0.12
Shallow aquifers (tea infusion)	1.7×10^{-2}	4.2×10^{-2}	2.6×10^{-2}	5.7×10^{-3}	0.28	0.70	0.44	0.10

4.3.2 Tea consumption

Numerous studies have shown that the fluoride content in tea leaves (*Camellia sinensis*) can be relatively high. It also varies depending on the tea variety, the soil type, leaf age, and the processing method.^[71] Tea is recognized as one of the main plants with a high capacity for fluoride accumulation in its leaves. In Kazakhstan, tea is a traditional and widely consumed beverage. Most of the population drinks it daily, both during and between meals, with black tea varieties being particularly popular. Given this context, the present study included tea consumption as an additional source of fluoride intake in the HQ assessment. To calculate CDI_{tea} and HQ_{tea} , the average fluoride concentration in brewed tea from seven popular brands in the region was determined as 0.86 mg L^{-1} . Because this concentration was measured using tea prepared with distilled water, the fluoride content of both drinking water and tea was summed when calculating CDI_{tea} . The resulting data are presented in Table 5.

Consumption of tea containing 0.86 mg L^{-1} of fluoride led to a substantial increase in mean CDI_{tea} and HQ_{tea} values. For water from deep aquifers, the increase was 132%, while for shallow aquifers it was 87%, for both children and adults. Analysis indicated that the non-carcinogenic risk for children reached 1.0 in two deep-aquifer sources (Sert and Ulgili), which contained fluoride concentrations of 1.10 and 1.07 mg L^{-1} , respectively. HQ_{tea} values for adults at these sources were 0.73 and 0.71. Relatively high HQ_{tea} values (> 0.7) for children were also observed in Samples 47 (Shekerbulak) and 56 (Aktobe). Among shallow aquifer sources, the highest HQ_{tea} was recorded at Sample 27 (Yntymak), reaching 0.98

for children and 0.70 for adults. In addition, HQ_{tea} values exceeding 0.7 for children were found in Samples 16, 29, 44, 45, and 51. These findings are consistent with previous studies, which reported increased non-carcinogenic risk ($HQ \geq 1$) associated with tea consumption.^[59,72]

Thus, tea consumption can substantially increase the daily intake of fluoride, especially when combined with elevated fluoride levels in drinking water. However, at low fluoride concentrations in drinking water ($< 0.7 \text{ mg L}^{-1}$), tea may serve as a beneficial supplementary source to address fluoride deficiency.

4.4 Correlation analysis

The chemical analysis of the investigated water sources included parameters such as pH, TDS, HCO_3^- , Ca^{2+} , Mg^{2+} , and Na^+ . These data enabled a correlation analysis of the relationships between fluoride content and these variables. The calculated Pearson correlation coefficients are presented in Table 6. Given the geological differences between aquifers supplying deep municipal wells and shallow private wells, separate analyses were conducted for these sources. Artesian wells were grouped with deep municipal wells due to comparable aquifer depths.

The correlation analysis revealed marked differences between the two aquifer types. In deep aquifers, fluoride exhibited a noticeable positive correlation with hydrogen carbonate, magnesium, and TDS ($r = 0.47\text{--}0.53$). This pattern is likely associated with the co-leaching of fluoride and carbonate rock components, such as limestone, dolomite, and magnesite.

Table 6: Results of the correlation analysis of water components in deep and shallow aquifers.

Deep aquifers							
	pH	TDS	HCO_3^-	F^-	Ca^{2+}	Mg^{2+}	Na^+
pH	1.00						
TDS	-0.02	1.00					
HCO_3^-	-0.01	0.69	1.00				
F^-	-0.13	0.47	0.53	1.00			
Ca^{2+}	-0.06	0.69	0.49	0.16	1.00		
Mg^{2+}	-0.02	0.74	0.58	0.53	0.56	1.00	
Na^+	-0.01	0.86	0.57	0.39	0.35	0.38	1.00
Shallow aquifers							
	pH	TDS	HCO_3^-	F^-	Ca^{2+}	Mg^{2+}	Na^+
pH	1.00						
TDS	-0.08	1.00					
HCO_3^-	-0.07	0.40	1.00				
F^-	0.13	0.16	0.19	1.00			
Ca^{2+}	-0.16	0.82	0.11	0.01	1.00		
Mg^{2+}	-0.16	0.86	0.26	0.04	0.88	1.00	
Na^+	-0.07	0.84	0.42	0.16	0.43	0.54	1.00

Fluoride may also occur as an impurity in these carbonate rocks, which act as geochemical barriers to fluoride migration. A moderate positive correlation was also found between fluoride and sodium ($r = 0.39$), likely related to fluoride release from clay minerals and ion-exchange processes involving Na^+ release and Ca^{2+} precipitation.^[73] Evidence of carbonate dissolution in deep aquifers is further supported by the joint positive correlations of Ca, Mg, HCO_3^- , and TDS ($r = 0.49\text{--}0.74$).

The mean fluoride concentration in shallow aquifers was higher than in deep aquifers, averaging 0.49 mg L^{-1} and 0.33 mg L^{-1} , respectively. Elevated mineralisation and fluoride content in shallow aquifers are likely due to relatively slow groundwater flow, caused by restrictive barriers. This increases contact time with aquifer rocks, promoting the accumulation of leaching products. Evaporation under arid climatic conditions further enhances this process. However, in shallow aquifers, the correlation coefficients of fluoride with Mg ($r = 0.04$), HCO_3^- ($r = 0.19$), and TDS ($r = 0.16$) were notably weaker. The limiting factor for fluoride content

appears to be the increase in calcium concentration. The correlation between fluoride and calcium was weak in deep aquifers ($r = 0.16$) and even lower in shallow aquifers ($r = 0.01$). This is consistent with the solubility product of CaF_2 ($K_{sp} = 3.9 \times 10^{-11}$), which constrains the co-occurrence of fluoride and calcium.

The elevated fluoride concentrations in the shallow aquifers compared to the deep aquifers may also result from anthropogenic. The elevated fluoride concentrations in shallow aquifers may also result from anthropogenic inputs, such as mineral fertilizers, particularly phosphate fertilizers used in rural areas. Before the widespread use of natural gas (prior to 2020), hard coal was extensively used as domestic fuel. Coal combustion and ash deposition represent another significant source of environmental fluoride pollution.

The correlation analysis revealed a weak negative association between pH and all studied water constituents. However, given the relatively narrow pH range (6.73–8.15), this relationship is of limited significance.

SWOT analysis

Strengths	Weaknesses
Wide coverage: 63 sources across 38 settlements.	Very low fluoride in 90.5% of sources (risk of dental caries).
Use of international indices (WQI, DWNQI, FPI, HQ).	Low mineralization and poor nutritional value (low DWNQI).
No exceedances of WHO fluoride limits (low fluorosis risk).	High mineralization in private shallow wells.
First assessment of fluoride intake from tea in the region.	Single-season sampling (September–October).
Spatial maps support water-management decisions.	Lack of data on population consumption habits (mineral water, tea volume).
Opportunities	Threats
Possibility to introduce centralized fluoridation.	Population growth may increase pressure on aquifers.
Expansion of supply from deep, safer aquifers.	Climate change may increase evaporation and salinity.
Use of low-cost sorbents for water treatment.	Household waste and fertilizers may raise Na/Ca → enhance fluoride leaching.
Public health programs for fluoride deficiency.	Economic barriers for improving water infrastructure.
Creation of regional microelement monitoring system.	High tea consumption may raise HQ in children.

5. Conclusion

This study provides, for the first time, a comprehensive assessment of fluoride concentrations in the drinking water of the Sauran District, considering not only compliance with regulatory standards but also the outcomes of various water quality assessment tools. The results were compared with findings from other regions, which made it possible to identify both common patterns and specific regional features. In addition, the contribution of tea consumption to overall fluoride intake was evaluated for the first time in this district.

Chemical analysis of drinking water from 63 sources revealed no exceedances of national or WHO-recommended standards for fluoride content. Across all sources, fluoride concentrations ranged from 0.01 to 1.10 mg L^{-1} . In 90.5% of the sources, fluoride levels were below the optimal value of 0.7 mg L^{-1} , and in 38.1% they were extremely low ($< 0.3 \text{ mg L}^{-1}$). Optimal fluoride concentrations were found in only six sources (Sert, Ulgili, Yntymak, Kumtiym, Shipan, Aktobe), two of which (Kumtiym and Shipan) were unsuitable for drinking due to high mineralisation. According to the WQI,

20.6% of the sources were classified as “excellent”, 71.4% as “good”, and 7.9% as “poor”. Although the overall water quality was satisfactory, most sources had low nutritional value and did not meet the daily human requirement for fluoride, calcium, magnesium, and sodium. The DWNQI showed that 82.5% of the sources were in the “poor” category and 15.9% in the “unsatisfactory” category. Spatial analysis of the FPI identified a high-risk zone in the central part of the Sauran District, particularly in the suburbs of Turkistan city, where population density is greatest. Mean HQ values did not exceed 0.33 for children and 0.24 for adults. These results indicate not only the absence of non-carcinogenic risk but also a deficiency of daily fluoride intake, which increases the risk of dental caries and potentially other fluoride-deficiency-related conditions. This deficiency may be partly compensated by tea consumption. With a daily intake of 1.0 L of tea for adults and 0.5 L for children, CDI and HQ values increased; however, mean HQ values remained below 0.62 for children and 0.44 for adults.

Thus, the low fluoride content of drinking water represents

a significant public health concern, as tea consumption alone is insufficient to ensure adequate fluoride intake. Therefore, when assessing the suitability of drinking water sources, water management authorities should consider not only ionic composition but also the presence of essential trace elements at optimal concentrations. As centralised water fluoridation is not practised in the study region, the population is recommended to consume bottled medicinal mineral waters containing fluoride and to use fluoride-containing toothpaste on a regular basis.

This study was limited to the Sauran District; therefore, further large-scale investigations are required across the entire South Kazakhstan region, where detailed data on fluoride content remain scarce. Future studies should also address seasonal variations in fluoride concentrations in groundwater and potential changes associated with global climate trends. Moreover, it is important to assess the impact of fluoride on population health across different age groups and dietary patterns, as well as to evaluate the contribution of other food products in addition to tea. The findings of this research have practical significance for public health protection, rational water use, and sustainable regional development.

From a pragmatic standpoint, the results support the necessity for targeted monitoring of low-fluoride zones and community-level educational programs promoting optimal fluoride intake through diet or fluoridated products. The implementation of water management strategies that are specific to the region could result in a substantial improvement in dental health outcomes in the Sauran District.

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Conflict of Interest

There is no potential conflict of interest was reported by the author(s).

Supporting Information

Not applicable.

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