

Hydrogeochemical Assessment of Stream Waters in Parts of Yadadri Bhuvanagiri and Rangareddy Districts, Telangana: Insights into Multipurpose Utilization and Sustainable Management

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Abstract

This study presents a detailed hydrogeochemical assessment of stream waters parts of Yadadri Bhuvanagiri and Rangareddy districts, Telangana, emphasizing the interplay of geological and anthropogenic factors shaping water quality. Nine higher-order stream samples reveal slightly alkaline pH (7.5–8.0) and variable total dissolved solids (395.85–2008.5 mg/L), reflecting rock water interaction alongside contamination from agricultural runoff and industrial effluents. Piper diagram analyses classify waters predominantly as Ca-Cl type (Type V), with sample C3 showing Ca-Mg-Cl characteristics (Type III), underscoring influences of ion exchange and pollution. Gibbs diagrams confirm rock–water interaction and evaporative enrichment as key processes governing solute chemistry. Irrigation suitability indices (SAR: 1.05–23.50; %Na: 9.55–61.58) indicate mostly low to moderate sodium hazards, although high-SAR samples warrant careful management. Industrial water quality assessment identifies challenges from elevated TDS, hardness, and chloride levels, suggesting pretreatment needs to mitigate scaling and corrosion risks. Elevated chloride, sulfate, and nitrate levels highlight anthropogenic impacts, signaling potential public health concerns. This comprehensive evaluation advocates for integrated water resource management incorporating continuous monitoring, targeted remediation, and land-use regulation to ensure sustainable multipurpose utilization and safeguard environmental and human health in this region.

Keywords: Hydrogeochemistry, Stream Water Quality, Sustainable Water Management, Multipurpose Water Use, Rock–Water Interaction

Introduction

Assessing surface water quality is essential for the sustainable management of water resources, as it directly influences their suitability for domestic, agricultural, and industrial applications (Trigun and Sahoo, 2022 and 2024; Choudhary *et al.*, 2025; Ravi *et al.*, 2026). In the present study, stream water samples from the Yadadri Bhuvanagiri and Rangareddy Districts of Telangana were systematically collected from the higher order streams flowing on the diverse geology of the area. The study area encompasses significant lithological units primarily Neoproterozoic granitoids of the Peninsular Gneissic Complex, Neoproterozoic sedimentary rocks, and associated Archean supracrustals which impart distinct mineralogical signatures to stream water chemistry through weathering and dissolution processes (Trigun and Sahoo, 2022; 2024).

Prominent rock types such as hornblende-biotite granite gneiss, banded magnetite quartzite, amphibolite, pegmatite, limestone, and sandstone influence the hydrochemical framework.

These inputs are further modulated by agricultural runoff, urbanization, industrial activities, and expanding infrastructure, resulting in variable concentrations of major solutes and deterioration of water quality in many semi-arid and urban environments (Hem, 1985; Rao *et al.*, 2012; Aslam and Reshma, 2024; Arun *et al.*, 2024; Sahoo *et al.*, 2024, 2025; Sane *et al.*, 2025). Major ions such as Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , HCO_3^- , and SO_4^{2-} serve as critical indicators in regional water quality assessment and facies classification (Todd and Mays, 2004). Evaluating the relationships among these ions, rather than isolated measurements, provides a robust framework for interpreting prevailing water chemistry (Wilcox, 1955; Ayers and Westcot, 1985). Similar hydrogeochemical and groundwater quality investigations have been carried out in different parts of India including Odisha, Chhattisgarh, Karnataka, Maharashtra, and Kerala using hydrochemical indices, GIS techniques, and statistical approaches (Panigrahi and Das, 2022; Chatterjee *et al.*, 2022; Jaunjalkar and Murkute, 2023; Nayak and Hota, 2024).

Supporting parameters such as pH (7.5–8.0), electrical conductivity (EC: 615–3090 $\mu\text{S}/\text{cm}$), total dissolved solids (TDS: 395–2008 mg/l), and total hardness (TH: 280–950 mg/l) as measured across nine stream water samples reflect both geogenic and anthropogenic controls. The assessment benchmarks

hydrochemical results against standards from the Bureau of Indian Standards (BIS, 2012) and the World Health Organization (WHO, 2017), ensuring multi-purpose safety and compliance within the study area. Irrigation water suitability is determined by indices such as Sodium Adsorption Ratio (SAR: 1.05–23.50) and Percentage of Sodium (Na%: 5.2–37.7%), which are vital for maintaining soil health and crop productivity (Ayers and Westcot, 1985). Facies characterization is accomplished using Piper trilinear diagrams to visualize cation-anion trends and dominant water types (Todd and Mays, 2004).

Preliminary hydrochemical profiling in the study area indicates a dominant Ca-Cl water type, consistent with extensive ion exchange processes and the weathering of granitoid and sedimentary bedrock. Additionally, marked heterogeneity in sodium, potassium, and chloride concentrations points to localized enrichment from agricultural runoff and untreated wastewater, specifically in lower catchment samples. These findings underscore the need for adaptive, region-specific water governance and ongoing assessment to ensure safe, sustainable utilization of stream water resources.

Despite the hydrogeological importance of the region, detailed hydrogeochemical information on stream waters from parts of Yadadri Bhuvanagiri and Rangareddy districts remains limited, particularly with respect to integrated evaluation for domestic, irrigation, and industrial suitability. Therefore, the present study aims to assess the physicochemical characteristics, hydrochemical facies, irrigation suitability, and industrial applicability of stream waters and to understand the influence of geogenic and anthropogenic factors controlling water chemistry in the study area.

This integrated evaluation underscores the critical need for continuous monitoring and region-specific water management strategies to mitigate emerging risks from localized contamination and to promote sustainable utilization of stream water resources in Yadadri Bhuvanagiri and Rangareddy Districts.

Geological Setting

Regional Geology

The study area, encompassing parts of Yadadri Bhuvanagiri and Rangareddy districts in Telangana (Survey of India Toposheet 56K/15), lies within the Eastern Dharwar Craton (EDC), a Neoproterozoic to Paleoproterozoic segment of the Indian Shield notable for its complex tectono-metamorphic evolution. The EDC is delineated from the Western Dharwar Craton by major crustal discontinuities, notably the Closepet Granite Batholith and the Chitradurga Boundary Fault, which mark suture zones and record a protracted history of crustal accretion and reworking spanning 3.0 to 2.5 Ga (Gokarn *et al.*, 2004). This craton is characterized by widespread TTG (tonalite-trondhjemite-granodiorite) gneisses, calc-alkaline granitoids, and supracrustal greenstone belts, representing episodic magmatic and metamorphic events shaped by intracontinental collisions and plume-related magmatism.

The physiography of the region exhibits gently undulating pediplains, inselbergs, and granitic hills sculpted by pervasive mafic dyke swarms oriented in multiple structural trends, which together control drainage architecture dominated by the Musi River and its tributaries (Chinna Musi and Chinnaeru). Drainage manifests predominantly dendritic and locally trellis patterns,

reflecting lithological contrasts and tectonic controls that modulate surface and subsurface hydrological regimes (Trigun and Sahoo, 2022). Geophysical surveys reveal east-dipping thrusts, shear zones, and suture complexes that corroborate the Neoproterozoic collisional and accretionary tectonics, providing a mantle-to-crust perspective on the craton's evolution (Gokarn *et al.*, 2004).

Local Geology

Lithologically, the area is dominated by the Peninsular Gneissic Complex-II (PGC-II), consisting of hybrid granite gneisses, grey hornblende-biotite granite gneisses, grey and pink biotite granites, alkali-feldspar granites, as well as leucogranites and pegmatites (Fig. 1). Sparse amphibolite and schist enclaves, representing the Dharwar Supergroup, attest to ancient supracrustal sequences that were subjected to high-grade metamorphism (Praveen *et al.*, 2024; Trigun and Sahoo, 2022). These crystalline basement rocks are transected by mafic dykes (dolerite and pyroxenite) with variable orientation and morphological expression reflective of multiple intrusive phases during Proterozoic to Mesozoic epochs.

Petrographic assemblages dominated by quartz, K-feldspar, plagioclase, biotite, and hornblende display geochemical enrichment in trace elements such as Ba, Co, V, and Zr, which importantly modulate the hydrogeochemical characteristics of stream water and surface waters within these lithologies, underscoring a strong linkage between lithology, geochemical signatures, and environmental resources (Praveen *et al.*, 2024). Economically, these granitoids and associated dolerite dykes serve as principal sources of construction materials and dimension stone, with quartz reefs holding potential industrial relevance.

The granitoids, granite gneisses, amphibolites, and carbonate-bearing lithologies of the study area play a significant role in controlling stream water chemistry through mineral weathering and rock-water interaction processes. Weathering of feldspars, ferromagnesian minerals, and carbonate phases contributes to the enrichment of major ions such as Ca^{2+} , Mg^{2+} , Na^+ , HCO_3^- , and Cl^- in stream waters, thereby influencing alkalinity, hardness, TDS, and hydrochemical facies observed in the study area.

Materials and Methods

Stream water sampling was systematically conducted during the post-monsoon season of 2021 across select parts of Yadadri Bhuvanagiri and Rangareddy District, Telangana, employing a well-defined 5' × 5' grid design corresponding to Survey of India Toposheet No. 56K/15 (Trigun and Sahoo, 2022) (Table 1; Fig. 1). Nine systematically chosen higher-order stream locations were targeted to encompass the spatial heterogeneity of hydrogeochemical parameters across the region. The sampling locations were selected to represent different lithological units, drainage characteristics, and upstream land-use conditions within the study area. Sampling adhered rigorously to multi-protocol guidelines standardized by the National Geochemical Mapping Program (NGCM) standard operating procedures (SOPs) of 2014 and 2021.

Water collection for ion chromatography (IC) entailed acquiring 500 ml samples by fully submerging pre-cleaned containers to mitigate atmospheric contamination. For inductively

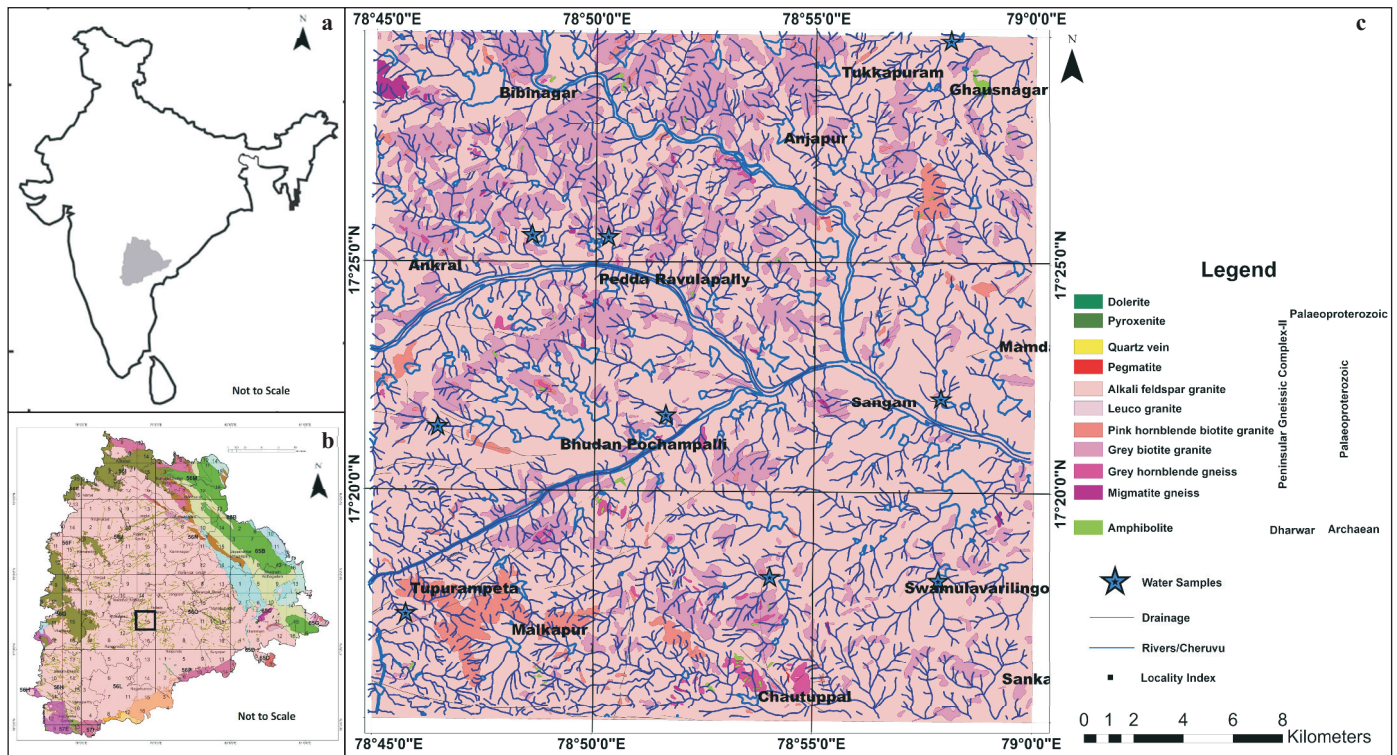


Fig. 1. a. Location map of Telangana in India map; b. Geological map of Telangana showing location of the Toposheet no. 56K/15; c. Drainage map with sample locations overlay on the geology of the Toposheet no. 56K/15, parts of Yadadri Bhuvanagiri and Rangareddy district, Telangana (Source: Trigun and Sahoo, 2022)

coupled plasma mass spectrometry (ICP-MS) analyses, aliquots of 100 ml were acidified with 1.0 ml concentrated nitric acid (HNO₃) within 24 hours of collection. Additionally, 60 ml of water, filtered yet unacidified, was reserved for dissolved organic carbon (DOC) analysis, while 100 ml aliquots, preserved with HNO₃ and potassium dichromate (K₂Cr₂O₇), were allocated for mercury quantification. All containers were pre-rinsed thrice with site water to prevent contamination.

In situ physicochemical parameters, including pH and electrical conductivity (EC), were measured immediately following sampling using portable meters to preserve data integrity. Standard quality assurance and quality control (QA/QC) procedures as per NGCM SOP guidelines were followed during sample collection, preservation, transportation, and laboratory analysis. Pre-cleaned sampling containers, proper filtration, acid preservation, and calibrated analytical instruments were used to maintain analytical reliability and minimize contamination during the study. Analytical procedures were performed at GSI laboratory facilities following standard operational protocols.

To validate the analytical accuracy of major ion chemistry, ion balance error (charge balance error, CBE) calculations were carried out for all water samples. Major cations (Ca²⁺, Mg²⁺, Na⁺, and K⁺) and major anions (HCO₃⁻, Cl⁻, SO₄²⁻, and NO₃⁻ where applicable) were converted from mg/L to milliequivalents per liter (meq/L). The charge balance error was calculated using the relation:

$$CBE (\%) = \frac{(\sum \text{cations} - \sum \text{anions})}{(\sum \text{cations} + \sum \text{anions})} \times 100 \dots (1)$$

Analytical results with charge balance error within ±5% were considered excellent, while values within ±10% were considered acceptable for natural water samples. The ion balance assessment confirmed the reliability and internal consistency of the hydrochemical dataset used for interpretation.

Results

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

Physicochemical Parameters

The pH of all stream water samples ranged from 7.5 to 8.0, 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 395.85 and 2008.50 mg/l. Two samples (A3 and C3) are within acceptable limits, six samples (A1, A2, B1, B3, C1, and C2) are above the acceptable limit and below the permissible limits. B2 sample is above the permissible limit (BIS, 2012). Electrical Conductivity (EC) values ranged from 508 to 931 μS/cm, following the TDS trends. Total Hardness (TH) ranged from 280 to 950 mg/L, exceeding the BIS acceptable limit (200 mg/l). All the samples are above the acceptable limit, six samples are below permissible limit, one sample (B2) is above Permissible limit., implying considerable calcium–magnesium enrichment likely derived from host lithologies (Karanth, 1987; Rajamani *et al.*, 1985).

The major ion geochemistry is characterized by variable concentrations of key cations and anions. Calcium concentrations ranged from 48.1 to 176.35 ppm, magnesium from 21.89 to 124.03 ppm, while sodium and potassium exhibited significant variability, with sodium reaching up to 288 ppm in sample B2 and potassium

peaking at 89.1 ppm in sample C1. Anionic concentrations of bicarbonate (HCO_3^-) were notably high between 305.1 and 537 ppm, consistent with alkaline pH. Chloride (Cl^-) levels showed high variability, 42.54 to 510.48 ppm, with several samples exceeding the acceptable limit of 250 ppm, notably B2 and C1, suggesting contamination likely from anthropogenic sources. Similar enrichment of dissolved ions, nitrate, and fluoride associated with anthropogenic activities and agricultural practices has also been reported from different parts of India (Arun *et al.*, 2024; Sane *et al.*, 2025). Sulphate (SO_4^{2-}) concentrations ranged from 15.72 to 165 ppm, all within acceptable limits but elevated enough to indicate possible industrial or agricultural influence. Nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations were within acceptable limits but showed elevated values in some samples indicating agricultural runoff impact. These ionic patterns suggest surface water contamination influenced by agricultural fertilizers, pesticides, and industrial waste, corroborated by seasonal dynamics of post-monsoon recharge and river flooding events in the region.

Hydro-chemical Facies and Water Type (Hill Piper Trilinear and Quadralinear Plot)

Piper (1944) proposed this diagram for determining the quality of water for domestic purposes especially for drinking. The piper diagram has two triangles (cations and anions) and central diamond shape (combined). Cations plotted as percent on Ca-Mg-(Na+K) triangle and the anions plotted as percent on HCO_3^- - SO_4 -Cl triangle. Points on the triangles are projected up to where they intersect on the diamond.

The axes of the trilinear and Quadralinear are read in different directions. Cations are read with values increasing clockwise along each side of the trilinear diagram from 0% to 100%. Ca is on the bottom axis of the left triangle ranging from 0% on the right end to 100% on the left end of the axis. Mg is on the left leg ranging clockwise from 0% at the bottom to 100% at the top of the triangle. Similarly, (Na + K) is on the right leg ranging clockwise from 0% at the top to 100% at the bottom.

Anions in the right triangle are read in anti-clockwise direction along each side in a similar way. Cl is plotted along the bottom axis, SO_4 or, ($\text{SO}_4 + \text{NO}_3$) along the right leg and ($\text{HCO}_3 + \text{CO}_3$) along the left leg.

Location of the datapoint in each diagram is then projected up into quadrilinear until intersection. Thus, each sample plots in each form of the Piper diagram once representing cations, once representing anions and once representing combination which reflect the classification of water.

The ions of Ca, Mg, Na, K, HCO_3 , SO_4 , Cl are considered for plotting Piper diagram. All the ions were converted to milli equivalent/L *i.e.*, divide by formula weight and multiply by charge. Then normalize Ca, Mg, Na + K to 100% and HCO_3 , SO_4 , Cl to 100%.

Piper divided the water into four basic types according to their placement near the four corners of the diamond. Water that plots at the top of the diamond is high in $\text{Ca}^{2+} + \text{Mg}^{2+}$ and the $\text{Cl}^- + \text{SO}_4^{2-}$, which results in an area of permanent hardness. The water that plots near the left corner is rich in $\text{Ca}^{2+} + \text{Mg}^{2+}$ and HCO_3^- and is the region of water of temporary hardness. Water plotted at the lower corner of the diamond is primarily of high alkali and carbonates ($\text{Na}^+ + \text{K}^+$ and HCO_3^- , CO_3^{2-}). Water lying near the right-hand side of the diamond may be considered as saline ($\text{Na}^+ + \text{K}^+$ and $\text{Cl}^- + \text{SO}_4^{2-}$).

In general, we can classify the sample points in the piper diagram into 6 fields. They 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 VI. NaHCO_3 type

After plotting the analytical values of water samples on piper trilinear plot, it is observed that, the majority of water samples are falling in the Ca-Cl field and are classified as Type-V water, reflecting the influence of ion exchange processes and mixed geogenic-anthropogenic contributions. Although Ca-Cl facies are commonly associated with evolved hydrochemical conditions, the relatively moderate TDS and salinity levels in most samples indicate comparatively fresh to moderately mineralized stream water within the study area (Fig. 2).

Thus, it has been derived that, the water of the study area is showing clear imprints of industrial activities, cross-contamination of nearby drainages from polluted Musi River, prolonged agricultural practices aided with prolific use of fertilizers and pesticides, etc which may have interacted with surface water and left behind hard Ca-Cl type of water rich in chlorides, sulphates, potassium, and sodium.

Table 1: Detailed list of stream water samples collected from T.S. No. 56K/15

| Quad-rant No. | Latitute | Longitude | Order of Stream | Locality |
|---------------|-------------|-------------|-----------------|----------------------------------|
| A1 | 17°25'36.6" | 78°48'34.9" | 2 nd | East of Ankirala |
| A2 | 17°21'25.1" | 78°46'29.4" | 3 rd | West of Bhudan Pochampalli |
| A3 | 17°17'20.1" | 78°45'38.8" | 3 rd | Near Tooparampeta |
| B1 | 17°25'35.3" | 78°50'18.3" | 3 rd | North of Pedda Ravulapally |
| B2 | 17°21'44.3" | 78°51'37.9" | 2 nd | North East of Bhudan Pochampalli |
| B3 | 17°18'6.1" | 78°53'51.6" | 3 rd | Near Chinna Kondur |
| C1 | 17°29'51.9" | 78°57'57.9" | 3 rd | North of Tukkapuram |
| C2 | 17°22'3.7" | 78°57'54.6" | 3 rd | East of Sangam |
| C3 | 17°17'51.5" | 78°57'45.6" | 3 rd | Near S.Lingotom |

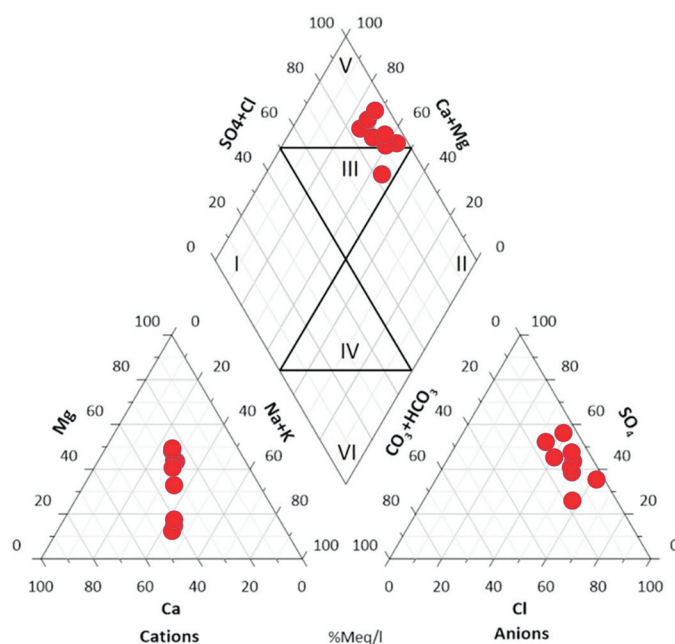


Fig. 2. Hill Piper Trilinear Plot of the water sample data collected from toposheet no.56K/15

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 | 7.7 | 7.5 | 7.8 | 7.9 | 7.6 | 7.6 | 7.6 | 8 | 7.8 | 6.5-8.5 | No relaxation | 7.5- 8.0 | All values are within the acceptable limits. |
| TDS | 908.7 | 904.15 | 395.85 | 607.75 | 2008.5 | 882.05 | 1488.5 | 542.75 | 399.75 | 500 | 2000 | 395.85-2008.50 | Two samples (A3 and C3) fall within the acceptable limits, while six samples (A1, A2, B1, B3, C1, and C2) exceed the acceptable limits but remain below the permissible threshold. In contrast, sample B2 exceeds the permissible limit. |
| TH | 400 | 460 | 295 | 350 | 950 | 370 | 560 | 370 | 280 | 200 | 600 | 280-950 | All the samples are above the acceptable limit, six samples are below permissible limit One sample (B2) is above Permissible limit. |
| Ca | 100.2 | 108.22 | 48.1 | 68.14 | 176.35 | 64.13 | 132.26 | 96.19 | 76.15 | 100.2 | 200 | 48.10-176.35 | All the samples are above the acceptable limit and below the permissible limit |
| Mg | 48.64 | 46.21 | 42.56 | 38.91 | 124.03 | 58.37 | 68.1 | 31.62 | 21.89 | 30 | 100 | 21.89-124.03 | One sample (C3) is within the acceptable limit. 07 samples (A1, A2, A3, B1, B3, C1 and C2) are above acceptable limit and below permissible limit. One sample (B2) is above permissible limit. |
| Cl | 255.24 | 184.34 | 42.54 | 106.35 | 510.48 | 262.33 | 404.13 | 85.08 | 42.54 | 250.00 | 1000 | 42.54-510.48 | Five samples (A2, A3, B1, C2 and C3) are within acceptable limits, Four samples (A1, B2, B3 and C1) are above acceptable limit and below permissible limit. |
| SO ₄ ²⁻ | 57.91 | 54.29 | 19.26 | 26.88 | 165 | 50.48 | 76.67 | 15.72 | 53.6 | 200 | 400 | 15.72-165 | All the samples are within the acceptable limits. |
| NO ₃ ⁻ | 6.2 | 9 | 2.5 | 2.5 | 19.5 | 24.8 | 19.6 | 20.1 | 2.5 | 45 | No relaxation | 2.5-24.8 | All the samples are within acceptable limits. |
| F | 0.92 | 1.7 | 1.6 | 1.2 | 1.5 | 1.3 | 0.94 | 0.8 | 1.12 | 1 | 1.5 | 0.8-1.7 | Three samples are within acceptable limits, and six samples (A2, A3, B1, B2, B3, and C3) are above the acceptable limit and below the permissible limits. |

Values in ppm

Gibbs Diagram

The Gibbs diagram is a widely applied framework for examining the relationship between dissolved ions and total dissolved solids (TDS) to identify the dominant hydrogeochemical processes controlling surface-and stream water chemistry (Gibbs, 1970; Singh *et al.*, 2020; Islam *et al.*, 2025; Ravi *et al.*, 2026). In this study, Gibbs diagrams were constructed for both cations and anions by plotting the ratios $(Na^+ + K^+) / (Na^+ + K^+ + Ca^{2+})$ and $Cl^- / (Cl^- + HCO_3^-)$ against TDS for the stream-water dataset (Fig. 3). The distribution of data points predominantly occupies the rock–water interaction and evaporation-dominance fields, indicating that the hydrochemistry is mainly governed by dissolution of minerals from

granitoid, amphibolite, and carbonate lithologies, together with evaporative concentration processes characteristic of the semi-arid setting of Yadadri Bhuvanagiri and Rangareddy districts. This pattern is consistent with the observed increase of TDS and electrical conductivity (EC) along the flow paths and the enrichment of weathering-derived ions reported in similar crystalline and mixed-lithology terrains (Gibbs, 1970; Singh *et al.*, 2020). All samples cluster within the rock–water interaction domain, highlighting the predominant role of lithology-controlled mineral dissolution under semi-arid conditions, whereas the sparse or negligible plotting in the precipitation-dominance field supports a limited direct influence of rainfall on stream chemistry in the study area (Gibbs, 1970; Singh *et al.*, 2020).

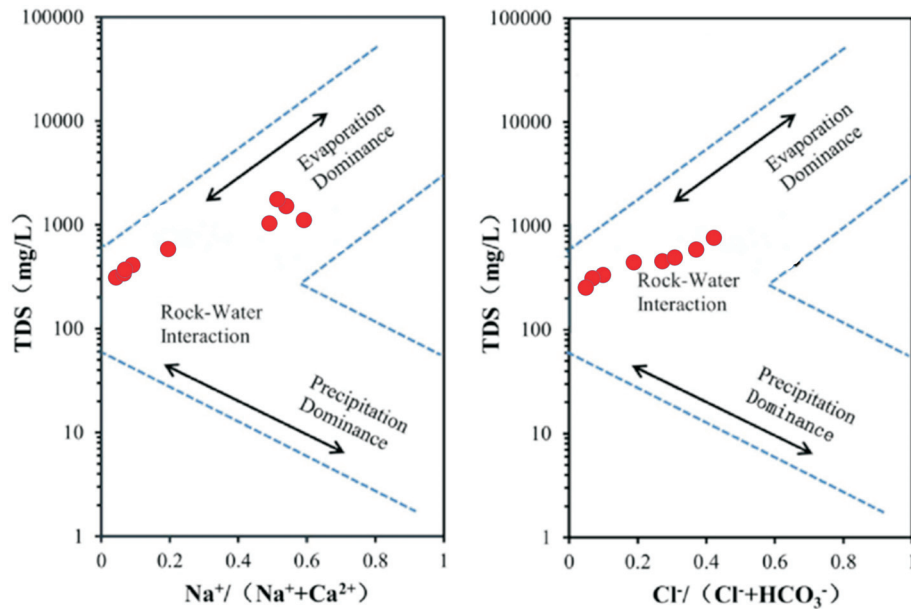


Fig. 3. Gibbs diagram showing the mechanisms controlling the water chemistry of the stream water of the study area

The dominance of the rock–water interaction field is mainly attributed to intensive weathering of granitoid, gneissic, amphibolitic, and carbonate-bearing lithologies present in the study area, which contribute major dissolved ions to stream waters. In addition to lithological control, evaporation under semi-arid climatic conditions and localized anthropogenic influences such as agricultural runoff and wastewater inputs were also considered as secondary processes affecting the hydrochemical composition.

Irrigational Water Quality

The suitability of stream water for irrigation was evaluated using key agronomic indices such as electrical conductivity (EC), sodium adsorption ratio (SAR), sodium percentage (%Na), and related salinity and sodicity criteria commonly applied in irrigation studies. The suitability of stream water for irrigation in the Yadadri Bhuvanagiri and Rangareddy 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 (Ca²⁺, Mg²⁺, Na⁺, K⁺) and anions (CO₃²⁻, HCO₃⁻, SO₄²⁻, 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 1.05 to 23.50 (Table 3), ranging from low to high sodium hazard, thereby classifying the water as “excellent to Doubtful” for irrigation use (Richards, 1954; Todd, 1959). This suggests risk of sodicity-related soil degradation

under current conditions. However, irrigation suitability was evaluated considering not only SAR values but also overall salinity conditions, sodium percentage, and local soil drainage characteristics. Although a few samples show relatively higher SAR values, such waters may still be used for irrigation under well-drained soil conditions and appropriate management practices, including proper leaching and crop selection.

$$SAR = [Na^+] / [\frac{1}{2}(\sqrt{Ca^{2+} + Mg^{2+}})] \dots\dots\dots(2)$$

Where all the concentrations are in epm value.

The sodium percentage (Na%), another important metric, ranged from 9.55% to 61.57% across the samples (Table 4), water class ranging from excellent to doubtful ranges. 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.

$$Na\% = [(Na^+ + K^+) / (Ca^{2+} + Mg^{2+} + Na^+ + K^+)] \times 100 \dots\dots(3)$$

Where all ion concentrations are expressed in milliequivalents per liter. The %Na values from the analyzed samples ranged from approximately 9.55% to 61.58%, reflecting moderate to high sodium levels in some samples. High %Na values indicate potential sodium hazards leading to reduced soil permeability and adverse effects on soil structure and crop productivity if used for irrigation without proper management. Most samples fall within the acceptable to moderate sodium hazard categories, but a few samples (B3 and C1) with %Na above 60%

Table 3: SAR classification of water samples

| SAR (in meq/L) | Class | Quality | No. of Samples |
|----------------|-------------------------|------------|-------------------------|
| 0-10 | Low sodium hazard | Excellent | 5 (A2, A3, B1, C2 & C3) |
| 10-18 | Medium sodium hazard | Good | 2 (A1 & B3) |
| 18-26 | High sodium hazard | Doubtful | 2 (B2 & C1) |
| >26 | Very high sodium hazard | Unsuitable | Nil |

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

| % Sodium | Water Class | No. of samples |
|----------|-------------|---------------------|
| <20 | Excellent | 4 (A3, B1, C2 & C3) |
| 20- 40 | Good | 1 (A2) |
| 40- 60 | Permissible | 2 (A1, B2) |
| 60- 80 | Doubtful | 2 (B3 & C1) |
| >80 | Unsuitable | Nil |

suggest the need for careful monitoring and possible treatment before irrigation use in order to prevent soil sodicity issues. Therefore, the irrigation suitability of stream water should be interpreted cautiously in locations showing elevated sodium hazard.

Industrial Use

The assessment of stream water quality for industrial use reveals crucial parameters that can significantly impact industrial processes, equipment efficiency, and compliance with regulatory standards. The evaluation was carried out using commonly accepted industrial water quality criteria and permissible limits recommended in standard water quality guidelines and published literature. The pH values in the present study range from 7.5 to 8.0, which is within the typical industrial acceptable range of 6.5–8.5, thereby minimizing risks of corrosion or scaling in pipelines and boilers (BIS, 2012; WHO, 2017; Bhawan and Nagar, 2020). Total dissolved solids (TDS) concentrations vary between 395.85 and 2008.5 mg/L, with most samples exceeding the commonly recommended limit for several industrial applications, indicating a moderate to high risk of scaling and conductivity-related issues, especially in sensitive processes such as electronics manufacturing or power generation. Total hardness (Ca + Mg) ranges from 280 to 950 mg/L; these elevated hardness levels surpass the soft to moderately hard classification preferred in industry, increasing the likelihood of scale formation on heat exchangers and cooling towers. Chloride concentrations range from 42.54 to 510.48 mg/L, with four samples exceeding the industrial recommended threshold of 250 mg/L, which poses a corrosion threat to metal components (Banerjee, 2025). Sulfates are well within the industrial limit of 200 mg/L, reducing scaling concerns from sulfate salts. Nutrients and minor ions such as nitrate and fluoride remain below industrial concern thresholds (Bhawan and Nagar, 2020). The high salinity and hardness values observed suggest that without treatment (such as softening or ion exchange), the stream water may lead to operational inefficiencies and increased maintenance costs in industrial processes. Thus, proper water management practices including pretreatment or blending with lower TDS waters are recommended for industrial use to maintain equipment longevity and process efficacy (Bhawan and Nagar, 2020). Industrial suitability interpretation was mainly based on pH, TDS, hardness, chloride, and sulfate concentrations in comparison with commonly adopted industrial water quality recommendations.

Discussion

Geogenic Controls Governing Hydrochemical Variability

The hydrochemical composition of stream waters in parts of Yadadri Bhuvanagiri and Rangareddy districts is predominantly controlled by geogenic factors such as lithological heterogeneity

and mineral weathering. The Gibbs diagram plots reveal that all samples fall within the rock–water interaction and evaporation dominance fields, indicating mineral dissolution from underlying granitoid, amphibolite, and carbonate lithologies as key processes (Gibbs, 1970; Singh *et al.*, 2020). Stream water pH values range between 7.5 and 8.0, consistent with alkaline conditions driven by weathering reactions (Hem, 1985; WHO, 2017). Major cations, including calcium (48.1–176.35 ppm) and magnesium (21.89–124.03 ppm), along with bicarbonate (305.1–537 ppm), confirm carbonate dissolution's role in controlling water chemistry. The dominance of Ca–Cl and Ca–Mg–Cl facies further reflect the influence of granitoid and amphibolitic lithologies combined with ion exchange processes operating within the drainage system. This natural geochemical setting forms the baseline against which anthropogenic impacts are assessed.

Anthropogenic Influences and Trace Element Mobilization Dynamics

Anthropogenic inputs significantly influence water chemistry, as indicated by elevated chloride concentrations (42.54–510.48 ppm), surpassing the acceptable limit (250 ppm) in multiple samples (B2, C1), and elevated sulfate (15.72–165 ppm) and nitrate (up to 24.8 ppm) levels, reflecting agricultural runoff and industrial discharges (Rajamani *et al.*, 1985; Collins and Jenkins, 1996). Piper diagram classification predominantly places samples in the Ca–Cl type field (Type V, shallow fresh stream water with ion exchange), with sample C3 plotting in the Ca–Mg–Cl field (Type III), highlighting direct anthropogenic influence and interaction with polluted sources including the Musi River. Elevated sodium (up to 288 ppm in B2) and potassium (up to 89.1 ppm in C1) further underscore contamination and complex geochemical processes altering water quality.

Multipurpose Resource Utilization: Agricultural and Industrial Suitability Assessment

Irrigational assessment using Sodium Adsorption Ratio (SAR ranging from 1.05 to 23.50, dimensionless) and sodium percentage (%Na from 9.55% to 61.58%) shows most water samples within “excellent” to “doubtful” irrigation quality (Richards, 1954; Todd, 1959). Waters plotting predominantly in moderate salinity hazard classes (C2–C3) and low to medium sodium hazard (S1–S2) quadrants suggest suitability for irrigation on well-drained soils with appropriate management, whereas high SAR (23.5 in B2) warns of potential sodicity risks requiring blending or treatment. Industrial suitability evaluation reveals pH within the acceptable 6.5–8.5 range but highlights concern with elevated TDS (up to 2008.5 mg/L), hardness (280–950 mg/L), and chloride levels (up to 510.48 mg/L), which challenge industrial operations via scaling and corrosion risks ((Banerjee, 2025; Bhawan and Nagar, 2020). Effective pretreatment strategies such as ion exchange or blending are recommended for water exceeding these thresholds.

Towards Integrated Water Resource Management: Monitoring and Policy Frameworks

This investigation underscores the necessity for integrated water management approaches encompassing continuous

hydrochemical monitoring, advanced water treatment technologies tailored to local hydrochemical conditions, and informed land use policies. Addressing both geogenic and anthropogenic influences is critical to optimizing water resource utilization for domestic, agricultural, and industrial demands while protecting environmental and public health (WHO, 2017; Bhawan and Nagar, 2020). Sustainable management plans should prioritize pollution source control, promotion of efficient irrigation practices, and community awareness to mitigate water quality degradation in the semi-arid landscapes of Telangana.

The present study is based on representative post-monsoon stream water samples collected following NGCM SOP guidelines. Although the dataset provides important baseline hydrogeochemical information for the study area, additional seasonal investigations and higher sampling density would further improve the understanding of temporal and spatial variability. Due to the limited number of representative stream water samples, advanced statistical analyses such as correlation matrix and multivariate techniques were not applied in the present study. Instead, the interpretation was primarily based on standard hydrogeochemical approaches, including major ion chemistry, Piper and Gibbs diagrams, irrigation indices, and comparison with established water quality standards.

Conclusions

The hydrogeochemical assessment of stream waters in parts of the Yadadri Bhuvanagiri and Rangareddy districts of Telangana reveals a complex interplay of geogenic and anthropogenic factors influencing water quality and suitability for diverse uses. Slightly alkaline pH values (7.5–8.0) and major ion compositions are reflective of mineral weathering of Neoproterozoic granitoids and associated lithologies, as confirmed by Gibbs diagram interpretations emphasizing rock–water interaction and evaporative concentration processes. Piper diagram analyses primarily classify waters in the Ca-Cl facies (Type V), with localized deviations such as the Ca-Mg-Cl type (Type III), underscoring the influence of ion exchange and anthropogenic contamination from agricultural runoff and industrial effluents. Water quality indices for irrigation, including Sodium Adsorption Ratio (SAR ranging from 1.05 to 23.50) and sodium percentage (9.55–61.58%), indicate most samples are suitable for irrigation on well-drained soils, though high SAR values in select locations suggest risks for sodicity requiring management interventions. For industrial applications, parameters such as electrical conductivity, total dissolved solids (up to 2008.5 mg/L), hardness (up to 950 mg/L), and chloride concentrations (up to 510.48 mg/L) highlight potential challenges of scaling and corrosion, necessitating pre-treatment approaches. Elevated chloride, sulfate, and nitrate concentrations further denote anthropogenic impacts, correlating with environmental and public health concerns. Overall, the

findings emphasize the necessity for integrated and adaptive water resource management strategies that address both geological controls and human influences. Continuous hydrochemical monitoring, coupled with targeted remediation and sustainable land-use planning, is vital for optimizing multipurpose water utilization. This study provides a crucial baseline for water quality in this semi-arid region and informs future environmental management policies to safeguard both ecosystem and human health. The present findings are consistent with several recent hydrogeochemical and environmental geochemistry studies conducted across different Indian terrains, highlighting the growing need for sustainable monitoring and management of surface and groundwater resources. Further seasonal investigations with larger datasets are recommended for a more detailed understanding of hydrochemical variability in the region.

Data Availability

The authors confirm that the data supporting the findings of this study are available within the article. Raw data that support the findings of this study are available from the author, upon reasonable request.

Conflict of Interests

The author declares that there is no conflict of interest regarding the publication of this paper.

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