Journal of Geointerface, Vol. 4, No. 2, December 2025, pp. 113–124 e-ISSN: 2583-6900

Hydrogeochemical insights into toxic element enrichment in stream waters from parts of Jagtial District, Telangana, India

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ABSTRACT

This hydrogeochemical investigation assesses the stream water quality in parts of the Jagtial District, Telangana. The area lies within a geologically diverse terrain comprising the Archean high-grade supracrustals of the Karimnagar Granulite Belt, Neoarchean to Paleoproterozoic granitoids (PGC-II), and Neoproterozoic Pakhal Supergroup sediments. Stream water exhibits acceptable physical parameters, including pH (7.6–7.9) and total dissolved solids (325–596 mg/l). However, hydrochemical analysis of nine representative stream water samples revealed significantly elevated concentrations of toxic elements like arsenic (0.5–2.56 ppm), uranium (1.0–3.7 ppm), and barium (59.7–196.7 ppm), substantially exceeding both national and international water quality guidelines. These anomalies are attributed to geogenic inputs from the weathering of local lithologies. Although irrigation indices such as Sodium Adsorption Ratio (SAR: 3.94–5.86), Percent Sodium (Na%: 19.64–26.45%), and water quality assessment using SAR, EC, and Wilcox diagram indicate water suitability for agricultural use, the toxic element load raises serious concerns regarding its safety for drinking and long-term irrigation purposes. Piper diagram classification indicates all samples fall in the magnesium-bicarbonate facies, while Gibbs diagrams suggest rock–water interaction and evaporation as the primary geochemical controls. This study highlights the imperative for region-specific water governance integrating hydrogeochemical risk management.

ARTICLE HISTORY
Received: 20 July 2025
Revised: 30 Aug 2025
Accepted: 31 Aug 2025

https://doi.org/10.5281/zenodo.17049069

KEYWORDS
Toxic Element Contamination
Hydrogeochemistry
Stream water
Rock–Water Interaction
Eastern Dharwar Craton
Karimnagar Granulite Belt

1. Introduction

Assessing surface water quality is crucial for the sustainable management of water resources, as it directly impacts their suitability for domestic, agricultural, and industrial uses. The study area, located between latitudes 18°45′00″–19°00′00″N and longitudes 78°45′00″–79°00′00″E, comprises a diverse geological framework that includes the Archean high-grade supracrustals of the Karimnagar Granulite Belt, Neoarchean to Paleoproterozoic granitoids and rocks of the Peninsular Gneissic Complex-II, and Neoproterozoic sedimentary units of the Pakhal Supergroup. Key rock types—such as hornblende-biotite granite gneiss, biotite granite, banded magnetite quartzite, amphibolite, pegmatite, quartz veins, limestone, and

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sandstone—contribute distinct mineralogical inputs to stream water chemistry (Patel and Sahoo, 2025).

The hydrochemical composition of stream waters is largely controlled by the weathering and dissolution of the bedrock units, agricultural runoff, and infrastructure development (Hem, 1985; Rao et al., 2012; Sahoo et al., 2024). Major ions such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, HCO_3^{-}, and SO_4^{2-} serve as vital indicators of water quality and are used to classify hydrochemical facies (Todd and Mays, 2004). A comprehensive interpretation of these ions, rather than isolated concentrations, facilitates a better understanding of the prevailing water chemistry and the relationships between cations and anions (Wilcox, 1955; Ayers and Westcot, 1985). Supporting parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), and total hardness (TH) further inform the quality assessment.

To evaluate the water's suitability for domestic and agricultural use, hydrochemical results are benchmarked against both national and international standards, including those of the Bureau of Indian Standards (BIS, 2012) and the World Health Organization (WHO, 2017). For irrigation assessments, indices such as Sodium Adsorption Ratio (SAR) and Percent Sodium (Na%) are employed due to their implications for soil health and crop productivity (Ayers and Westcot, 1985). Piper trilinear and quadralinear diagrams are also used to identify dominant water types and visualize ionic trends.

Preliminary investigations in the parts of Jagtial region indicate a dominant magnesium-bicarbonate water type, consistent with the weathering of local granitoid, amphibolitic, and carbonate-bearing rocks. However, elevated concentrations of toxic elements—namely arsenic (up to 2.56 ppm), uranium (up to 3.75 ppm), and barium (up to 196.7 ppm) have been recorded, surpassing BIS and WHO permissible limits (Smedley and Kinniburgh, 2002). These anomalies suggest geogenic enrichment, possibly intensified by sustained agrochemical usage.

This study presents a detailed hydrogeochemical assessment of stream waters in the parts of Jagtial District, focusing on toxic element distribution and the geogenic–anthropogenic controls influencing water quality. The results emphasize the need for region-specific water management strategies and continuous monitoring to safeguard public health and promote sustainable water resource utilization.

2. Geological setup

2.1. Regional Geology

The study area, located on the northeastern fringe of the Eastern Dharwar Craton (EDC), forms part of the Penninsular Gneissic Complex (PGC). The EDC, a segment of the Dharwar Craton, comprises greenstone–granite suites and intra-cratonic basins such as the Cuddapah, Pakhal, Bhima, and Godavari Graben, and is bordered by the high-grade granulites of the Eastern Ghats Mobile Belt (EGMB) (Swami Nath et al., 1976). The present study area, lies within the EDC, which is dominated by calc-alkaline granitoids interspersed with thin, linear greenstone belts (~2.7 Ga) and intruded by younger granitoids (Balakrishnan et al., 1999; Chadwick et al., 2000; Bidyananda et al., 2011; Anand and Balakrishnan, 2010). The EDC is bounded by the Deccan Traps and Bastar Craton to the north, EGMB to the east, and the Southern Granulite Terrane to the south. Granitoids and gneisses, mostly dated between 2.6 and 2.5 Ga, are considered to have originated from mantle-derived sources, as well as from the partial melting of metasomatized mantle (Martin, 1994; Nutman et al., 1996). The region also features the Karimnagar Granulite Belt, comprising orthopyroxene-bearing gneiss, charnockite, and banded magnetite quartzite, reflecting a complex tectonothermal history (Rajesham et al., 1993; Acharyya, 1997; Mishra et al., 1999; Santosh, 2004).

2.2. Local Geology

The study area, situated in the Survey of India Toposheet No. 56J/13, Jagtial district, Telangana encompasses a diverse lithological assemblage representing three principal tectonic and stratigraphic groups: Archean high-grade supracrustals of the Karimnagar Granulite Belt (KGB), Neoarchean to Paleoproterozoic rocks of the Peninsular Gneissic Complex-II (PGC-II), and Neoproterozoic Pakhal Supergroup sediments (Fig. 1). The KGB is characterized by linear to lensoidal enclaves of orthopyroxene-bearing quartzofeldspathic gneiss, amphibolite, and banded magnetite quartzite, often forming prominent hillocks (Rajesham et al., 1993; Acharyya, 1997). PGC-II rocks, predominantly grey biotite granite, porphyritic granite, and alkali feldspar granite, constitute the main lithologies, with pegmatite and quartz veins as minor intrusives. These granites

Journal of Geointerface, Vol. 4, No. 2, December 2025, pp. 113–124 e-ISSN: 2583-6900

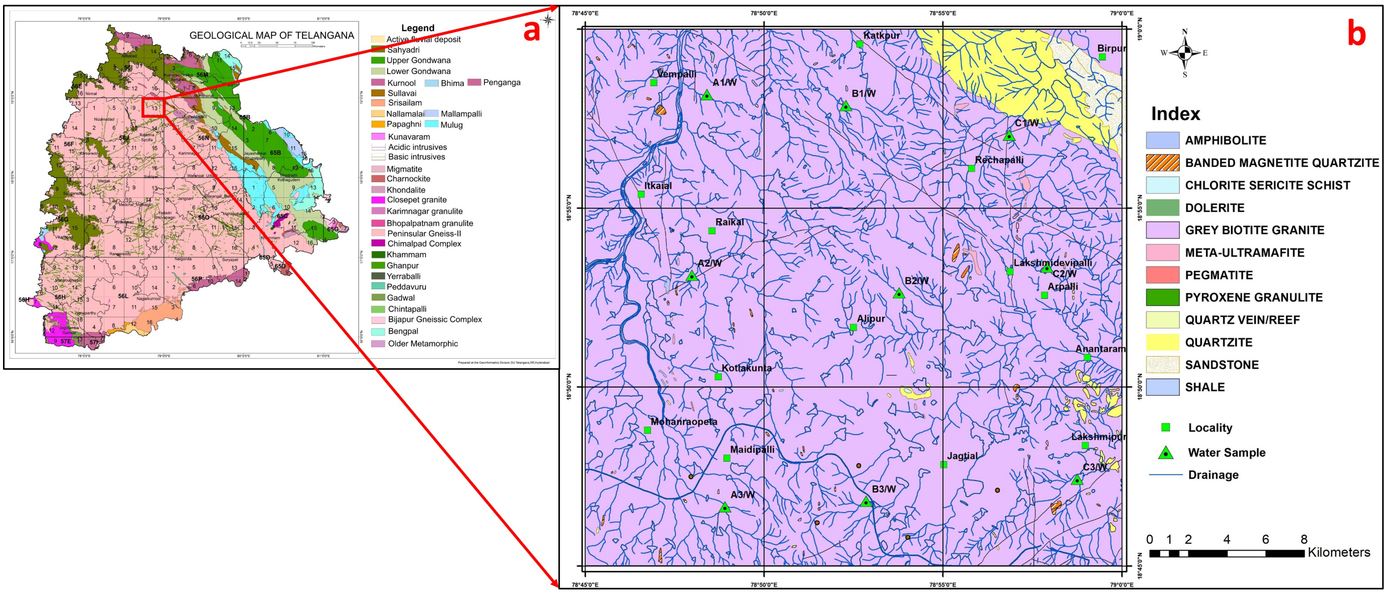

Fig. 1. Geological map of Telangana showing the study area (Source: Geo Informatics division, State Unit: Telangana, GSI, SR, Hyderabad). **b.** Drainage map with sample locations overlaid on the geology of the Toposheet no. 56J/13, parts of Jagtial District, Telangana (Source: Geo Informatics division, State Unit: Telangana, GSI, SR, Hyderabad).

Table 1. Detailed list of stream water samples collected from toposheet no 56J/13.

Quadrant No.	Latitute	Longitude	Order of Stream	Locality
A1	18°58′10.2″	78°48′24″	3^{rd}	SE of Vempalli
A2	18°53′7.1″	78°47′58.9″	3^{rd}	SW of Mahtepur
A3	18°46′38.8″	78°48′54.2″	2^{nd}	SE of Kondapur
B1	18°57′51.8″	78°52′17″	3^{rd}	SE of Dharmajipeta
B2	18°52′37.9″	78°53′46.2″	3^{rd}	NE of Alipur
B3	18°46′48.1″	78°52′50.9″	3^{rd}	NW of Antargaon
C1	18°57′2.2″	78°56′51″	2^{nd}	NE of Madhapur
C2	18°53′20.8″	78°57′54.2″	2^{nd}	NE of Lakshmidevipalli
C3	18°47′22.6″	78°58′45.3″	2^{nd}	North of Zabtapur

are medium to coarse-grained, featuring quartz, K-feldspar, plagioclase, biotite, and hornblende. The Pakhal Supergroup, exposed in the northeastern sector, comprises well-bedded limestone and cyclically deposited sandstone, unconformably overlying the granitoids. Structural trends are primarily NW–SE, with granite gneiss foliation and Pakhal bedding dipping moderately southwest and northeast, respectively. Basic intrusives, such as dolerite dykes, further diversify the lithological framework, collectively influencing the region's hydrogeochemistry and stream water composition (Santosh, 2004).

3. Materials and methods

Stream water sampling was carried out during the post-monsoon season of 2021 across parts of Jagtial District, Telangana, following a systematic 5′ × 5′ grid framework (Table 1 and Fig. 2) based on Survey of India Toposheet No. 56J/13 (Patel and Sahoo, 2025). A total of nine higher-order stream sites were selected to capture the spatial variability of hydrogeochemical parameters across the toposheet. Water samples were collected using standardized multi-protocol procedures as per NGCM guidelines (SOP, 2014, 2021). For ion chromatography (IC) analysis, 500 ml of water was collected via complete submersion to eliminate atmospheric interference. A 100 ml sample, acidified with 1.0 ml of concentrated HNO within 24 hours, was prepared for ICP-MS/ICP-AES analysis. Additionally, 60 ml of filtered and unacidified water was reserved for dissolved organic carbon (DOC), and 100 ml was preserved with HNO and K Cr O for mercury analysis. In situ measurements of pH and electrical conductivity were recorded immediately after sample containers were rinsed thrice with site water prior to collection. Filtration preceded preservation for ICP and DOC samples to avoid contamina-

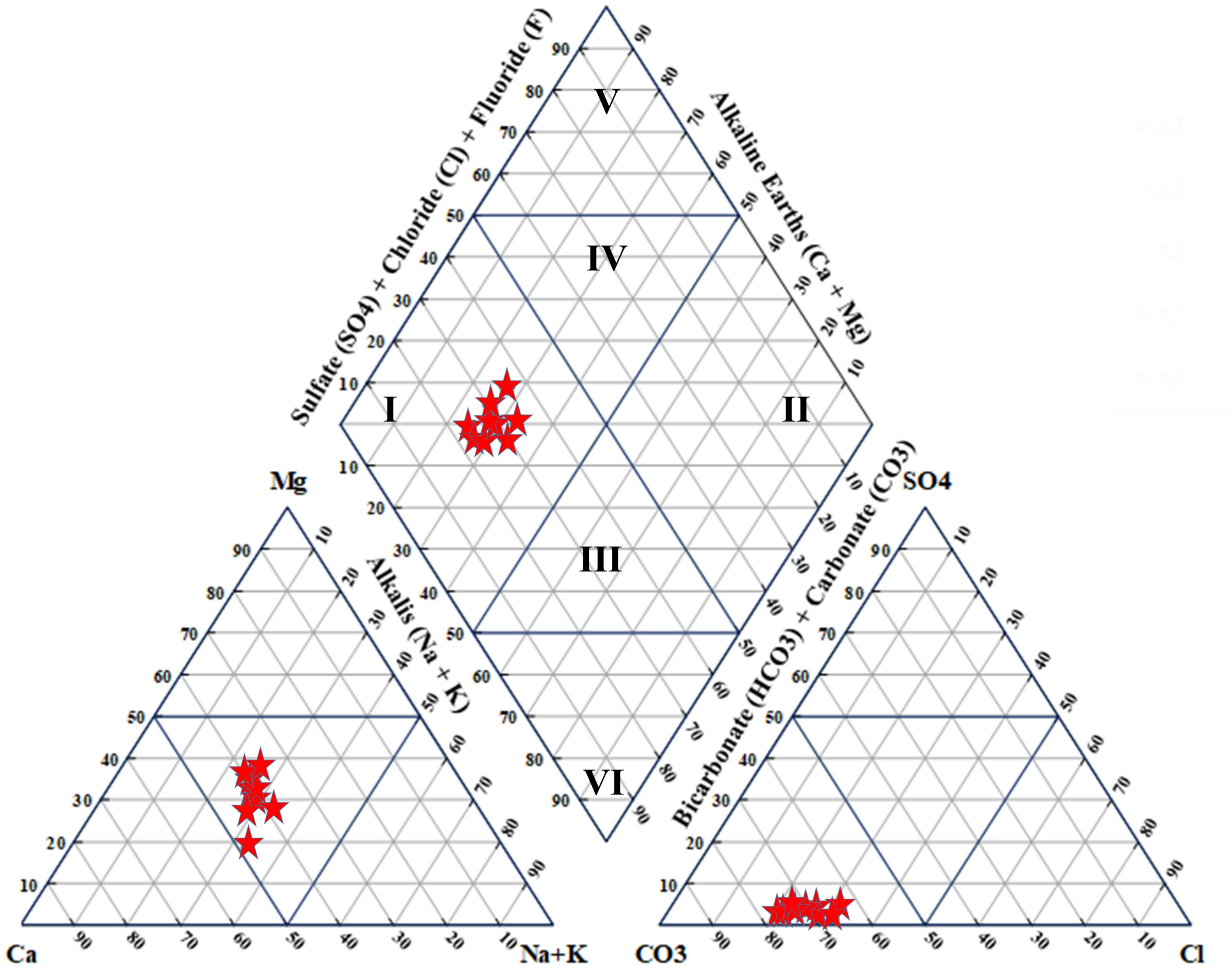

Fig. 2. Hill Piper Trilinear Plot of the water sample data collected from toposheet no.56J/13.

tion. Total alkalinity, primarily bicarbonate (HCO_3^-) in the pH range 4.5–8.3, was determined via titration and expressed in mg/L CaCO . All methods ensured consistency and accuracy in trace element and hydrochemical assessments.

4. Results

A comprehensive hydrochemical evaluation of nine stream water samples from the Jagtial district of Telangana reveals considerable spatial variability in physicochemical characteristics, major ion chemistry, toxic element concentrations, and water suitability for various uses (Table 2).

4.1. Physicochemical Parameters

The pH of all stream water samples ranged from 7.64 to 7.91, indicating slightly alkaline conditions. This could be due to the interaction of stream water with granite and gneissic under semi-arid climatic conditions (Hem, 1985; WHO, 2017). Total Dissolved Solids (TDS) varied between 325.12 and 595.84 mg/l. Seven samples fell within the BIS acceptable limit of 500 mg/l, while two samples (A1 and C3) slightly exceeded this threshold but remained below the permissible limit of 2000 mg/l (BIS, 2012). Electrical Conductivity (EC) values ranged from 508 to 931 S/cm, following the TDS trends. Total Hardness (TH) ranged from 350 to 490 mg/L, exceeding the BIS acceptable limit (200 mg/l), but remained within the permissible range (600 mg/l), implying considerable calcium–magnesium enrichment likely derived from host lithologies (Karanth, 1989).

4.2. Major Ions and Hydrochemical Facies

The dominant major ions included Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-, and F^-, most of which were within acceptable drinking water limits. However, fluoride concentrations exceeded the 1 mg/l with references to BIS/WHO guidelines. The source of fluo-

Table 2. Analytical results of physicochemical parameters of water samples.

Sample Ref No.	A1	A2	A3	B1	B2	B3	C1	C2	C3	Prescribed Limits BIS, 10500 (2012)		Value range in the study area	Remarks
										Acceptable limit	Permissible limit		
pH	**7.8**	**7.7**	**7.8**	**7.6**	**7.8**	**7.9**	**7.9**	**7.9**	**7.8**	**6.5–8.5**	**No relaxation**	**7.640–7.910**	**All values are within the acceptable limits.**
TDS (ppm)	**595.8**	**325.1**	**334.1**	**419.8**	**455.0**	**445.4**	**394.9**	**452.5**	**515.2**	**500.0**	**2000.0**	**325.120–595.840**	**Seven samples are within acceptable limits, and two samples (A1 and C3) are above the acceptable limit and below the permissible limits.**
TH (ppm)	**490**	**350**	**370**	**490**	**400**	**430**	**480**	**430**	**490**	**200.0**	**600.0**	**350–490**	**All the samples are above the acceptable limit and below the permissible limit**
Ca (ppm)	**140.3**	**84.2**	**80.2**	**100.2**	**92.2**	**96.2**	**100.2**	**92.2**	**96.2**	**75.0**	**200.0**	**80.160–140.280**	**All the samples are above the acceptable limit and below the permissible limit**
Mg (ppm)	**34.0**	**34.0**	**41.3**	**58.4**	**41.3**	**46.2**	**55.9**	**48.6**	**60.8**	**30.0**	**100.0**	**34.048–60.800**	**All the samples are above the acceptable limit and below the permissible limit**
Cl (ppm)	**148.9**	**74.4**	**102.8**	**99.3**	**99.3**	**85.1**	**85.1**	**78.0**	**120.5**	**250.0**	**1000.0**	**74.445–148.890**	**All the samples are in acceptable limits.**
SO_4^{2-} (ppm)	**13.0**	**16.0**	**19.0**	**25.0**	**22.0**	**23.0**	**11.0**	**10.0**	**17.0**	**200.0**	**400.0**	**10 25**	**All the samples are within the acceptable limits.**
NO^{3-} (ppm)	**2.5**	**6.0**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**45.0**	**No relaxation**	**2.5–6**	**All the samples are within acceptable limits.**
F (ppm)	**1.6**	**1.3**	**1.0**	**1.3**	**1.6**	**2.0**	**1.1**	**1.1**	**1.7**	**1.0**	**1.5**	**1.020–1.960**	**Five samples are within acceptable limits, and four samples (A1, B2, B3, and C3) are above the acceptable limit and below the permissible limits.**
As (ppb)	**2.6**	**0.5**	**0.5**	**0.5**	**1.4**	**0.5**	**0.5**	**0.5**	**1.2**	**0.0**	**0.1**	**0.5–2.560**	**All the samples are above the permissible limits.**
Pd (ppb)	**0.5**	**0.3**	**0.3**	**0.4**	**0.4**	**0.4**	**0.3**	**0.4**	**0.5**	**0.0**	**No relaxation**	**0.250–0.514**	**All the samples are above the permissible limits.**
Ba (ppb)	**105.0**	**192.2**	**59.7**	**103.0**	**114.4**	**84.6**	**88.9**	**127.9**	**196.7**	**0.7**	**No relaxation**	**59.683–196.734**	**All the samples are above the permissible limits.**
U (ppb)	**2.7**	**1.9**	**3.2**	**1.6**	**3.3**	**2.6**	**1.0**	**3.7**	**2.2**		**0.0**	**0.997–3.745**	**All the samples are above the permissible limits.**

ride is likely geogenic, derived from the weathering of fluoride-bearing minerals in granitic rocks, given the regional lithology.

4.3. Toxic Elements

All water samples exhibited elevated levels of toxic elements relative to both national and international safety standards. These include: Arsenic: 0.5–2.56 ppm, Uranium: 0.997–3.75 ppm, Barium: 59.7–196.7 ppm, Palladium: 0.25–0.51 ppm. These concentrations far exceed WHO permissible limits (Smedley and Kinniburgh, 2002; Rao et al., 2012), raising serious concerns for both human consumption and agricultural application. The likely source is geogenic leaching from granitoid rocks, possibly enhanced by weathering and mineral dissolution.

5. Hill Piper trilinear and Quadra linear Plot (Hydro-chemical facies and water type)

The Piper trilinear diagram, introduced by Piper (1944), is a widely used tool for assessing water quality, particularly for domestic and drinking purposes. This diagram features two triangular fields one for major cations (Ca^{2+}, Mg^{2+}, and Na^{+} + K^{+}) and another for major anions (HCO_3^{-}, SO_4^{2-}, and Cl^{-}) as well as a central diamond-shaped field that integrates both ion groups. Cations and anions are plot-

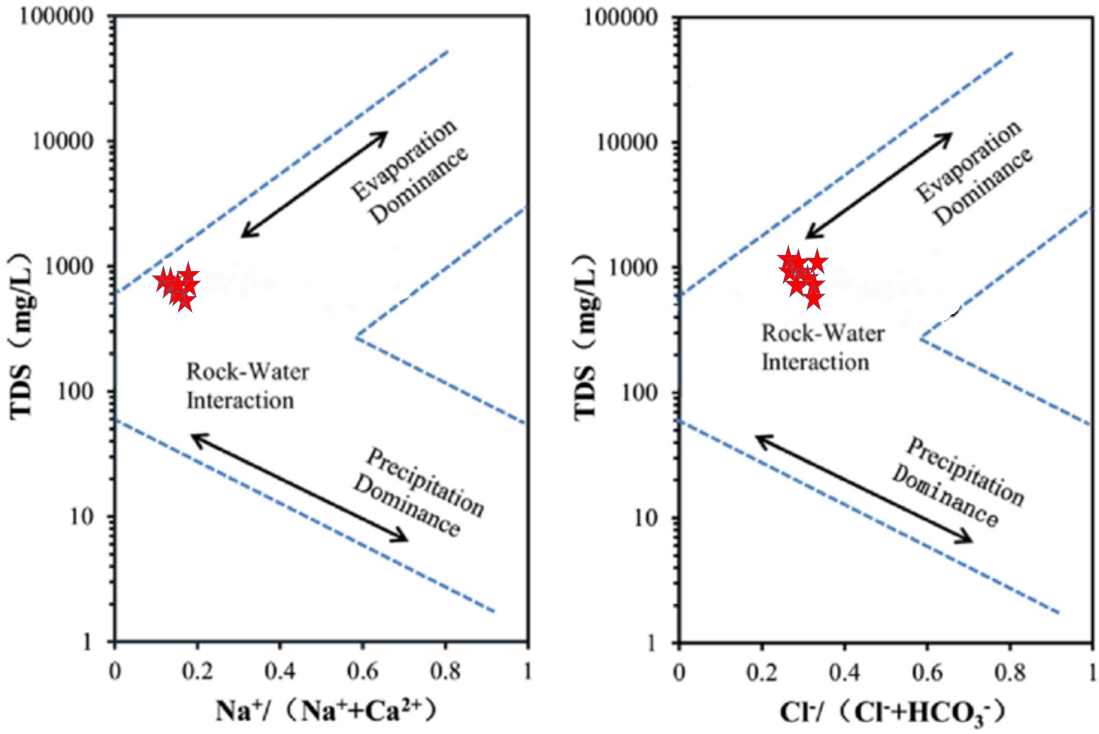

Fig. 3. Gibbs diagram showing the mechanisms controlling the water chemistry of the stream water of the study area.

ted as percentages within their respective triangles, and their intersection within the diamond provides insight into the overall hydrochemical character of the water. Piper diagrams classify water types into six distinct fields based on these ion proportions (Piper, 1944) and are I. Ca–HCO_3 type, II. Na–Cl type, III. Ca–Mg–Cl type, IV. Ca–Na–HCO_3 type, V. Ca–Cl type and VI. $NaHCO_3$ type

Upon plotting the analytical data from nine stream water samples in Jagtial District, Telangana (Fig. 2), it is evident that calcium is the dominant cation, reflecting the influence of calcium-rich source rocks such as those containing amphibole (hornblende) and/or pyroxene (augite, diopside) minerals. The anion data indicate that bicarbonate (HCO_3^-) is the most prevalent anion, could be due to the rock-water interactions as well as the decomposition of organic matter and root respiration in the soil zone (Hem, 1985; Todd and Mays, 2004). All samples plot within the magnesium-bicarbonate type on the Piper diagram. In the cation triangle, samples fall within the “no dominant type” category, while in the anion triangle, they consistently cluster as “bicarbonate type.” The observed hydrochemical characteristics collectively indicate that the stream waters in the study area are influenced by both geogenic and anthropogenic processes. The dominant signature reflects intensive water–rock interaction, governed by the local lithology, along with the impact of prolonged agricultural activity, particularly the extensive application of fertilizers and pesticides, which has contributed to the mobilization and enrichment of various chemical constituents in the stream water (Rao et al., 2012).

6. Gibbs diagram

The Gibbs diagram is a widely used tool for evaluating the interrelationship among hydrochemical constituents and discerning the dominant hydrogeochemical processes influencing water chemistry (Gibbs, 1970; Singh et al., 2020). This approach distinguishes between three principal mechanisms i.e., precipitation dominance, rock–water interaction, and evaporation dominance which control the chemical evolution of natural waters. In the present study, Gibbs diagrams were constructed for both cations and anions by plotting the ratios of $(Na^+ + K^+)/ (Na^+ + K^+ + Ca^{2+})$ and $Cl^-/(Cl^- + HCO_3^-)$ against total dissolved solids (TDS) for the stream water samples (Fig. 3). The distribution of the data points falls within the rock–water interaction and evaporation dominance fields, indicating that the hydrochemistry of the stream waters is primarily governed by

Table 3. SAR classification of water samples.

SAR (in meq/L)	CLASS	QUALITY	No. of Samples
0–10	Low sodium hazard	Excellent	9
10–18	Medium sodium hazard	Good	Nil
18–26	High sodium hazard	Doubtful	Nil
>26	Very high sodium hazard	Unsuitable	Nil

the dissolution of minerals from the underlying granitoid, amphibolite, and carbonate lithologies, as well as by evaporative concentration processes prevalent in the semi-arid climatic setting of Jagtial District and is correlatable with the TDS and EC. All samples plot within the rock–water interaction domain. This trend reflects mineral dissolution from granitoid and carbonate-bearing rocks under semi-arid conditions. Minimal clustering in the precipitation dominance field supports the limited influence of direct rainfall on stream (Gibbs, 1970; Singh et al., 2020).

7. Irrigational water quality

The suitability of stream water for irrigation in the Jagtial District is evaluated through its salinity and sodium hazard, both of which are critical for sustaining soil structure, crop productivity, and long-term agricultural viability (Richards, 1954; Todd, 1959; Karanth, 1989). Electrical conductivity (EC) is a key parameter influencing the accumulation of salts in soils, with elevated EC values potentially leading to detrimental effects on plant growth and soil permeability (WHO, 2017). The dissolved salts in irrigation water, derived from the weathering of local granitic, gneissic, and carbonate lithologies as well as anthropogenic sources, include major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (CO ^{2} , HCO_3^{-}, SO_4^{2-}, Cl^{-}), which collectively determine the hydrochemical character and agricultural suitability of the water (Raghunath, 1987; Collins and Jenkins, 1996).

A central index for assessing sodium hazard is the Sodium Adsorption Ratio (SAR), which reflects the relative abundance of sodium to calcium and magnesium. High SAR values are associated with reduced soil permeability and poor internal drainage, negatively impacting crop yields. In the present study, SAR values for all stream water samples ranged from 3.94 to 5.86 (Table 3), well below the critical threshold of 10, thereby classifying the water as "excellent" for irrigation use (Richards, 1954; Todd, 1959). This suggests minimal risk of sodicity-related soil degradation under current conditions.

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\frac{1}{2}(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+})}},$$

where all the concentrations are in epm value.

The sodium percentage (Na%), another important metric, ranged from 19.64% to 26.45% across the samples (Table 4), remaining comfortably below the 60% maximum recommended for irrigation waters. Elevated sodium levels can lead to deflocculation of soil particles, reduced permeability, and ultimately, poor crop performance (Karanth, 1989). However, the observed Na% values indicate that the stream water is suitable for irrigation without significant risk of sodium-induced soil structure deterioration.

$$\mathrm{Na\%} = \frac{(\mathrm{Na}^{+} + \mathrm{K}^{+})}{(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{Na}^{+} + \mathrm{K}^{+})}$$

Table 4. Water Classes Based on Percent Sodium (After Wilcox, 1955).

% Sodium	Water Class	No. of samples
<20	Excellent	1 (C1)
20–40	Good	08 (All samples except C1)
40–60	Permissible	Nil
60–80	Doubtful	Nil
>80	Unsuitable	Nil

Despite these favorable indices, it is crucial to note that the presence of toxic element such as arsenic and uranium in concentrations exceeding permissible limits (Table 1) poses an additional risk to agricultural sustainability and food safety, underscoring the need for integrated monitoring and management strategies (Smedley and Kinniburgh, 2002; Rao et al., 2012). Overall, while the stream waters in Jagtial District are classified as suitable for irrigation based on SAR and Na% values, ongoing assessment of both conventional and toxicological parameters is essential for ensuring long-term agricultural productivity and environmental health.

Based on the distribution of SAR and EC values (Fig. 4a), all water samples—except for A1 and C3—fall within the C2–S1 category, indicating medium salinity and low sodium hazard, and are thus considered suitable for irrigation. The Wilcox diagram

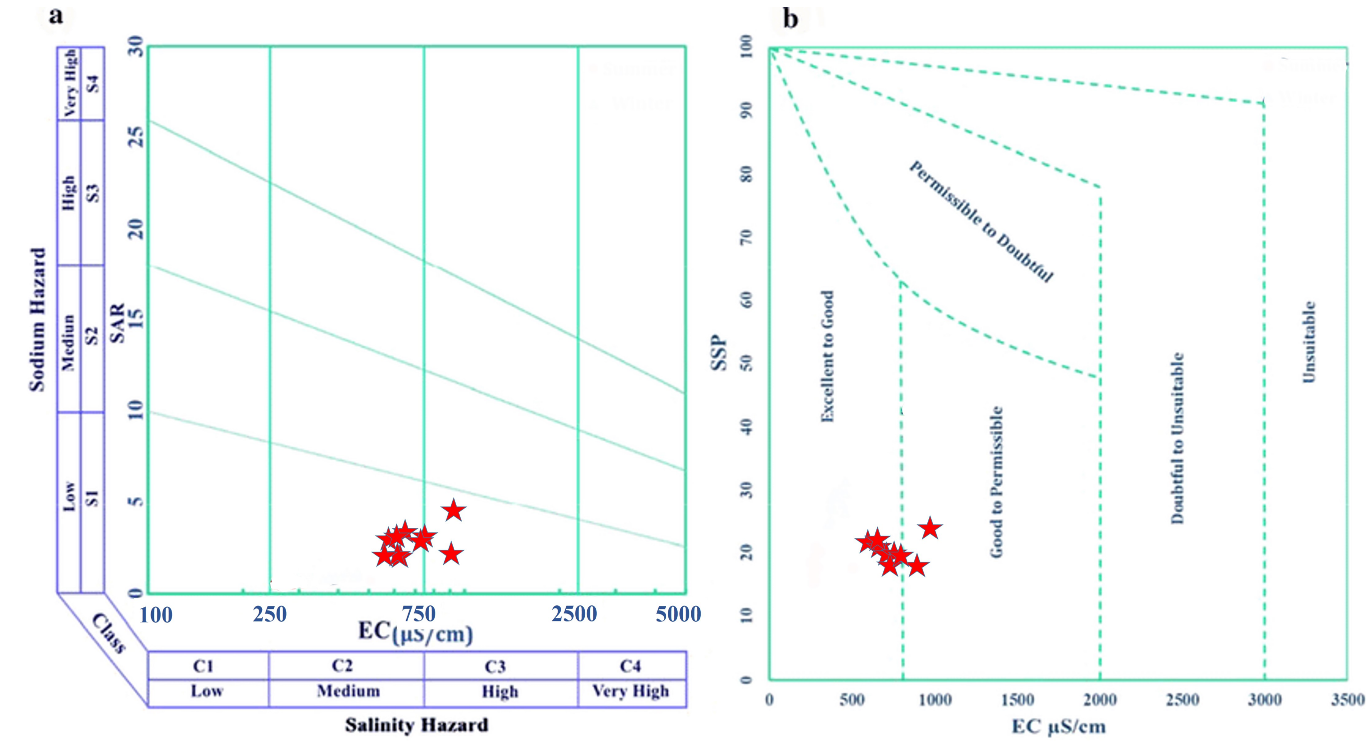

Fig. 4. Irrigation water quality diagrams (a) USSL diagram, used for the categorization of irrigation water quality based on salinity and sodium hazard (b) Wilcox diagram, water quality classification based on percent sodium and electrical conductivity (after Wilcox, 1955).

(Wilcox, 1955), which evaluates the combined impact of salinity and sodium percentage on water quality, was employed for further assessment. Elevated sodium levels in irrigation water can adversely affect soil permeability and hinder plant growth (Roy et al., 2018). According to the Wilcox classification (Fig. 4b), the water samples range from permissible to excellent categories, suggesting that the majority of the samples are safe for irrigation use.

Despite favorable parameters such as SAR and sodium percentage indicating excellent suitability for irrigation, the stream water samples exhibit elevated concentrations of toxic elements—notably arsenic (0.5–2.56 ppm), uranium (0.997–3.75 ppm), barium (59.7–196.7 ppm), and palladium (0.25–0.51 ppm). These values substantially exceed the permissible limits set by WHO and other international guidelines. These elevated levels pose a significant risk to soil health, crop productivity, and long-term agricultural sustainability, as these elements can be absorbed by crops and enter the food chain, warranting further agronomic and toxicological evaluations.

8. Industrial Use

8.1. Physical Parameters and General Use Potential

The stream water samples from Jagtial District exhibit pH values between 7.64 and 7.91, which fall within the acceptable range for most industrial processes and pose minimal corrosion or scaling risks (BIS, 2012; WHO, 2017). Total Dissolved Solids (TDS) range from 325 to 596 mg/L. While two samples slightly exceed the BIS acceptable limit of 500 mg/L, all remain well below the permissible limit of 2000 mg/L, suggesting moderate mineralization. Such TDS levels are generally suitable for non-contact applications like cooling systems, construction, and textiles, where ultra-pure water is not essential (Raghunath, 1987; Todd and Mays, 2004). However, Total Hardness (TH) values between 350 and 490 mg/L exceed the BIS acceptable limit of 200 mg/L, indicating a high scaling potential. For industries sensitive to hardness—such as boiler operations, textile finishing, and electronics manufacturing—pretreatment through lime softening, membrane filtration, or ion exchange is advisable (Karanth, 1989).

8.2. Toxicological Implications and Treatment Requirements

All samples reveal consistently elevated concentrations of arsenic (0.5–2.56 ppm), uranium (0.997–3.75 ppm), barium (59.7–196.7 ppm), and palladium (0.25–0.51 ppm). These levels significantly exceed both potable and industrial water quality standards (Smedley and Kinniburgh, 2002; Rao et al., 2012; WHO, 2017). The Bureau of Indian Standards (BIS) and the Central Pollution Control Board (CPCB) have established thresholds for heavy metals in industrial effluents, and exceedance of these values may lead to regulatory non-compliance and environmental penalties. Industries requiring high-purity water—such as pharmaceuticals, food and beverage production, electronics, and precision manufacturing—are particularly at risk, as these elements can contaminate products or damage sensitive equipment. Effective mitigation requires the deployment of advanced water treatment technologies, including reverse osmosis for uranium and palladium, ion exchange systems for barium, and adsorption filters or activated alumina for arsenic removal (Collins and Jenkins, 1996; WHO, 2017). Routine water quality monitoring and process-specific remediation strategies are essential to ensure operational safety, product integrity, and compliance with environmental discharge norms.

9. Discussion

9.1. Geogenic Controls on Hydrogeochemistry

The hydrogeochemical characteristics of stream waters in the Jagtial District are primarily governed by intensive rock–water interaction, underpinned by the region's diverse lithological units, including granites, amphibolites, and limestones of the Karimnagar Granulite Belt and Peninsular Gneissic Complex (Rajesham et al., 1993; Karanth, 1989). The slightly alkaline pH (7.64–7.91) and moderate TDS (325–596 mg/L) observed across all samples can be attributed to mineral weathering and evaporative concentration, typical of semi-arid climatic conditions (Hem, 1985; Todd and Mays, 2004). Elevated total hardness (350–490 mg/L) is consistent with the dissolution of calcium- and magnesium-bearing minerals such as calcite, amphibole, and plagioclase.

Hydrochemical facies identified from Piper diagrams confirm that magnesium-bicarbonate water types dominate, found in all nine samples, indicative of significant carbonate and silicate weathering. Simultaneously, Gibbs plots show that 7 out of 9 samples fall within the rock–dominance field, reinforcing the interpretation that water chemistry is lithologically controlled (Gibbs, 1970; Singh et al., 2020).

Of critical concern is the consistent detection of trace elements—notably arsenic (0.5–2.56 ppm), uranium (0.997–3.75 ppm), barium (59.7–196.7 ppm), and palladium (0.25–0.51 ppm)—at concentrations well above national and international safety thresholds (Smedley and Kinniburgh, 2002; Rao et al., 2012; WHO, 2017). These are likely mobilized through geogenic weathering of mineralized supracrustal rocks, granitoids, and associated accessory phases, including uraninite, arsenopyrite, and barite.

9.2. Anthropogenic Contributions and Trace Metal Mobilization

While geogenic processes serve as the principal source of major and trace elements, anthropogenic influences, especially from agricultural intensification, also play a significant role. The study area experiences extensive cultivation, and the application of phosphate fertilizers, agrochemicals, and irrigation return flows may be contributing to enhanced mobility of arsenic and uranium in the subsurface and surface waters (Rao et al., 2012; Smedley and Kinniburgh, 2002).

In particular, arsenic and uranium are known to associate with phosphate complexes, and their mobility may increase in oxidizing conditions with elevated phosphate loading—a scenario consistent with catchments undergoing intensive cropping. Although direct fertilizer data for the study area were not available, the land use patterns and agricultural practices imply a high potential for agrochemical-induced mobilization.

Furthermore, the slightly higher TDS and NO_3^- concentrations in samples A1 and C3, both collected downstream of agricultural fields, may suggest localized impacts from runoff and leaching of fertilizer residues. These inputs, though secondary to lithological control, represent a critical pathway for sustained contamination, especially under conditions of low runoff and high evapotranspiration.

9.3. Resource Implications and Suitability Assessment

9.3.1. Agricultural Use

All samples exhibit low SAR values (3.94–5.86) and Na% well below 60%, placing them in the "Excellent" category for irrigation suitability (Richards, 1954). However, the ubiquitous presence of toxic metals, particularly arsenic and uranium, raises long-term concerns for soil degradation, plant toxicity, and bioaccumulation risks (Smedley and Kinniburgh, 2002). Regular soil–water–crop monitoring is thus essential, especially in areas reliant on stream water for irrigation.

9.3.2. Industrial Use

From an industrial perspective, pH and TDS values fall within acceptable ranges for non-contact and general-purpose industrial processes (BIS, 2012; WHO, 2017). However, high total hardness could lead to scaling in boilers, heat exchangers, and cooling systems, requiring pre-treatment via lime softening or nano-filtration (Karanth, 1989).

More critically, the consistently elevated levels of arsenic, uranium, barium, and palladium pose challenges for industries such as electronics, pharmaceuticals, and food processing, which demand high-purity water (Collins and Jenkins, 1996; WHO, 2017). These toxicants may also render industrial effluents non-compliant with CPCB discharge norms, necessitating advanced treatment technologies. Recommended systems include: Ion exchange resins for uranium and barium, Adsorption media (e.g., activated alumina, iron hydroxides) for arsenic, Reverse osmosis (RO) for broad-spectrum removal of elements, etc.

9.3.3. Integrated Water Management and Monitoring Needs

The interplay of geogenic weathering, agricultural inputs, and semi-arid hydrodynamics has resulted in a complex hydrochemical regime in the Jagtial District. While the waters remain suitable for irrigation and some industrial uses, the presence of multiple toxic elements and mineral-induced hardness necessitate a multi-pronged water management strategy. This includes:

Routine monitoring of both physical and chemical water quality

Source-specific treatment for high-risk contaminants

Regulatory alignment with BIS and CPCB standards

Sustainable agricultural practices to minimize agrochemical runoff

10. Conclusion

This comprehensive hydrogeochemical assessment of stream waters in the Jagtial District, Telangana, reveals a complex interplay between the region's varied lithology and anthropogenic influences, resulting in significant enrichment of toxic elements. The underlying geology—including Archean high-grade supracrustals, Peninsular Gneissic Complex-II granitoids, and Pakhal Supergroup sediments—plays a crucial role in establishing the baseline hydrochemistry, as reflected in the dominance of calcium, magnesium, and bicarbonate ions. Key physicochemical parameters such as pH (7.64–7.91), TDS (325–596 mg/L), and total hardness (350–490 mg/L) indicate that the surface waters are moderately mineralized and hard, with values generally within or slightly exceeding the recommended limits for domestic and industrial use (BIS, 2012; WHO, 2017). Notably, of the nine samples analyzed, 100% exceeded WHO permissible limits for at least one toxic element, particularly arsenic (0.5–2.56 ppm), uranium (0.997–3.75 ppm), barium (59.7–196.7 ppm), and palladium (0.25–0.51 ppm), all well above national and international safety standards (Smedley and Kinniburgh, 2002; Rao et al., 2012). While major ion chemistry and irrigation suitability indices (SAR, sodium percentage, Wilcox classification) suggest the waters are generally suitable for agriculture, elevated concentrations of toxic elements pose a considerable risk to food safety and public health via their potential for bioaccumulation.

Given these findings, there is an urgent need for integrated water resource management in the region. Establishing a district-level water quality surveillance program, alongside targeted geochemical mapping of vulnerable zones, is essential to safeguard community health and sustainable agricultural productivity. Alignment with state-level groundwater and watershed management initiatives, such as the Jal Shakti Abhiyan, should be prioritized to ensure routine monitoring, adoption of advanced treatment technologies, and implementation of effective mitigation strategies. Without these interventions, continuing geogenic and anthropogenic contamination is likely to compromise the long-term suitability of stream waters for domestic, agricultural, and industrial applications in part of the Jagtial District.

Acknowledgements

The authors sincerely acknowledge the Additional Director General and Head of Department, Geological Survey of India (GSI), Southern Region (SR), Hyderabad, for the continuous support and facilitation of necessary resources, which were vital for the successful completion of the field season programme in Jagtial District, Telangana. We are deeply grateful to the Deputy Director General (DDG), Regional Mission Head, GSI, SR, and the DDG, State Unit: Telangana, for their valuable guidance, encouragement, and administrative support during both field and office phases of the work. The authors also extend heartfelt thanks to senior colleagues and technical staff of GSI, SR, whose constructive feedback and insightful discussions significantly contributed to the refinement of this study. Special appreciation is due to the laboratory teams for their dedicated efforts in conducting precise chemical analyses. The views expressed by the authors are not necessarily the views of the organization to which they belong.

CRediT statement

JS: Conceptualization, Investigation, Methodology, Data generation, Writing – review & editing. TCP: Investigation, Methodology, Data generation, Writing & editing, corresponding author. AAK: Writing, review, editing, supervision.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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