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Water governance and population health: Evaluating the efficacy of drinking water standards in Angren, Uzbekistan

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Abstract

Ensuring safe drinking water that meets both hydrochemical and physiological standards remains a key environmental challenge. In industrial regions, evaluating local water sources against international criteria is essential to identifying hidden risks to public health. This study investigates the hydrochemical characteristics of surface and groundwater in Angren, Uzbekistan, and evaluates their specific impact on public health within the framework of national and international safety standards. The salt composition formulas of the water samples were determined, and corresponding Piper diagrams were generated. It was also found that the fluorine content in samples taken from Angren water is much lower than the norm, which may cause several issues for public health. A statistical hypothesis test was conducted to scientifically substantiate the correctness of this idea. The low fluorine content was analyzed in relation to World Health Organization data. Suggestions and recommendations were made to eliminate problems related to the impact of the fluorine element in water below the norm on public health. Although the surface and groundwater in Angren were considered suitable for consumption, some physiological deficiency in essential ions was discovered. The study recommends the adoption of Community Water Fluoridation and systemic mineralization strategies aligned with the "Uzbekistan-2030" strategy to mitigate these long-term public health risks.

Keywords: Health geography; Nosogeography; Public health; Water quality; Spatiotemporal analysis

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1. Introduction

While extensive global literature addresses water quality and public health,[1] significant knowledge gaps remain regarding regional nosogeographical patterns in arid and semi-

arid piedmont basins of Central Asia.[2] Previous regional studies have predominantly focused on macro-scale hydrochemical classifications or general transboundary river basin management,[3] often overlooking the localized health impacts of chronic mineral imbalances in drinking water supplies—such as specific ionic deficiencies or localized mineralization anomalies typical of foothill zones.[4,5] Unlike prior broad-scale assessments, the incremental contribution of this study lies in establishing a rigorous localized framework that links hydrochemical indicators, Piper classifications, and statistical validation with specific public health risks in an industrial-mining piedmont hub (Angren). By integrating localized water quality monitoring with regional health assessments, this study bridges the gap between regional environmental hydrochemistry and specific public health vulnerabilities in Central Asian urban-industrial ecosystems, offering a targeted methodological framework previously unexplored in regional literature.

Water quality studies are also important in the nosogeographic study of public health. An excess of nitrates in water leads to hemoglobinemia in children.[6] An increase in ammonia leads to an exacerbation of intestinal diseases.[7] An excess of sulfates leads to gastrointestinal diseases.[8] When assessing water quality, attention is paid to its microbiological, physical, and chemical properties.[9] Water analysis can be carried out using modern instrumental methods.[10] Water quality control is of urgent importance all over the world, including in the Republic of Uzbekistan, according to Decree No. PF-21 of the President of the Republic of Uzbekistan dated February 16, 2026, measures were adopted to consistently continue reforms and advance the "Uzbekistan-2030" strategy.[11]

This article discusses the impact of surface and groundwater quality in Angren on public health. The city of Angren, where we are conducting our research, is located in the Tashkent region, one of the 12 regions of the Republic of Uzbekistan (**Figure 1**). Angren is one of the largest industrial cities in the Tashkent region. Angren is located in a natural geographical location between the Chatkal and Kurama mountain ranges, on the right bank of the Akhangaron River valley. The average altitude above sea level is 900–960 m.[12] Situated within the piedmont zone of the Chatkal–Kurama mountain system, the hydrogeological framework of the Angren region is characterized by complex geological origins that dictate its water chemistry. The local aquifer systems primarily comprise Quaternary alluvial-proluvial deposits and fractured Paleozoic bedrock formations, where groundwater recharge is predominantly driven by seasonal snowmelt and precipitation from the surrounding mountain ranges, transitioning through active subsurface runoff toward regional discharge zones. Crucially, the lithological background of the Chatkal–Kurama metallogenic belt—dominated by igneous, metamorphic, and carbonate rocks with specific mineralogical compositions—naturally lacks sufficient fluoride-bearing minerals (such as fluorite, micas, or apatites) capable of releasing significant fluoride into aqueous solutions. This specific lithological and geochemical setting constitutes the primary hydrogeological prerequisite governing the naturally low fluoride concentrations observed in both surface and groundwater across the region, an aspect that has largely remained unaddressed in prior local environmental assessments. The important Tashkent–Osh (A-373) highway, connecting the central part of Uzbekistan with the Fergana Valley, passes through Angren.[13] The Angren–Pop electrified railway also passed through this city.

Initially, water samples were taken from the Dukentsoy and Qorabovsoy streams and from the Appartak sanatorium in Angren, and a chemical analysis of the water was conducted in the laboratory. In the first part of the article, based on the results of the chemical analysis of three water samples, the amount of chemical elements in the water was determined and compared with the normative indicators. At the same time, the salt composition formula was also determined for each water sample and a Piper diagram was drawn up. A significantly low amount of fluorine was found in water samples taken from three parts of Angren. In order to gain confidence that fluorine is indeed much lower than the norm, a statistical hypothesis test was conducted. The results of the statistical hypothesis test also proved that fluorine is less than the norm.

The low fluoride content was analyzed based on World Health Organization (WHO) data, and its impact on public health was considered.[14] Suggestions and recommendations were made to improve the nosogeographic problems associated with fluorine deficiency. In the next part of the article, the amount of chemical elements in the samples was compared with the norm through chemical analysis of water samples taken from two observation wells of the groundwater of the city of Angren. The salt composition of water samples from the two wells was determined, and a Piper diagram was drawn. The impact of groundwater on public health was considered. Based on all the collected data and analyses, it was determined that the water of the city of Angren is suitable for consumption. As a result of the analyses conducted on all water samples, we can assume that the water of the city of Angren does not contain harmful compounds that pose a serious threat to public health. However, it would be appropriate to pay attention

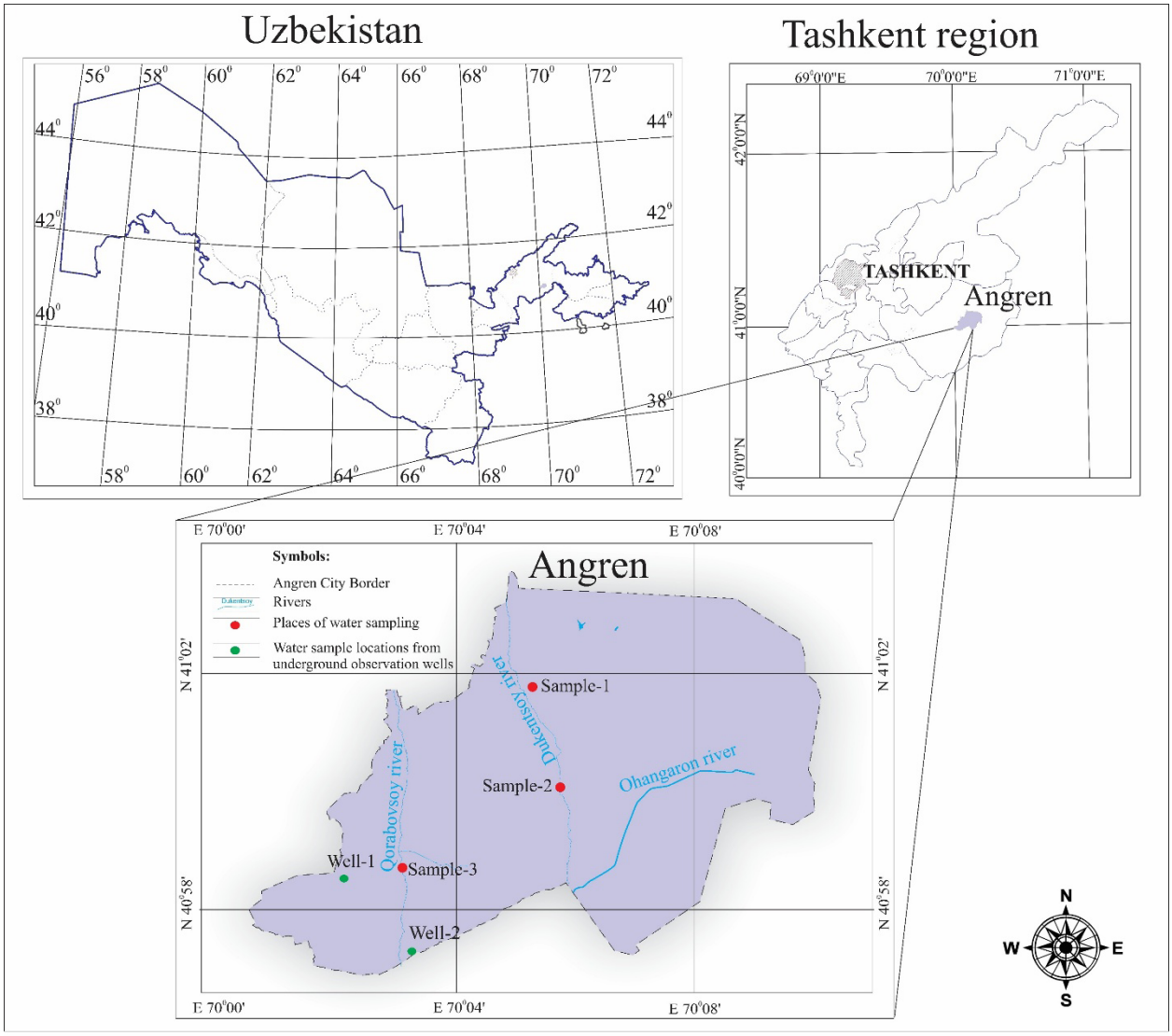


Figure 1. The visual map of the location of the study area and locations of water samples taken for water-chemical analysis and underground observation wells in the city of Angren. Source: Map created by the authors.

to the problems associated with fluorine deficiency and take preventive measures.

The analysis of surface and groundwater samples across the Angren region, specifically from the Appartak sanatorium, Qorabovsoy, and Dukentsoy, revealed that cation concentrations remain well below established normative indicators. Hydrochemical classification identified the Appartak surface water and the second groundwater monitoring well as calcium-magnesium hydrocarbon type, while the Qorabovsoy and Dukentsoy samples were characterized as calcium-hydrocarbon water. The first groundwater monitoring well was uniquely identified as calcium-sodium hydrocarbon water.

Critically, while both surface and groundwater sources are chemically suitable for public consumption regarding mineral limits, fluoride levels were found to be significantly lower than required health standards across all sampling sites. This deficiency suggests that the primary impact of water quality on public health in the Angren region is not toxicological, but rather linked to the long-term risks associated with low fluoride intake.

2. Related work

Several studies on the impact of drinking water on human

health and their interrelationships highlighted how water quality directly affects the human body and its organs.[15-17] There are also studies on the classification of water quality and related diseases, which are divided into groups such as waterborne diseases, water scarcity diseases, water-based diseases, water-related diseases, and waterborne infectious diseases.[18] Some studies focus on the impact of water quality on health in rural areas.[19,20] Studies on water quality also analyzed the level of compliance of water with sanitary and hygienic requirements in regions of the world.[21,22]

Knowledge of water pollutants is essential in water quality research. According to established scientific classifications, pollutants are generally categorized into five primary groups: infectious agents (bacteria, viruses, and protozoa), organic chemicals (oils, dyes, and pesticides), inorganic substances (acids, salts, and heavy metals), radioactive materials, and eroded sediments such as soil and silt.[23]

3. Methods

In this section, we provide an account of the methodological framework employed to evaluate the intersection of hydrochemistry and population health in Angren. To methodologically evaluate the contribution of local water quality to the United Nations Sustainable Development Goals (SDGs)—specifically Target 6.1 (achieving universal and equitable access to safe and affordable drinking water) and Target 3.9 (substantially reducing the number of deaths and illnesses from hazardous chemicals and pollution)—the hydrochemical parameters were benchmarked against national (UzDSt 950:2011) and international (WHO 2022[14]) potability thresholds. Chemical compliance ratios and health risk indicators (e.g., fluoride deficiency margins) were calculated across all sampling sites to quantitatively assess drinking water safety and potential public health vulnerabilities in the Angren region.

We detailed the sampling sites and procedures, laboratory instrumentation, and analytical standards. We described the analytical protocols for chemical assessment, statistical hypothesis testing, and the use of Piper diagrams for hydrochemical facies classification.

3.1. Sampling procedures and analytical protocols

Water samples were collected from a groundwater source (35 m deep) located in the Appartak sanatorium in Angren city, from the Dukentsoy and Karabovsoy streams (Figure 1). The samples were collected in sterilized 1.5 L bottles. Prior to sample collection, high-density polyethylene 1.5 L bottles were thoroughly rinsed three times with the target source water. During field collection, physical parameters such as water temperature and pH were preliminarily recorded. All collected samples were stored in portable cool boxes maintained at approximately 4 °C and transported to the laboratory within 24 hours to prevent biological and chemical alterations. Samples for groundwater analysis were taken from two active monitoring wells operated by the state hydrogeological services. The chemical composition was determined in the "Geoecologist-Chemistry" laboratory of the "Institute of Hydrogeology and Engineering Geology" using the state standard UzDSt 950:2011.

The first water sample was collected at the Appartak sanatorium, where the water originates from 35 m underground. This water is used as drinking water by patients undergoing treatment at the Appartak sanatorium and the local population. For this reason, it is meaningful to chemically analyze this water sample and assess its impact on the health of the population. The second water sample was collected from the Dukentsoy stream because the local population around Dukentsoy uses the stream water for local needs, crop irrigation, and drinking water. The third water sample was collected from the Qorabovsoy stream, which is mainly used for the irrigation of crops.

Water samples were subjected to a series of chemical analyses. Titrimetry was used to determine the content of hydrocarbons and calcium, and spectrophotometry was used to determine the concentration of nitrates, nitrites, and ammonium ions. Potentiometry with ion-selective electrodes was used for precise pH and fluoride measurements. Gravimetric analysis was performed to determine dry residue and total mineralization:

- Titrimetry: Used to determine hydrocarbon content and calcium. Bicarbonate (HCO_3^-) was measured via acid-base titration (0.1 N HCl), while calcium (Ca^{2+}) and total hardness were determined using complexometric ethylenediaminetetraacetic acid titration.
- Ultraviolet–visible light spectrophotometry was used to quantify:
  - Nitrates (NO_3^-) at 410 nm with sodium salicylate.
  - Nitrites (NO_2^-) at 540 nm via Griess reagent.
  - Ammonium (NH_4^+) at 420 nm using Nessler's reagent.
- Ion-selective electrode potentiometry: Water pH was measured using a glass electrode. Fluoride (F^-) was precisely quantified via a lanthanum fluoride (LaF_3) ion-selective electrode with total ionic strength adjustment buffer to eliminate interferences.
- Gravimetric analysis: Total dissolved solids (TDS) and dry residue were evaluated gravimetrically by evaporating 0.45 μm filtered samples and drying to constant weight at 105 °C– 110 °C (±0.0001 g).

To evaluate the potability and hydrochemical quality of the investigated water bodies in Angren, all experimental values in Tables 1–5 were benchmarked against national maximum permissible concentrations established by the State Standard of Uzbekistan O'zDSt 950:2011 (*Drinking Water: Hygienic Requirements and Quality Control*) and supplemented by international reference baselines from the World Health Organization (WHO 2022 Guidelines for Drinking-water Quality[14]).

In Section 5, parameters conforming to $C_i \leq C_{\text{norm}}$ reflect safe background conditions, whereas notable deviations—such as the regional deficit of fluoride ($F^- < 0.05$ mg/dm^3 versus the optimal WHO/O'zDSt range of 0.7–1.5 mg/dm^3) and a slight organoleptic elevation of color intensity (24° vs. ≤ 20°)—are evaluated against these specific normative thresholds.

The parameter selection focused primarily on baseline inorganic hydrochemistry, major cation-anion balances ($Na^+ + K^+$, Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-}, Cl^-), and essential trace micronutrients (e.g., fluoride F^-) to establish the natural geochemical facies and drinking water mineral adequacy (O'zDSt 950:2011; WHO, 2022[14]).

- TDS: TDS was explicitly quantified gravimetrically as total mineralization (0.093–0.375 g/dm^3) across all sampling sites (Tables 1–3).
- Chemical oxygen demand (COD), biochemical oxygen demand (BOD), and total suspended solids: COD and BOD are specific indicators for organic load and municipal/industrial wastewater pollution, while total suspended solids quantify particulate turbidity. Since the investigated water points (Appartak, Dukentsoy, and Qorabovsoy) represent oligotrophic, high-altitude mountain tributaries and natural drinking water recharge sources with negligible organic enrichment and low turbidity (<1.5 NTU), organic loading parameters (COD/BOD) fell outside the primary scope of this hydrogeochemical mineralization assessment.

These chemical assessments were crucial in identifying potential health risks and assessing whether element concentrations in the Angren surface and groundwater provide adequate mineral intake or pose a toxicological threat to the local population. Column charts of the study were drawn using Microsoft Excel. Schematic maps showing the location of Angren and groundwater analyses, as well as Piper diagrams, were drawn using CorelDRAW (CorelDRAW.Graphics.Suite.2025.v26.0.0.101, Corel Corporation, Canada).

3.2. Statistical hypothesis testing

A statistical hypothesis test was used to scientifically substantiate that the fluoride content in the samples taken from the Angren city water is significantly lower than the norm. We used a one-sample, one-sided *t*-test to compare the observed mean values (x) with the normative standards (μ0). To ensure the statistical significance of the observed mineral deficiencies, the standard deviation and standard error were calculated to determine the *p*-values. This helps draw clear conclusions about whether fluoride content is below the norm or whether random deviations occurred in the laboratory analysis, and it provides clear information about differences not visible to the human eye.

3.3. Hydrochemical facies classification with Piper diagrams

The Piper diagram is used to determine the type of water, water hardness, and assess its impact on public health. A Piper diagram is constructed for each water sample. It allows you to simultaneously view the relative concentrations of the main cations and anions in water samples. The points in the central rhombus of the Piper diagram indicate which group the water belongs to. By determining which group the water belongs to, we can determine how beneficial or harmful its consumption is for public health. The left triangle indicates the hardness of the water; that is, the closer the points are to the calcium and magnesium sides, the higher the water hardness. Determining the degree of water hardness also plays an important role in analyzing and assessing the impact of water on public health.

4. Results

The comprehensive chemical analysis of surface and groundwater in the Angren region revealed a distinct hydrochemical profile characterized by high toxicological safety but a certain extent of physiological mineral imbalance, namely, that fluoride levels in Angren region waters are much lower than the norm. The following sections detail the elemental concentrations, the statistical verification of observed deficiencies, and the subsequent implications for regional public health policy.

4.1. Water contents analysis

Chemical laboratory analysis of the obtained water samples allows us to determine the amount of elements present in the water. We first focused on the amount of cations in samples collected from water bodies in the city of Angren (Table 1).

The results of the analysis showed that in all three samples, the content of all cations is within the norm (Figure 2). The concentration of Na^+ and K^+ cations in Dukentsoy was much lower than in the other two water samples. We found that in the water sample from the

Table 1. Contents of cations in samples taken from water bodies in Angren city

No.	Cations	Appartak (Sample 1)	Dukentsoy (Sample 2)	Qorabovsoy (Sample 3)	Normal (mg/L)
1	Na^+–K^+	17.12 ± 0.45	2.08 ± 0.12	16.85 ± 0,38	≤200
2	Ca^{2+}	100.25 ± 1.82	28.14 ± 0.65	27.90 ± 0.58	≤200
3	Mg^{2+}	16.92 ± 0.35	2.05 ± 0.10	1.95 ± 0.08	≤50
4	NH^+	<0.1	<0.1	<0.1	≤2.0
5	Fe^{3+}	0.1 ± 0.02	< 0.10 ± 0.02	0.9 ± 0.01	≤0.3

Source: Compiled by the authors based on the results of water analysis.

Appartak sanatorium, the content of the Ca^{2+} element was much higher than in the other two water samples. The content of Mg^{2+} cation in Dukentsoy and Karabovsoy was much lower than in the water from the Appartak sanatorium. The low content of ammonium ions in all water samples indicates the absence of organic pollution in these waters. We found that the content of anions in all water samples, in particular, the content of hydrocarbon ions, sulfates, chlorides, nitrates, and nitrite ions, was also within the norm (Table 2). The content of hydrocarbon ions, chlorides, and nitrates in the water from the Appartak sanatorium was much higher than in other water samples, but within the norm.

The fact that the nitrite ion was the lowest in the Appartak water sample indicates that this water is free of bacterial and organic pollution. The nitrite ion content in Dukentsoy and Qorabovsoy is also low, which means that organic and bacterial pollution, i.e., nitrification, did not occur. The occurrence of the chemical process of nitrification also plays an important role in assessing the organic and bacterial pollution of waters.[24]

The fluoride content in all water samples (Table 3) was well below the standard. The pH value of the water samples was slightly alkaline, but within the normal range for drinking water. The turbidity of the water in all water samples was normal. The color index of the water should be up to 20 in the standard and up to 24 in the water samples. However, if the color index of the water is between 20 and 30, it is considered light in color and is allowed for drinking in some cases.[25] All other physicochemical properties of the water from which the Appartak, Dukentsoy and Qarabovsoy samples were collected were normal.[26]

The salinity of three water samples collected from the waters of the city of Angren was also determined. By determining the salinity of water, the type of water can be determined.[27] The salinity of water can be calculated using

Equation 1:

$$R = \frac{\text{Specific component } \left(HCO_3^- \text{ or } SO_4^{2-}\right)}{\text{Sum of total anions or cations}} \quad (1)$$

If R < 0.5, this is water of the hydrocarbon type; if R ≈ 0.5–0.7, this is water of the mixed type; If R > 0.7, this is water of the sulfate or chloride type. We use this formula to determine the salt content of water samples (Table 4). The salt content formula of the water collected from the Appartak sanatorium was 0.4. This water is considered soft and suitable for drinking. It has beneficial properties due to the high calcium-magnesium ratio in the water.[28] The water sample collected from Dukentsoy was found to be highly soft water with a high calcium bicarbonate content. The water sample collected from Karabovsoy was found to be soft, carbonated calcium water. Based on the salt content of the water, all water samples are suitable for consumption and do not pose any health risks to the population.

The Piper diagram values (Figure 3) of the three water samples indicated that the waters were chemically safe for drinking. The extremely low fluoride content in the samples may pose a risk of fluoride deficiency for dental health and the skeletal system.[29] The water from the Appartak sanatorium is considered suitable for balanced drinking and potentially beneficial. The waters of Dukentsoy and Karabovsoy are also safe for drinking and do not pose a risk to public health, but long-term consumption may lead to insufficient intake of certain minerals and diseases associated with mineral deficiencies.

Hydrochemical characterization based on the Piper trilinear diagram classified the analyzed water sources into specific hydrochemical facies according to the standardized Back nomenclature:

- Surface waters (Dukentsoy and Qorabovsoy): Categorized as Ca-HCO_3 (calcium–bicarbonate) hydrochemical facies, indicating low mineralization, active atmospheric recharge, and carbonate mineral

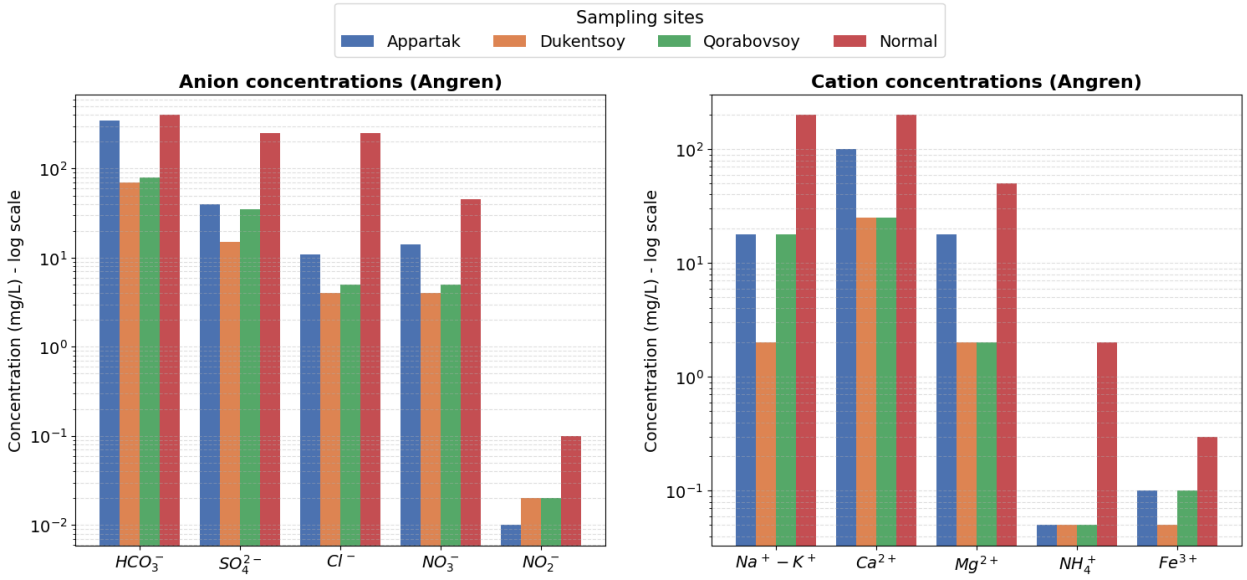


Figure 2. Anion and cation concentrations from water samples taken from Angren: Appartak (Sample 1), Dukentsoy (Sample 2), and Qorabovsoy (Sample 3). Source: Compiled by the authors based on analytical data.

Table 2. Content of anions in samples taken from water bodies of Angren city

No.	Anions	Appartak (Sample 1)	Dukentsoy (Sample 2)	Qorabovsoy (Sample 3)	Normal (mg/L)
1	HCO_3^-	354.15 ± 2.85	73.10 ± 1.20	85.25 ± 1.45	≤400
2	SO_4^{2-}	40.08 ± 0.92	16.05 ± 0.48	34.12 ± 0.75	≤250
3	Cl^-	11.05 ± 0.32	4.02 ± 0.15	5.04 ± 0.18	≤250
4	NO_3^-	14.10 ± 0.42	4.03 ± 0.16	5.02 ± 0.19	≤45
5	NO_2^-	0.010 ± 0.002	0.020 ± 0.003	0.020 ± 0.003	≤0.1

Source: Compiled by the authors based on the results of water analysis.

Table 3. Physical and chemical properties of water samples in Angren city

No.	Parameter	Appartak (Sample 1)	Dukentsoy (Sample 2)	Qorabovsoy (Sample 3)	Normal
1	pH	7.38 ± 0.05	7.6 ± 0.04	7.92 ± 0.06	6–9
2	Total mineralization (g/dm³)	0.375 ± 0.012	0.093 ± 0.005	0.133 ± 0.006	≤1.0
3	H_2S	<0.01	<0.01	<0.01	0
4	Fluorides (mg/dm³)	<0.05	<0.05	<0.05	0.7–1.5
5	SiO_2 (mg/dm³)	5.6 ± 0.18	3.75 ± 0.12	1.00 ± 0.08	0.5–10
6	Turbidity (mg/dm³)	0.03 ± 0.002	0.03 ± 0.002	0.03 ± 0.002	≤1.5
7	Color (t°)	24 ± 0.5	24 ± 0.5	24 ± 0.5	≤20

Source: Compiled by the authors based on the results of water analysis.

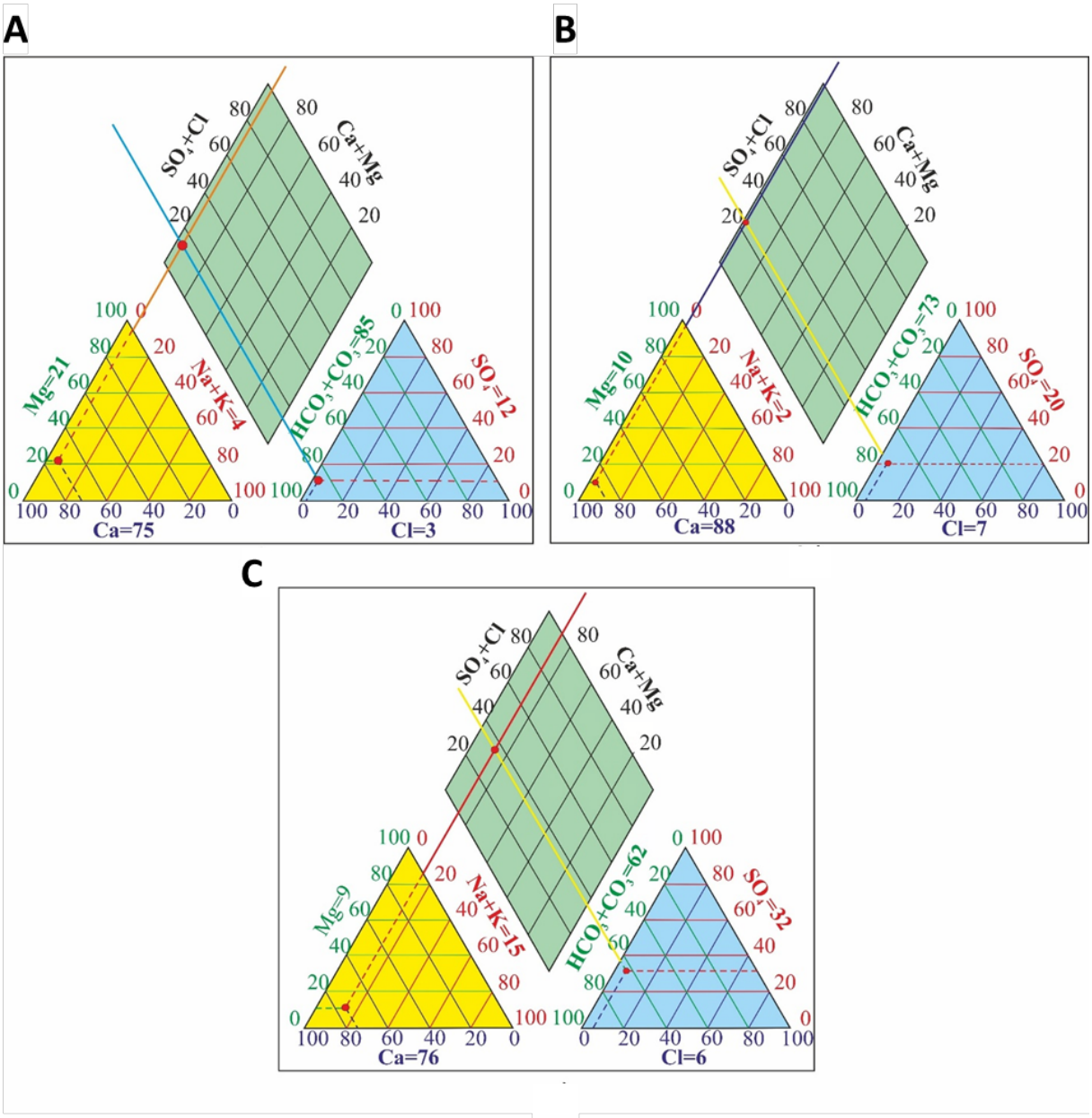


Figure 3. Piper diagrams for water samples from the city of Angren. (A) Appartak (Sample 1). (B) Dukentsoy (Sample 2). (C) Qorabovsoy (Sample 3). Source: Compiled by the authors based on analytical data.

dissolution.

- Groundwater site 1 (Appartak Sanatorium and Well 2): Identified as Ca-Mg-HCO_3 (calcium–magnesium–bicarbonate) hydrochemical facies, reflecting silicate weathering and localized water-rock interactions.
- Groundwater site 2 (Monitoring Well 1): Classified as Ca-Na-HCO_3 (calcium–sodium–bicarbonate) hydrochemical facies, demonstrating ion-exchange processes along the flow path.

We concluded that almost all indicators in the Appartak, Dukentsoy, and Karabovsoy water samples are significantly below the norm and assessed their impact on public health from this perspective. A statistical hypothesis test was conducted to scientifically substantiate this.

4.2. Hypothesis testing

A statistical hypothesis test was conducted to assess the chemical parameters of three water samples against the

established norms (μ_0). To determine whether the mineral levels were significantly below the normative limits, the null hypothesis ($H_0 : \mu = \mu_0$) was tested against the one-sided alternative hypothesis ($H_a : \mu < \mu_0$).

Table 4. Formulas for the salt content of water samples taken from the city of Angren

Name	Result	Salt formula
Appartak	0.40	$\frac{HCO_3^{81}\ SO_4^{12}}{Ca^{70}Mg^{20}}$
Dukentsoy	0.10	$\frac{HCO_3^{70}\ SO_4^{19}}{Ca^{82}Mg^{18}}$
Qorabovsoy	0.14	$\frac{HCO_3^{60}\ SO_4^{30}}{Ca^{60}Mg^{9}}$

Source: Compiled by the authors based on the results of water analysis.

The mean value was calculated for the parameters, the standard deviation was found based on the sample values, the standard error was determined, a one-sample one-tailed *t*-test was performed, *p*-values were estimated, values below the limit of detection were replaced by the limit of detection/2 substitution rule, and the corresponding conclusion was drawn. The degrees of freedom and t-statistics were derived using standard frequentist methods. The results of the general statistical hypothesis test for all water samples were calculated and summarized (Table 5). Statistical hypothesis testing confirmed that all elements in the water samples, especially fluoride, were significantly lower than normal.

4.3. World Health Organization-based analysis of geogenic fluoride deficiency

According to the WHO Guidelines for Drinking-Water Quality (4th edition),[30] fluoride is unique among water constituents. Fluoride is classified as an essential ion for the prevention of dental caries.[31] The WHO defines a concentration of 0.5 mg/L as the lowest threshold for therapeutic benefit, with an optimal range of 0.7–1.5 mg/L depending on local climatic conditions and water consumption levels. In Angren, the observed concentration represents a severe "geogenic deficiency." To quantify this, we propose the deficit ratio (**Equation 2**):

$$DR = \frac{C_{observed}}{C_{WHO}} = \frac{0.025\ mg/L}{0.5\ mg/L} = 0.05 \quad (2)$$

This calculation demonstrates that the Angren population receives only 5% of the minimum fluoride intake required to sustain dental integrity. The public health impact of this deficiency is primarily centered on the "pre-eruptive" stage of dental development in children. From a biochemical perspective, the presence of systemic fluoride allows for the ionic substitution of the hydroxyl group in hydroxyapatite, the primary mineral in tooth enamel:

$$Ca_{10}(PO_4)_6(OH)_2 + 2F^- \rightarrow Ca_{10}(PO_4)_6F_2 + 2OH^- \quad (3)$$

The resulting fluorapatite has a significantly lower solubility product compared to hydroxyapatite, rendering the enamel resistant to acid-induced demineralization. In the absence of this ion in Angren's water supply, the population is susceptible to high rates of dental caries and potentially weakened skeletal mineralization.

Based on WHO-sanctioned mitigation strategies for low-fluoride regions, several interventions are recommended for the Angren administrative region. Primary efforts should focus on community water fluoridation, which involves the artificial adjustment of fluoride concentrations to 0.7 mg/L at central treatment plants. In areas where centralized water infrastructure remains limited, the WHO suggests utilizing alternative mineralization methods, such as salt or milk fluoridation, as effective secondary non-geographic vehicles. Furthermore, because topical fluoride treatments like toothpaste provide only surface-level protection, systemic supplementation is necessary to ensure deep-tissue enamel fortification during critical stages of childhood development.

Table 5. Statistical hypothesis test results of Angren samples

Indicators	Normal (μ_0)	$\bar{x}$	SE	*t*	*p*-value
Na^+K (mg/L)	200	12.0	5.00	−37.60	0.00035
Ca (mg/L)	200	52.0	24.01	−6.17	0.0127
Mg (mg/L)	50	7.0	5.00	−8.60	0.0066
F (mg/L)	~1.2	0.025	0.00	–	≪0.001

Source: Compiled by the authors based on the results of the hypothesis test.

4.4. Groundwater analysis

To provide a comprehensive assessment of the region's hydrological profile, it is essential to evaluate the hydrochemical state of the groundwater resources in Angren. These resources are monitored through strategic observation wells maintained by the State Institution "Institute of Hydrogeology and Engineering Geology," which serve as the primary conduits for long-term water quality surveillance (Figure 4).

The chemical analysis of samples retrieved from these wells (Table 6) reveals the baseline mineralization and elemental concentrations available to the population. By examining these results, we can identify specific geogenic patterns and assess their physiological compatibility with public health requirements.

In both wells, all elements in groundwater are within the normal range. The very low nitrate content is considered a positive condition for drinking water.[32] The almost complete absence of the ammonium element indicates the absence of bacterial contamination in these waters.[33] The fact that the sulfate and chloride elements are much lower than the norm indicates that the taste and composition of the water are hygienically safe.[34] Magnesium, calcium, sodium, and potassium are also within the normal range. According to the physical and chemical characteristics of Angren groundwater, we can see that the pH is neutral in both water samples.

Table 6. Element concentrations in groundwater monitoring wells (mean ± standard deviation)

Elements	Well 1	Well 2	Normal (mg/L)
HCO_3^-	179.4 ± 5.2	218.1 ± 6.4	30–400
Cl^-	20.3 ± 0.9	26.8 ± 1.1	≤350
SO_4^{2-}	94.8 ± 2.7	101.2 ± 3.1	≤500
NO_3^-	1.2 ± 0.1	3.8 ± 0.2	≤45
Ca^{2+}	56.5 ± 1.6	75.2 ± 2.3	≤180
Mg^{2+}	13.8 ± 0.5	22.9 ± 0.8	≤50
Na^+/K^+	32.6 ± 1.3	20.1 ± 0.8	≤200

Source: Compiled by the authors based on the results of water analysis.

This is an ideal indicator for drinking water.[35] The

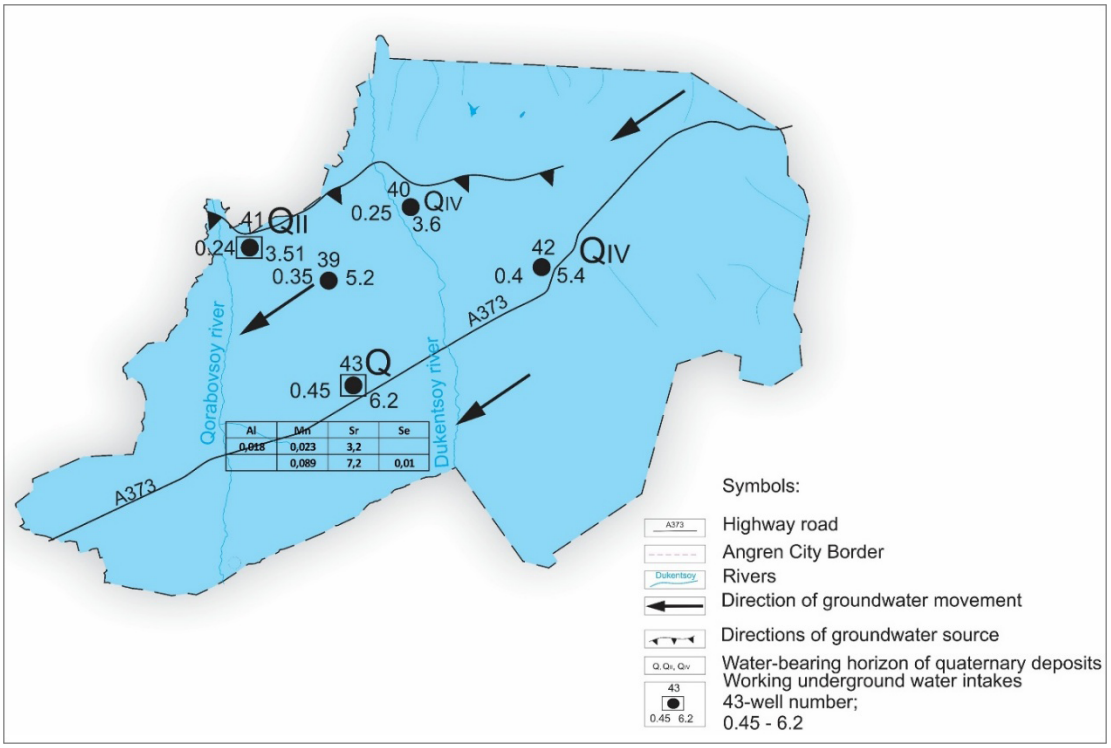


Figure 4. Hydrogeological map of groundwater in the city of Angren. Source: Compiled by the authors based on data from the "Uzbek Hydrogeology State Enterprise."

total hardness and carbonate hardness of groundwater also have normative values.[36] It is also observed that the dry residue in water[37] is within the normal range (Table 7). The complete absence of hydrogen sulfide in the water samples[38] indicates that the water is safe for drinking, free from contamination. Dissolved carbon dioxide and silica[39] are not present in the groundwater of the city of Angren. According to the physical and chemical characteristics of the samples, the city's groundwater is considered suitable for consumption and domestic needs.

Table 7. Physicochemical properties of water samples taken from groundwater in the city of Angren (mean ± standard deviation)

Indicators	Well 1	Well 2	Normal
Overall hardness (mg/L)	4.15 ± 0.12	5.58 ± 0.18	≤7.0
Carbonate hardness (mg/L)	2.82 ± 0.08	3.68 ± 0.11	≤5.0
pH	6.95 ± 0.05	7.14 ± 0.04	6.5–8.5
Dry residue (mg/L)	318.5 ± 8.2	378.2 ± 9.5	≤1,000
CO_2 (dissolved form) (mg/L)	–	–	≤100
H_2S (hydrogen sulfide) (mg/L)	–	–	≤0.05
SiO_2 (silicon oxide) (mg/L)	–	–	≤10

Source: Compiled by the authors based on the results of water analysis.

Based on the salt composition formula of the water samples, Water Sample 1 is calcium–sodium hydrogencarbonate water, and Water Sample 2 is calcium–magnesium hydrogencarbonate water. According to the salt composition formula, it does not pose a threat to public health.

Based on the Piper diagram for the water sample from Well 1 (Figure 5A), the cation composition is rich in calcium. The water is calcium-magnesium hydrocarbonate water. If we look at the Piper diagram of the water sample from Well 2 (Figure 5B), the amount of calcium is the highest, followed by a significant amount of magnesium. It shows that the water belongs to the calcium-hydrocarbonate water type.

5. Discussion

The hydrogeological regime and ionic composition of surface and groundwater in the Angren basin are primarily controlled by local lithology and water-rock interaction dynamics. The Chatkal–Kurama mountain system's piedmont zone is predominantly characterized by volcanic, intrusive, and carbonate bedrock formations. The dominance of calcium (Ca^{2+}), magnesium (Mg^{2+}), and bicarbonate (HCO_3^-) ions across the analyzed samples reflects active silicate weathering and carbonate dissolution processes along groundwater flow paths.

The low fluoride (F^-) concentrations observed across all sampling sites can be attributed to three specific hydrochemical and lithological mechanisms:

(i) Mineral source deficiency: The host rocks in the recharge area (predominantly granitoids and volcanic facies) naturally lack abundance in fluoride-bearing minerals such as fluorite (CaF_2), fluorapatite, or fluorine-rich micas.

(ii) Precipitation controls ($Ca^{2+} - F^-$ equilibrium): The abundance of Ca^{2+} derived from limestone weathering and gypsum/calcite dissolution acts as a solubility control mechanism. According to the chemical equilibrium governed by the solubility product constant of fluorite (K_{sp} of $CaF_2 \approx 3.9\times10^{-11}$ at 25 °C), elevated concentrations of dissolved Ca^{2+} limit the mobility of free fluoride in solution through precipitation reactions:
$$Ca^{2+} + 2F^- \rightleftharpoons CaF_2 \downarrow$$

(iii) Hydrodynamics and residence time: Fast subsurface runoff dynamics and intense seasonal snowmelt recharge in the upper piedmont zone shorten the contact residence time between water and host minerals, thereby hindering significant dissolution and enrichment of trace elements like fluorine.

Consequently, the hydrogeochemical regime of Angren is governed by alkaline-earth carbonate weathering rather than mineral-fluoride leaching, explaining the persistent regional fluoride deficiency.

The hydrochemical facies identified in this study (Ca-HCO_3 and Ca-Mg-HCO_3) align with classical regional hydrogeological baseline studies conducted in the Akhangaron River basin.[40,41] The dominance of calcium and bicarbonate ions reflects the natural weathering of carbonate and silicate rocks in the Chatkal and Kurama mountain ranges, which is characteristic of high-altitude recharge zones in Central Asia.[42]

Comparing our findings with recent environmental and hydrochemical assessments in adjacent industrial and urbanized corridors of Uzbekistan reveals several key dynamics:

- Ionic concentrations and mineralization: The low total mineralization (0.093–0.375 g/dm^3) observed across

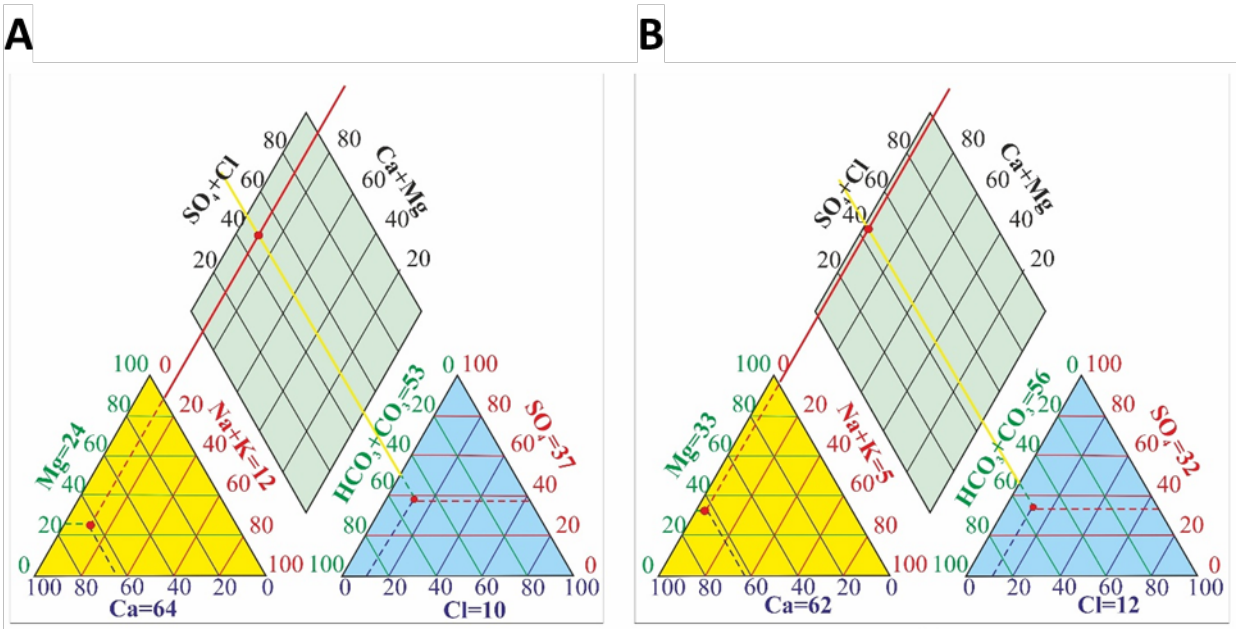


Figure 5. Piper diagrams for groundwater samples in the city of Angren. (A) Well 1. (B) Well 2. Source: Compiled by the authors based on analytical data.

Appartak, Dukentsoy, and Qorabovsoy is consistent with upstream surface water characteristics reported by Eshanbabayev *et al.*[13] along the A-373 transit corridor. Unlike heavily salinized downstream basins in western Uzbekistan, the upper Akhangaron valley retains fresh background conditions, with major cations ($Na^+ + K^+$, Ca^{2+}, Mg^{2+}) remaining significantly below maximum permissible concentrations (O'zDSt 950:2011; WHO, 2022[14]).

- Fluoride deficit and public health vulnerability: The pronounced fluoride deficiency observed in all sampled water bodies (<0.05 mg/dm^3) strongly concurs with broader regional epidemiological and hydrochemical surveys across the Tashkent Oasis and Fergana Valley. While global studies in volcanic or rift environments often highlight fluoride toxicity/fluorosis risks[31], our results confirm that the mountainous runoff of the Chatkal–Kurama system is severely fluoride-depleted relative to the optimal human biological range (0.7–1.5 mg/dm^3). This finding directly reinforces the public health imperative linked to SDG Target 3.9 and SDG Target 6.1, underscoring the need for targeted fluoridation strategies or dietary supplementation for the local population of Angren.

By contextualizing our empirical data with prior literature, this study establishes that while anthropogenic transit and industrial activities along the A-373 highway and Angren–Pop infrastructure corridor have not yet degraded major ion balances beyond regulatory limits, natural hydrogeochemical limitations (severe fluoride deficit) pose the primary health-related risk in the region.

The hydrochemical analysis of surface and groundwater in the Angren region provides crucial inferential insights into how regional geogenic hydrochemistry influences long-term public health outcomes. While the analytical results confirm excellent microbiological and toxicological safety—evidenced by the absence of hydrogen sulfide, negligible ammonium, and low levels of nitrites and nitrates—the identified mineral profile reveals a distinct physiological imbalance that warrants targeted epidemiological attention (Figure 6).

The most striking finding is the deficit in geogenic fluoride across all sampled surface and groundwater sources. With fluoride concentrations yielding a deficit ratio of 0.95, the Angren population receives only 5% of the WHO-recommended lower therapeutic threshold. Systemic fluoride during childhood development replaces the hydroxyl group in hydroxyapatite to form fluorapatite, which drastically reduces enamel acid solubility.[43,44] In the absence of adequate systemic fluoride ingestion, the pediatric population faces heightened susceptibility to rampant dental caries, compromised enamel structural integrity, and altered bone mineralization dynamics.[45] Contemporary epidemiological reviews indicate that while topical fluorides (such as toothpastes) provide superficial

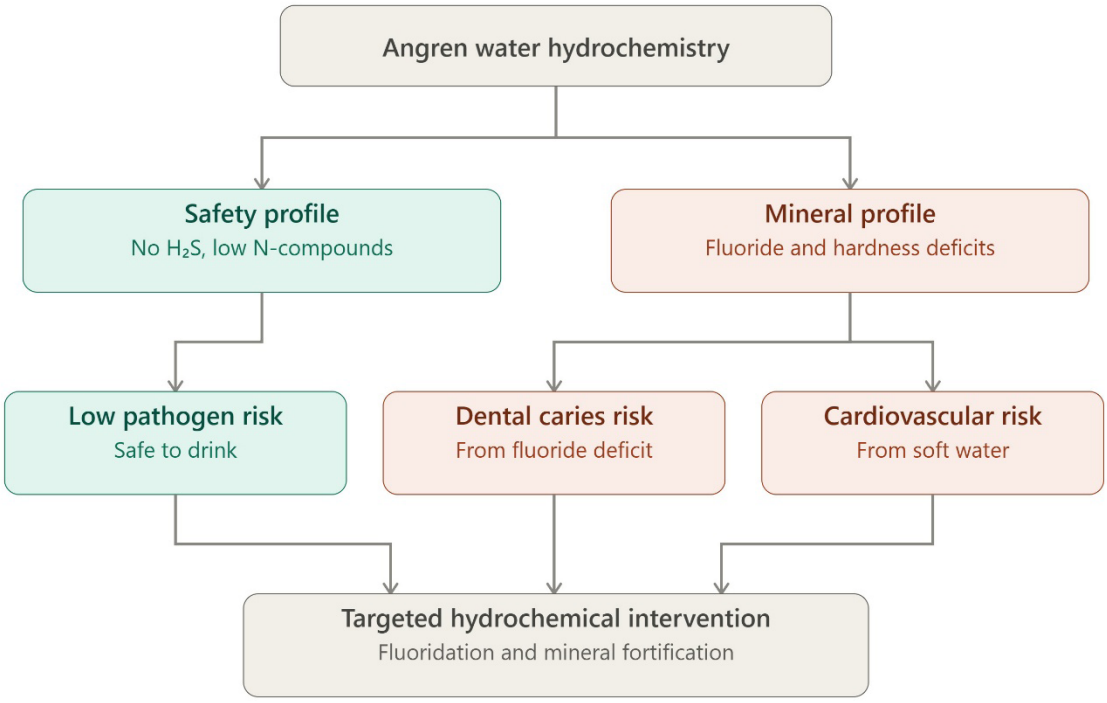


Figure 6. Conceptual framework linking the Angren region's hydrochemical dual-profile to downstream oral and cardiovascular health outcomes and the proposed intervention pathway.

protection, communities in naturally fluoride-deficient regions experience disproportionately higher rates of early childhood caries unless systemic or community-level interventions are implemented.[46,47]

Furthermore, the salt composition formulas and hydrochemical classifications reveal that the region's waters are predominantly soft to extremely soft hydrocarbon-type waters. Although soft water with low overall dissolved solids is visually clear and pleasant to consume, long-term dependence on soft drinking water with low mineral density may carry indirect cardiovascular and metabolic consequences. Population-level studies examining soft water consumption demonstrate an inverse relationship between drinking water hardness (specifically calcium and magnesium concentrations) and cardiovascular disease risk.[48] Magnesium acts as a critical cofactor in enzyme activation, vascular regulation, and myocardial electrical stability.[49,50] While the Appartak sanatorium water demonstrated a relatively favorable calcium-to-magnesium ratio, the Dukentsoy and Karabovsoy sources are markedly soft. Inhabitants relying solely on these low-mineral surface waters without compensating dietary mineral intake may face increased risks of sub-optimal electrolyte intake, altered vascular tone, and higher long-term cardiovascular stiffness.[51]

From a nosogeographical and environmental health perspective, the Angren region presents a dual-profile baseline: an exceptional natural defense against waterborne infectious pathogens paired with chronic micronutrient hydro-deficiencies. Interventions must therefore shift from traditional decontamination to active hydrochemical enhancement. Implementing targeted community fluoridation strategies, promoting mineral-fortified salt or milk programs, and monitoring population-level dental and cardiovascular health indicators form the necessary basis for mitigating these geogenic risks.

6. Conclusion

Based on the chemical analysis of the specific surface and groundwater monitoring sites investigated in this study (including Dukentsoy, Karabovsoy, Appartak, and targeted monitoring wells), the hydrochemical parameters evaluated comply with established potable water quality standards (UzDSt 950:2011). Within the temporal framework and spatial scope of these analyzed sampling points, no acute toxicological hazards or critical chemical contamination threatening public health were detected, suggesting localized hydrochemical safety.

However, these conclusions are strictly applicable to the evaluated sampling locations and cannot be broadly

generalized to all drinking water sources across the entire municipality of Angren. Notably, the statistical hypothesis testing confirmed a persistent and significant fluoride deficiency across all sampled sites. While non-toxicological, this deficiency highlights localized long-term risks for dental and skeletal health. Consequently, targeted public health interventions—such as dental fluoride varnish applications for children, dietary adjustments, caries prevention campaigns, and the promotion of fluoridated toothpastes—are recommended for populations relying on these specific water supply zones. Continuous, expanded hydrochemical monitoring across additional spatial sites in Angren remains essential, as water quality parameters exhibit spatiotemporal variability that warrants ongoing assessment.

In this study, we could not investigate the relationship between surface and groundwater quality in Angren City and the incidence of dental diseases in the population. This was due to the limited availability of data on the prevalence and types of dental diseases in Angren City. In this study, we could not thoroughly examine changes in water quality in Angren over years and seasons due to limited data and study challenges.

Future work should examine how surface and groundwater quality in Angren City may relate to fluoride levels and the incidence of dental diseases in the population. Moreover, it is necessary to analyze the dynamics of changes in water quality and element concentrations, study how water chemistry changes over years and seasons, and identify other water-quality risks to population health. When conducting new studies, it is also important to group regions by the level of quality drinking water provision and water quality, and to conduct research that yields similarly effective results.

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Conflict of interest

The authors declare no conflicts of interest.

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Availability of data

The data used for this study are included in **Tables 1–7** in the article.

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