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The Health Effects of Fluoride and Nitrate in Drinking Water in Tunceli (Türkiye)

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Abstract: Fluoride (F^-) and nitrate (NO_3^-) are common inorganic constituents of drinking water and can cause significant public health effects when present at inadequate or excessive concentrations. This study determines the levels of fluoride and nitrate in drinking water collected from 18 stations across Tunceli Province, Türkiye, during 2021, and evaluates the non-carcinogenic health risks for four age groups (infants, children, adolescents, and adults). Fluoride and nitrate concentrations were measured using spectrophotometric methods and Estimated Daily Intake (EDI) and Hazard Quotient (HQ) values were calculated. Fluoride concentrations ranged from 0.06 to 0.31 mg L^{-1} and were below the WHO guideline value, with all HQ values <1. Nitrate concentrations varied more widely (0.45–64.38 mg L^{-1}), and exceedances of WHO limits were recorded at several rural stations. Infants and children exhibited HQ>1 values, indicating potential health risks associated with nitrate exposure. The findings highlight spatial heterogeneity in water quality across Tunceli and emphasize the need for age-specific monitoring programs and improved groundwater protection strategies.

Keywords: Drink water, Fluoride, Health risk assessment, Nitrate, Tunceli

Tunceli, Türkiye'de İçme Sularındaki Florür ve Nitratın Sağlık Üzerine Etkileri

Özet: Florür (F^-) ve nitrat (NO_3^-), içme sularında yaygın olarak bulunan ve hem eksik hem de aşırı maruziyet durumunda halk sağlığı açısından önemli riskler oluşturabilen bileşiklerdir. Bu çalışma, Tunceli ilindeki 18 istasyondan 2021 yılında alınan içme suyu örneklerinde florür ve nitrat düzeylerini belirlemekte ve dört yaş grubuna (bebekler, çocuklar, ergenler ve yetişkinler) yönelik kansere yol açmayan (non-carcinogenic) sağlık risklerini değerlendirmektedir. Konsantrasyonlar spektrofotometrik yöntemlerle analiz edilmiş; tahmini günlük alım (EDI) ve tehlike katsayısı (HQ) değerleri hesaplanmıştır. Florür seviyeleri 0.06–0.31 mg L^{-1} aralığında olup WHO (2017) sınır değerlerini aşmamıştır ve tüm HQ değerleri 1'in altında kalmıştır. Nitrat seviyeleri ise 0.45–64.38 mg L^{-1} aralığında değişmiş, bazı kırsal istasyonlarda WHO limitlerinin aşıldığı görülmüştür. Nitrat için bebek ve çocuklarda HQ>1 değerleri elde edilmiş ve bu durum hassas gruplarda potansiyel sağlık riski ortaya koymuştur. Sonuçlar, Tunceli'de içme suyu kalitesinin mekânsal değişkenlik gösterdiğini ve özellikle nitrat kaynaklı riskler için yaşa özgü izleme programları ile su kaynaklarının korunmasına yönelik stratejilerin önemini vurgulamaktadır..

Anahtar Kelimeler: İçme Suyu, Florür, Nitrat, Sağlık Riski Değerlendirmesi, Tunceli

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1. Introduction

Access to clean and safe drinking water is essential for public health and is widely recognized as a fundamental human right (Arcentales-Ríos et al., 2022; Ghani et al., 2022; Iqbal et al., 2023a). Reliance on groundwater for drinking purposes is particularly high in rural areas where alternative water sources are limited (Ullah et al., 2022a; Zhu et al., 2022). However, global climate variability and changing precipitation patterns are increasingly affecting both the quantity and quality of groundwater, placing additional stress on water supply systems, especially in economically vulnerable communities (Jat Baloch et al., 2021).

Fluoride contamination in groundwater typically originates from the prolonged interaction between water and fluoride-bearing rocks. Minerals such as fluorite (CaF_2) and apatite ($Ca_5(PO_4)_3F$) are highly susceptible to weathering, thereby elevating fluoride levels in groundwater (Iqbal et al., 2023b; Salve et al., 2008). These geochemical processes alter groundwater composition and may compromise its safety for human consumption. The National Research Council (NRC) has proposed age-specific guidelines for fluoride intake, ranging from 0.1–0.5 mg L^{-1} for infants to a maximum tolerance of 4 mg L^{-1} for adults (WHO, 2017). Prolonged exposure to high fluoride levels (>10 mg L^{-1}) has been linked to health problems such as hypertension, neurological disorders, reproductive complications, and skeletal deformities (Pitts et al., 2017; Bordoni, 2021). To balance protective and harmful effects, the WHO (2017) recommends maintaining fluoride concentrations in drinking water between 0.5 and 1.5 mg L^{-1}, with an optimal level of around 1.0 mg L^{-1} to prevent dental caries while minimizing the risk of fluorosis (Velez et al., 2023; Filho et al., 2021).

Like fluoride, nitrate is one of the most widespread contaminants in groundwater systems, mainly due to its high solubility and mobility. In recent decades, nitrate accumulation in drinking water has become a global environmental and public health concern. High nitrate levels are associated with adverse health outcomes, particularly among infants, including carcinogenic effects, hepatotoxicity, and methemoglobinemia (blue baby syndrome), a potentially life-threatening condition caused by reduced oxygen transport in the blood (Dehghani et al., 2018). Recent epidemiological evidence has also linked nitrate contamination to increased risks of certain cancers, reproductive disorders, and even diabetes. Outbreaks of waterborne diseases have been associated with nitrate-contaminated drinking water sources (Zhan et al., 2011; Qasemi et al., 2020), and nitrate enrichment in surface waters contributes to eutrophication and algal blooms, further degrading water quality (Lin, 2019). To mitigate these risks, many countries have established maximum allowable limits of 10 mg L^{-1} for nitrate-nitrogen (NO_3-N), equivalent to 50 mg L^{-1} nitrate (WHO, 2017; Mohsenibandpei et al., 2016). Agricultural runoff, septic system failures, landfill leachates, urban stormwater, livestock operations, and industrial effluents are among the main contributors to nitrate contamination (Bhatnagar et al., 2019; Amouei et al., 2012).

The Tunceli region of Eastern Anatolia, Turkey, is rich in surface water resources, including rivers, lakes, springs, mineral waters, and waterfalls (Kutlu et al., 2017). Both surface and groundwater systems are critical not only for drinking purposes but also for agricultural production and ecological balance. Nevertheless, data on the spatial distribution and health impacts of fluoride and nitrate in the region remain scarce. To address this gap, the present study investigates fluoride and nitrate concentrations in drinking water collected from 18 locations across Tunceli Province and evaluates the associated non-carcinogenic health risks. The findings are expected to provide a scientific basis for policymakers and support the design of effective, locally adapted water quality management strategies.

2. Materials and Methods

This study involved water quality assessment at 18 different sampling locations across Tunceli Province. These stations (St), labeled St1 to St18, are shown in Figure 1, while their precise names and GPS coordinates are listed in Table 1. Tap water samples were collected during 2021 using thoroughly cleaned high-density polyethylene (HDPE) containers to avoid contamination.

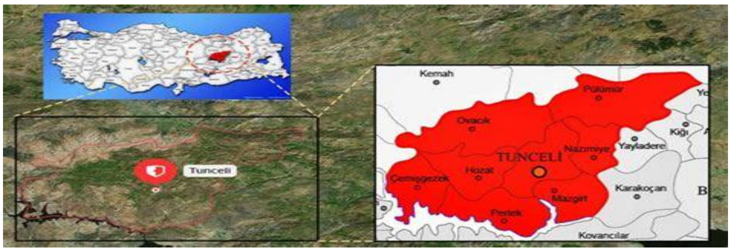

Figure 1. Location of the sampling stations in Tunceli Province.

Table 1. Sampling locations in Tunceli

Station	Village	District	Latitude (N)	Longitude (E)
St1	Hasan Gazi Village	Pülümür	39.45800°N	40.00131°E
St2	Hacılı Village	Pülümür	39.46800°N	39.95641°E
St3	Kopuzlar Village	Tunceli	38.99800°N	39.48945°E
St4	Karyemez	Tunceli	39.88900°N	39.46121°E
St5	Başakçı Village	Tunceli	39.03300°N	39.36889°E
St6	Geçimli Village	Tunceli	39.03200°N	39.26639°E
St7	Altınçevre Village	Tunceli	39.02700°N	39.24299°E
St8	Kızılkale Village	Tunceli	38.94600°N	39.75531°E
St9	Kavaktepe Village	Tunceli	38.96300°N	39.71958°E
St10	Beşoluk Village	Tunceli	38.97300°N	39.77384°E
St11	Gümüşgün Village	Tunceli	39.02000°N	39.67779°E
St12	Pertek	Tunceli	38.86700°N	39.32694°E
St13	Pertek	Tunceli	38.86700°N	39.32694°E
St14	Gövdeli Village	Tunceli	39.91200°N	39.11847°E
St15	Konaklar Village	Ovacık	39.35200°N	39.21639°E
St16	Arpaderen Village	Çemişgezek	39.01400°N	38.85926°E
St17	Cene Village	Çemişgezek	39.04200°N	38.91330°E
St18	Vişneli Village	Çemişgezek	39.01800°N	38.89690°E

Prior to sampling, the HDPE containers were washed with a non-phosphate detergent, rinsed with deionized water, soaked in 10% nitric acid for at least 24 hours, and finally rinsed three times with the water to be sampled. For nitrate analysis, samples were stored in dark containers at 4 °C and transported to the laboratory within 24 hours to minimize microbial degradation. For fluoride analysis, no specific preservation was required due to its stability; however, samples were also refrigerated and analyzed promptly. All sampling and handling procedures followed the Standard Methods for the Examination of Water and Wastewater (APHA, 2017).

Fluoride and nitrate concentrations were determined using a spectrophotometric approach with a Hach Lange DR 3900 spectrophotometer (320–1100 nm) and Hach Lange LCK 323 Cuvette Test Kits (Hach, Germany). Fluoride was quantified by the SPADNS colorimetric method (SM 4500-F^- D), which measures the absorbance of a red zirconium–fluoride complex at 570 nm. Nitrate was measured using the cadmium reduction method (SM 4500-NO_3^- E), in which nitrate is reduced to nitrite in a cadmium column, followed by a diazotization reaction that produces a pink azo dye measured at 543 nm.

To ensure analytical accuracy and precision, routine quality assurance and control protocols were applied. Duplicate samples were analyzed, with measurement errors ranging between 4% and 7%.

For health risk assessment, the study population was divided into four age groups: infants (<2 years), children (2–6 years), adolescents (6–16 years), and adults (>16 years). Daily fluoride exposure for each group was estimated using Equation (1), while non-carcinogenic risk was assessed using Hazard Quotient (HQ) (Equation (2); Yousefi et al., 2018). An HQ value < 1 indicates negligible risk, whereas HQ> 1 reflects a potential health risk, particularly fluorosis. The risk assessment framework is summarized in Table 2.

Table 2. In this research, multiple parameters were analyzed to assess potential health impacts from drinking water consumption (EPA, 1992)

Parameter	Risk exposure factors	Values for groups			
		Infant	Children	Teenagers	Adults
Fluoride	Cf mg L^{-1}	-	-	-	-
	Cd Ld^{-1}	0.08	0.85	2	2.5
	B kg	10	15	50	78
	RfD mg K^{-1} d^{-1}	0.06	0.06	0.06	0.06
Nitrate	Cf mg L^{-1}	-	-	-	-
	Cd L d^{-1}	0.08	0.85	2	2.5
	B Kg	10	15	50	78
	Rf D mg kg $^{-1}$ d^{-1}	16	1.6	1.6	1.6

EDI=$\frac{Cf*Cd}{Bx}$ (1)

HQ=$\frac{EDI}{Rf}$ (2)

To analyze the spatial variation of fluoride levels, variance was calculated using the non-parametric ranking method, the Wilcoxon rank sum test. A comprehensive quality control process was applied to all data used in the study. The Kolmogorov-Smirnov (K-S) and Shapiro-Wilk (S-W) tests were used to assess the normality of the fluoride datasets during the rainy season, depending on the size of the dataset.

For nitrate, the Estimated Daily Intake (EDI) and Hazard Quotient (HQ) were calculated using the following equations:

EDI (mg/kg/day) = (C × IR × EF × ED) / (BW × AT)

Where: C is the concentration of nitrate in drinking water (mg/L), IR is the ingestion rate (L/day), EF is the exposure frequency (days/year), ED is the exposure duration (years), BW is the body weight (kg), and AT is the averaging time (days).

HQ = EDI / RfD

Where: RfD for nitrate is 1.6 mg/kg/day, as recommended by the US EPA.

The nitrate concentrations were evaluated in relation to the World Health Organization (WHO) guideline, which sets a maximum permissible limit of 50 mg L^{-1} in drinking water, and the US EPA standard of 44 mg L^{-1}. Similarly, fluoride concentrations were assessed with respect to the WHO guideline range of 0.5–1.5 mg L^{-1} (optimal ~1.0 mg L^{-1}) and the maximum permissible limit of 1.5 mg L^{-1} established by both WHO and the US EPA.

3. Results

3.1 Fluoride

The spatial distribution of fluoride concentrations in drinking water is given in Table 3, together with the Estimated Daily Intake (EDI) and Hazard Quotient (HQ) values for four age groups. Graphical representations are shown in Figures 2 and 3.

Table 3. Fluoride concentrations, Estimated Daily Intake (EDI), and Hazard Quotient (HQ)

Station	F (mg/L)	EDI Infa	EDI Child	EDI Teena	EDI Adu	HQ Infar	HQ Childr	HQ Teena	HQ Adul
St1	0.08	0.0006	0.004	0.003	0.002	0.01	0.075	0.053	0.042
St2	0.06	0.0004	0.003	0.002	0.001	0.008	0.056	0.04	0.032
St3	0.06	0.0004	0.003	0.002	0.001	0.008	0.056	0.04	0.032
St4	0.25	0.002	0.014	0.014	0.008	0.033	0.236	0.166	0.133
St5	0.06	0.0004	0.003	0.002	0.001	0.008	0.056	0.04	0.032
St6	0.11	0.0008	0.006	0.004	0.003	0.014	0.103	0.073	0.058
St7	0.16	0.0012	0.009	0.006	0.005	0.021	0.151	0.106	0.085
St8	0.08	0.0006	0.004	0.003	0.002	0.01	0.075	0.053	0.042
St9	0.06	0.0004	0.003	0.002	0.001	0.008	0.056	0.04	0.032
St10	0.12	0.0009	0.006	0.004	0.003	0.016	0.113	0.08	0.064
St11	0.06	0.0004	0.003	0.002	0.001	0.008	0.056	0.04	0.032
St12	0.12	0.0009	0.006	0.004	0.003	0.016	0.113	0.08	0.064
St13	0.06	0.0008	0.006	0.004	0.003	0.014	0.103	0.073	0.058
St14	0.06	0.0008	0.0056	0.004	0.003	0.013	0.094	0.066	0.053
St15	0.11	0.0024	0.0175	0.012	0.009	0.041	0.292	0.206	0.165
St16	0.1	0.0004	0.0034	0.002	0.001	0.008	0.056	0.04	0.032
St17	0.31	0.002	0.014	0.01	0.008	0.033	0.236	0.166	0.133
St18	0.06	0.0008	0.0068	0.004	0.003	0.013	0.113	0.08	0.064
Min	0.06	0.0004	0.003	0.002	0.001	0.008	0.056	0.04	0.032
Max	0.31	0.0024	0.0175	0.014	0.009	0.041	0.292	0.206	0.165
Mean	0.1	0.0008	0.006	0.004	0.003	0.014	0.102	0.072	0.058

The Estimated Daily Intake (EDI) values for fluoride ranged approximately from 0.0004 to 0.0024 mg/kg/day across the sampling stations, with children exhibiting the highest exposure levels among the age groups. Corresponding HQ values were 0.01437 for infants, 0.010284 for children, 0.072593 for adolescents, and 0.058167 for adults (Figure 2).

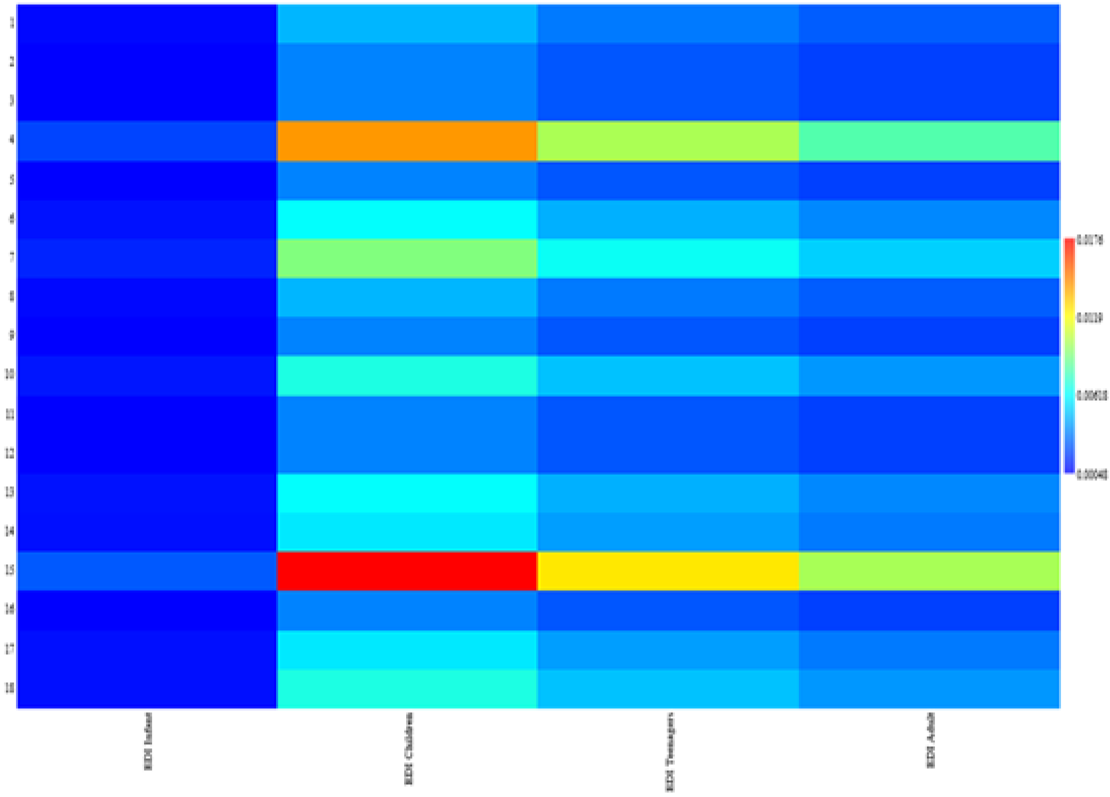

Figure 2. Estimated Daily Intake (EDI) of fluoride for four age groups in Tunceli

The highest HQ was observed in children (P95 = 0.10), which is below the non-carcinogenic risk threshold (HQ = 1). Figure 3 indicates mean HQ values of 0.14 (infants), 0.07 (adolescents), and 0.05 (adults) (Figure 3).

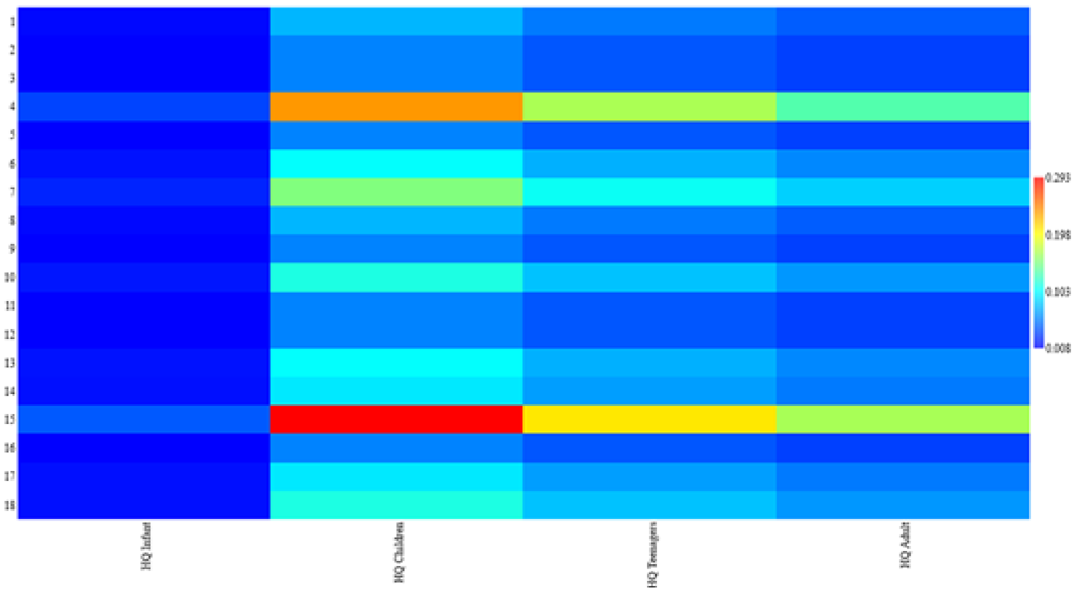

Figure 3. Hazard Quotient (HQ) values for fluoride exposure for four age groups in Tunceli

3.2 Nitrate

Nitrate concentrations measured in 2021 ranged from 0.45 to 64.38 mg/L (Table 4). Only Station 16 exceeded the WHO permissible limit of 50 mg/L.

Table 4. Nitrate concentrations, Estimated Daily Intake (EDI), and Hazard Quotient (HQ)

Station	NO3 (mg	EDI Infar	EDI Child	EDI Teena	EDI Adu	HQ Infar	HQ Childr	HQ Teenag	HQ Adul
St1	0.45	0.0006	0.025	0.018	0.014	0.002	0.015	0.011	0.009
St2	1.02	0.0014	0.056	0.04	0.032	0.637	0.637	0.025	0.02
St3	1.62	0.0022	0.091	0.064	0.051	1.012	1.012	0.04	0.032
St4	1.22	0.0016	0.069	0.048	0.039	0.762	0.762	0.03	0.024
St5	6.51	0.0087	0.368	0.26	0.208	4.068	4.068	0.162	0.13
St6	5.1	0.0068	0.289	0.204	0.163	3.187	3.187	0.127	0.102
St7	4.19	0.0056	0.237	0.167	0.133	2.618	2.618	0.104	0.083
St8	5.88	0.0079	0.332	0.235	0.188	3.675	3.675	0.147	0.117
St9	14.34	0.0192	0.819	0.573	0.458	8.962	8.962	0.358	0.287
St10	1.86	0.0025	0.105	0.074	0.059	1.162	1.162	0.046	0.037
St11	1.2	0.0016	0.068	0.048	0.038	0.75	0.75	0.03	0.024
St12	21.4	0.0286	1.212	0.856	0.684	13.37	13.37	0.535	0.428
St13	15.41	0.0206	0.873	0.614	0.492	9.631	9.631	0.382	0.308
St14	7.84	0.0105	0.444	0.31	0.248	4.9	4.9	0.196	0.157
St15	49.98	0.067	2.832	1.999	1.6	31.23	31.23	1.249	1.0
St16	64.38	0.0862	3.648	2.575	2.06	40.23	40.23	1.609	1.289
St17	7.03	0.0094	0.398	0.281	0.228	4.393	4.393	0.175	0.14
St18	7.27	0.0097	0.411	0.29	0.234	4.543	4.543	0.181	0.145
Min	0.45	0.0006	0.025	0.018	0.014	0.002	0.015	0.011	0.009
Max	64.38	0.0862	3.648	2.575	2.06	40.23	40.23	1.609	1.289
Mean	12.04	0.0153	0.682	0.481	0.385	7.508	7.509	0.3	0.241

Nitrate EDI values ranged from 0.0006 to 0.0862 mg/kg-day in infants, with mean values of 0.682 mg/kg-day for children, 0.481 mg/kg-day for teenagers, and 0.385 mg/kg-day for adults (Figure 4).

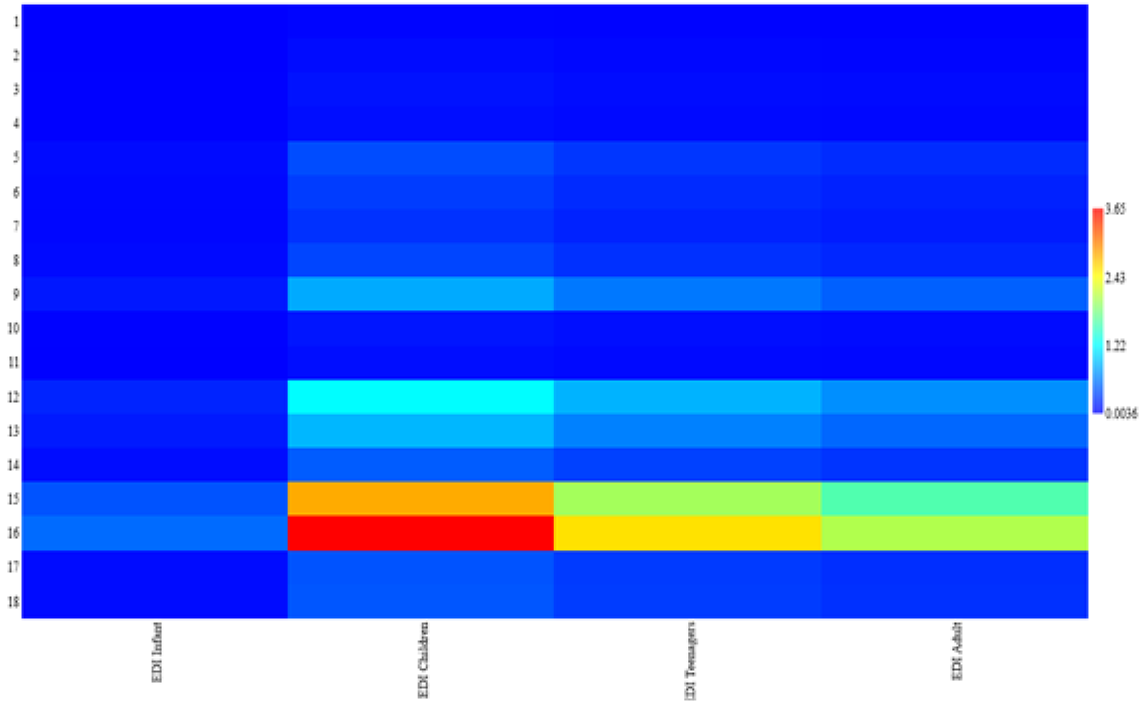

Figure 4. Estimated Daily Intake (EDI) of nitrate for four age groups in Tunceli

The Hazard Quotient (HQ) values for nitrate varied from 0.002 to 40.23 for infants, 0.015 to 40.23 for children, 0.011 to 1.609 for teenagers, and 0.009 to 1.289 for adults, reflecting substantial variability in exposure risk across the sampling stations, indicating potential non-carcinogenic risks in some rural areas (Figure 5).

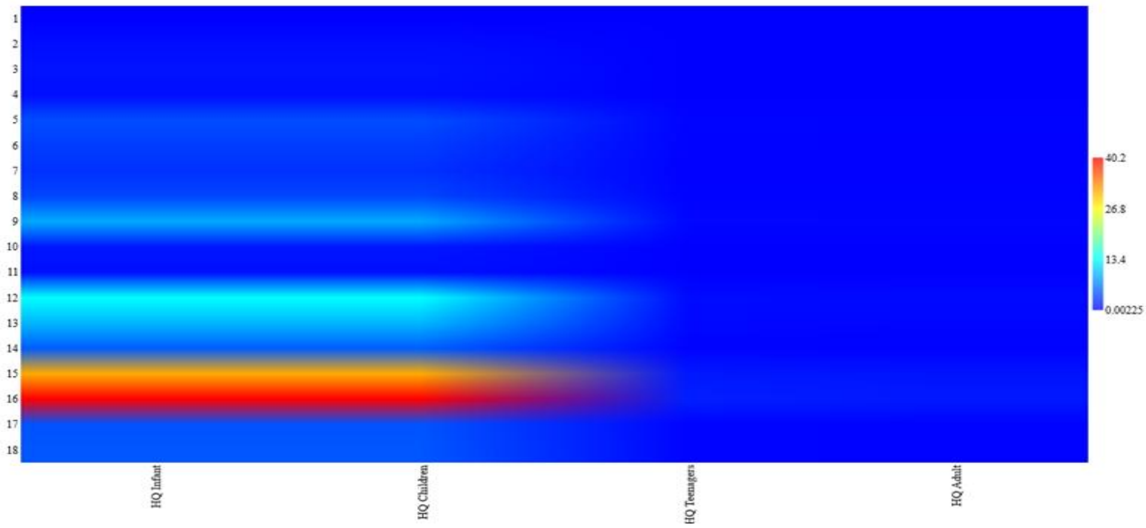

Figure 5. Hazard Quotient (HQ) values nitrate exposure for four age groups in Tunceli

4. Discussion

Children exhibited the highest susceptibility to fluoride exposure, which is consistent with their physiological development, including incomplete skeletal ossification (Wang et al., 2020; Guissouma et al., 2017). Fluoride mobility in groundwater is influenced by pH, temperature, anion exchange, and Ca^{2+}/HCO_3^- balance (Yidana et al., 2012). Its high solubility enables significant variation even within small hydrogeological zones (Zango et al., 2021). "Variations in geological formations and salinity levels can substantially influence groundwater chemistry, leading to rapid changes in water quality in many regions of Eastern Anatolia (Dehghani et al., 2019)."

Globally elevated fluoride levels have been reported in Chile, Argentina, the Middle East, Asia, and parts of Europe (Brindha & Elango, 2011; Abanyie et al., 2023). In Türkiye, fluoride concentrations vary regionally and maintaining concentrations within 0.5–1.0 mg/L is considered optimal for dental health while preventing fluorosis (Tokatlı & Güner, 2020).

Excessive fluoride intake is strongly associated with dental fluorosis, while insufficient intake increases the risk of dental caries (Rasool et al., 2017; Aslani et al., 2019). As drinking water constitutes the primary exposure pathway, routine monitoring, risk mapping, public awareness, and local mitigation strategies are essential. Additionally, elevated fluoride can adversely impact aquatic ecosystems (Iqbal et al., 2023b; Talpur et al., 2020). Previous studies have shown that the spatial distribution of fluoride and other ions in groundwater is strongly controlled by regional hydrogeochemical processes (Guo et al., 2012). Fluoride concentrations often exhibit considerable spatial and temporal uncertainty, highlighting the need to incorporate local variability into health risk assessments (Ijumulana et al., 2021).

Although nitrate concentrations in most stations of Tunceli remained within the World Health Organization (WHO) guideline value, localized exceedances—particularly at Station 16—indicate potential risks for certain communities. Infants and children were the most affected age groups, as reflected by their higher EDI and HQ values. This increased sensitivity is associated with their lower body weight, higher water consumption per kilogram of body mass, and limited metabolic capacity to detoxify ingested nitrate. “Due to its high solubility and mobility, nitrate can easily migrate through groundwater systems, and its removal using conventional treatment methods remains challenging (Bhatnagar & Sillanpää, 2011). Nitrate contamination has been widely documented in agricultural regions, where elevated levels pose potential health risks, particularly for vulnerable age groups (Zhai et al., 2017).

The presence of HQ values exceeding 1 at several rural stations (Stations 5–10 and 12–18) suggests that nitrate exposure may pose non-carcinogenic health risks for sensitive populations. These findings align with international studies reporting similar concerns in rural or agricultural regions. For instance, Chen et al. (2017) documented nitrate levels of 2.66–103 mg/L in northwestern China, many exceeding WHO limits. Arumi et al. (2006) observed HQ values up to 3.1 in infants in Chile, while Sadler et al. (2016) identified HQ_{95} values above 1.0 for Indonesian communities relying on unprotected groundwater sources. Mohammadi et al. (2017) reported that nitrate concentrations in Bandar-e Gaz, Iran, were mostly within acceptable limits, reflecting substantial regional variability.

The spatial heterogeneity observed in Tunceli is likely influenced by topography, agricultural activities, livestock waste, and surface–groundwater interactions. Elevated nitrate levels in rural areas may reflect fertilizer use, manure leaching, or seasonal runoff. Furthermore, the Karstic and fractured geological structure in parts of the region may facilitate the rapid transport of nitrate into groundwater, increasing contamination risks during rainfall or snowmelt periods.

Overall, the results indicate that nitrate contamination in Tunceli is not a widespread issue, but localized hotspots require urgent attention—particularly where vulnerable populations rely on untreated groundwater. Establishing regular monitoring programs, reducing agricultural nitrogen inputs, protecting recharge zones, and improving sanitation and livestock management practices would significantly reduce exposure risks. Public awareness campaigns targeting households that rely on well water may also contribute to reducing nitrate-related health impacts.

5. Conclusion

This study provides a comprehensive assessment of fluoride and nitrate levels in drinking water across Tunceli and its surrounding settlements, revealing substantial spatial and demographic variations in exposure and potential health risks. Fluoride concentrations ranged between 0.06–0.31 mg/L, while nitrate levels varied from 0.0025 to 64.38 mg/L. Although most samples complied with international guideline values, specific stations—particularly Station 16 for nitrates showed elevated concentrations that may pose a concern for sensitive populations.

Health risk assessment demonstrated that children are the most susceptible group to fluoride exposure, whereas infants and children exhibited the highest vulnerability to nitrate, with HQ values exceeding 1 in several rural locations. These outcomes emphasize the importance of considering age-specific physiological differences when evaluating exposure risks.

The observed spatial heterogeneity in water quality likely reflects underlying hydrogeochemical processes, agricultural practices, livestock activities, and seasonal hydrological dynamics. The combined influence of these factors highlights the need for continuous monitoring, localized mitigation strategies, and integrated watershed management approaches to ensure safe drinking water supplies.

Overall, the findings underscore the critical importance of strengthening water quality surveillance programs, enhancing public awareness, and implementing environmentally sustainable resource management practices.

Coordinated, multidisciplinary efforts at regional and national levels are essential to safeguard public health, protect aquatic ecosystems, and promote long-term sustainability of drinking water resources in Tunceli and comparable regions.

6. Acknowledgement

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7. Compliance with Ethical Standard

a) Author Contributions

1. Banu KUTLU: Conceptualization, process, software, verification, formal analysis, research, materials, composing the first draft, composing the review, and editing,
2. Serdar ÇETİNDAĞ.: Conceptualization, process, software, verification, formal analysis, and oversight. The published version of the manuscript has been read and approved by both authors.

b) Conflict of Interests

There is no conflict of interest, according to the authors.

c) Statement on the Welfare of Animals

Not relevant,

d) Statement of Human Rights

There are no human subjects in this study.

e) Declaration of Not Using AI

f) Funding

8. References

Abanyie, S. K., Apea, O. B., Abagale, S. A., Amuah, E. E. Y., & Sunkari, E. D. (2023). Sources and factors influencing groundwater quality and associated health implications: A review. Emerging Contaminants, 100207. https://doi.org/10.1016/j.emcon.2023.100207

Arcentales-Ríos, R., Carrión-Méndez, A., Cipriani-Ávila, I., Acosta, S., Capparelli, M., Moulatlet, G., & Pinos-Vélez, V. (2022). Assessment of metals, emerging contaminants, and physicochemical characteristics in drinking water and wastewater of Cuenca, Ecuador. Journal of Trace Elements and Minerals, 2, 100030. https://doi.org/10.1016/j.jtemin.2022.100030

Arumi, J. L., Núñez, J., Salgado, L., & Claret, M. (2006). Risk analysis of nitrate contamination in wells supplying drinking water in a rural area of Chile. Revista Panamericana de Salud Pública, 20(6), 385–392. https://doi.org/10.1590/s1020-49892006001100004

Aslani, H., Zarei, M., Taghipour, H., Khashabi, E., Ghanbari, H., & Ejlali, A. (2019). Monitoring, mapping and health risk assessment of fluoride in drinking water supplies in rural areas of Maku and Poldasht, Iran. Environmental Geochemistry and Health. https://doi.org/10.1007/s10653-019-00282-x

Bhatnagar, A., & Sillanpää, M. (2011). A review of emerging adsorbents for nitrate removal from water. Chemical Engineering Journal, 168(2), 493–504. https://doi.org/10.1016/j.cej.2011.01.103

Bordoni, N. E., Salgado, P. A., & Squassi, A. F. (2021). Comparison between indexes for diagnosis and guidance for treatment of dental caries. Acta Odontológica Latinoamericana, 34, 289–297. https://doi.org/10.54589/aol.34/3/289

Brindha, K., Rajesh, R., Murugan, R., & Elango, L. (2011). Fluoride contamination in groundwater in parts of Nalgonda District, Andhra Pradesh, India. Environmental Monitoring and Assessment, 172, 481–492. https://doi.org/10.1007/s10661-010-1348-0

Chen, J., Wu, H., Qian, H., & Gao, Y. (2017). Assessing nitrate and fluoride contaminants in drinking water and their health risks. Exposure and Health, 9, 183–195. https://doi.org/10.1007/s12403-016-0231-9

Dehghani, M. H., Asghari, F. B., & Yousefi, M. (2019). Effect of salt basins on groundwater quality changes in Tabriz Plain. Desalination and Water Treatment, 137, 403–411. https://doi.org/10.5004/dwt.2019.22991

EPA. (1992). Framework for Ecological Risk Assessment. U.S. Environmental Protection Agency.

Filho, A. P. R., Chávez, B. A., Giacaman, R. A., Frazão, P., & Cury, J. A. (2021). Community interventions and strategies for caries control in Latin America and the Caribbean. Brazilian Oral Research, 35, 1–17. https://doi.org/10.1590/1807-3107bor-2021.vol35.0054

Ghani, J., Ullah, Z., Nawab, J., Iqbal, J., Waqas, M., Ali, A., … Shah, M. (2022). Hydrogeochemical characterization and suitability assessment of drinking groundwater. Frontiers in Environmental Science, 10, 874464. https://doi.org/10.3389/fenvs.2022.874464

Guissouma, W., Hakami, A., Al-Rajab, A. J., & Tarhouni, J. (2017). Risk assessment of fluoride exposure in drinking water of Tunisia. Chemosphere, 177, 102–108. https://doi.org/10.1016/j.chemosphere.2017.03.011

Guo, H., Zhang, Y., Xing, L., & Jia, Y. (2012). Spatial variation in arsenic and fluoride concentrations of shallow groundwater. Applied Geochemistry, 27(11), 2187–2196. https://doi.org/10.1016/j.apgeochem.2012.01.016

Ijumulana, J., Ligate, F., Irunde, R., Bhattacharya, P., Maity, J. P., Ahmad, A., & Mtalo, F. (2021). Spatial uncertainties in fluoride levels and health risks. Groundwater for Sustainable Development, 14, 100618. https://doi.org/10.1016/j.gsd.2021.100618

Iqbal, J., Amin, G., Su, C., Haroon, E., & Baloch, M. Y. J. (2023a). Assessment of landcover impacts on groundwater quality. Environmental Science and Pollution Research, 1–21. https://doi.org/10.21203/rs.3.rs-2771650/v1

Iqbal, J., Su, C., Wang, M., Abbas, H., Baloch, M. Y. J., Ghani, J., Huq, M. (2023b). Groundwater fluoride and nitrate contamination. Environmental Science and Pollution Research, 1–20. https://doi.org/10.1007/s11356-023-25958-x

Iqbal, J., Su, C., Rashid, A., Yang, N., Baloch, M. Y. J., Talpur, S. A., … Sajjad, M. M. (2021). Hydrogeochemical assessment of groundwater. Water, 13(24), 3589. https://doi.org/10.3390/w13243589

Jannat, J. N., Khan, M. S. I., Islam, H. T., Islam, M. S., Khan, R., Siddique, M. A. B., & Islam, A. R. M. T. (2022). Hydro-chemical assessment of fluoride and nitrate. Journal of Cleaner Production, 372, 133675. https://doi.org/10.1016/j.jclepro.2022.133675

Jat Baloch, M. Y., Zhang, W., Chai, J., Li, S., Alqurashi, M., Rehman, G., Munir, M. (2021). Shallow groundwater quality assessment. Water, 13(23), 3361. https://doi.org/10.3390/w13233361

Kutlu, B., Özcan, G., & Özcan, T. (2017). Tunceli İli Su Kaynakları ve Özellikleri. Munzur Üniversitesi Yayınları.

Lin, K., Zhu, Y., Zhang, Y., & Lin, H. (2019). Determination of ammonia nitrogen in natural waters: Recent advances and applications. Trends in Environmental Analytical Chemistry, 24, e00073. https://doi.org/10.1016/j.teac.2019.e00073

Mohammadi, A. A., Yaghmaeian, K., Hossein, F., Nabizadeh, R., Dehghani, M. H., Khaili, J. K., & Mahvi, A. H. (2017). Temporal and spatial variation of chemical parameters in drinking water. Desalination and Water Treatment, 68, 170–176. https://doi.org/10.5004/dwt.2017.20341

Mohsenibandpei, A., et al. (2016). Water solution polishing of nitrate using potassium permanganate modified zeolite. Global NEST Journal, 18(3). https://doi.org/10.30955/gnj.001833

Pitts, N. B., Zero, D. T., Marsh, P. D., Ekstrand, K., Weintraub, J. A., & Ramos-Gomez, F. (2017). Dental caries. Nature Reviews Disease Primers, 3, 17030. https://doi.org/10.1038/nrdp.2017.30

Qasemi, M., Farhang, M., Morovati, M., Mahmoudi, M., Ebrahimi, S., Abedi, A., … Ghaderpoury, A. (2020). Human health risks from fluoride and nitrate. International Journal of Environmental Analytical Chemistry, 102(2), 307–318. https://doi.org/10.1080/03067319.2020.1720668

Rasool, A., Farooqi, A., Xiao, T., Ali, W., Noor, S., & Abiola, O. (2017). Fluoride contamination in groundwater: A global perspective. Environmental Geochemistry and Health, 40, 1–17. https://doi.org/10.1007/s10653-017-0054-z

Sadler, R., Maetam, B., Edokpolo, B., Connell, D., Yu, J., Stewart, D., & Laksono, B. (2016). Health risk assessment for nitrate in village wells. Environmental Pollution, 216, 738–745. https://doi.org/10.1016/j.envpol.2016.06.041

Salve, P., Maurya, A., Kumbhare, P., Ramteke, D., & Wate, S. (2008). Assessment of groundwater quality with respect to fluoride. Bulletin of Environmental Contamination and Toxicology, 81, 289–293. https://doi.org/10.1007/s00128-008-9466-x

Saxena, S., Sahay, A., & Goel, P. (2012). Effect of fluoride exposure on intelligence of school children. Journal of Neurosciences in Rural Practice, 3, 144–149. https://doi.org/10.4103/0976-3147.98213

Talpur, S. A., Noonari, T. M., Rashid, A., Ahmed, A., Jat Baloch, M. Y., Talpur, H. A., & Soomro, M. H. (2020). Hydrogeochemical signatures and suitability assessment of groundwater with elevated fluoride. SN Applied Sciences, 2, 1–15. https://doi.org/10.1007/s42452-020-2821-1

Tokatlı, C., & Güner, Ş. (2020). Fluoride levels in drinking water and water quality assessment. Acta Aquatica Turcica, 16(2), 238–245. https://doi.org/10.22392/actaquatr.644087

Ullah, Z., Rashid, A., Ghani, J., Nawab, J., Zeng, X.-C., Shah, M., … Iqbal, J. (2022). Groundwater contamination through potentially harmful metals. Frontiers in Environmental Science, 10, 1021596. https://doi.org/10.3389/fenvs.2022.1021596

Vélez León, E. M., Albaladejo Martínez, A., Preciado Sarmiento, M. A., Cordero López, M. A., Armas, A. del C., & Encalada Verdugo, L. S. (2023). Caries experience in preschoolers. Children, 10(7), Article 4. https://doi.org/10.3390/children10071123

Wang, M., Liu, L., Li, H., Li, Y., Liu, H., Hou, C., Wang, A. (2020). Thyroid function, intelligence and low–moderate fluoride exposure. Environment International, 134, 105229. https://doi.org/10.1016/j.envint.2019.105229

WHO. (2017). Guidelines for Drinking-Water Quality (4th ed.). World Health Organization.

Yidana, S. M., Ophori, D., Banoeng-Yakubo, B., & Samed, A. A. (2012). Hydrochemistry and fluoride enrichment causes. ARPN Journal of Engineering and Applied Sciences, 7(1), 50–68.

Yousefi, M., Ghoochani, M., & Mahvi, A. H. (2018). Health risk assessment to fluoride. Ecotoxicology and Environmental Safety, 148, 426–430. https://doi.org/10.1016/j.ecoenv.2017.10.057

Zango, M. S., Pelig-Ba, K. B., Anim-Gyampo, M., & Gibrilla, A. (2021). Hydrogeochemical and isotopic controls on fluoride sources. Groundwater for Sustainable Development, 12, 100526. https://doi.org/10.1016/j.gsd.2020.100526

Zhai, Y., Zhao, X., Teng, Y., Li, X., Zhang, J., Wu, J., & Zuo, R. (2017). Groundwater nitrate pollution and health risk assessment. Ecotoxicology and Environmental Safety, 137, 130–142. https://doi.org/10.1016/j.ecoenv.2016.11.010

Zhu, M., Wang, J., Yang, X., Zhang, Y., Zhang, L., Ren, H., & Wu, B. (2022). Machine learning in water quality evaluation. Eco-Environment & Health, 1(2), 107–116. https://doi.org/10.1016/j.eehl.2022.06.001