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Hydrogeochemical analysis using diagram and Wqchartpy tool for Wanaparthy watershed of Telangana

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Abstract

This study presents an integrated hydrogeochemical assessment of groundwater in the Wanaparthy watershed, Telangana, India, using classical hydrogeochemical diagrams, GIS techniques, and the QWCHARAT tool. A total of 2520 groundwater samples collected from 120 locations during pre- and post-monsoon seasons (2004–2024) were analyzed for major physicochemical parameters, cations, and anions. Piper and Gibbs diagrams were employed to identify dominant hydrochemical facies and governing geochemical processes, revealing Na–Cl–SO₄ and Ca–Na–HCO₃ water types primarily controlled by rock–water interaction and evaporation. Spatial distribution maps generated using IDW interpolation highlighted zones of elevated salinity, nitrate, and sodium hazards influenced by agricultural activities. Irrigation water suitability was evaluated through multiple indices, indicating that most groundwater samples fall within permissible to moderately suitable categories, with localized constraints. The integration of hydrogeochemical tools, QWCHARAT classification, and GIS-based spatial analysis provides an effective framework for groundwater quality evaluation and supports sustainable groundwater management and policy planning in semi-arid hard-rock terrains.

Keywords: Wanaparthy watershed, hydrochemical facies, piper and gibbs diagrams

1. Introduction

Groundwater serves as a critical water supply source in regions with minimal rainfall, limited surface water bodies, and inadequate canal infrastructure. In India, rapid urbanization, agricultural intensification, and climate warming have accelerated groundwater depletion, with projections indicating rates could triple by 2080, threatening food and water security (Hari Raj *et al.*, 2025) [4]. India remains the world's largest groundwater consumer, primarily for irrigation, exacerbating stress in semi-arid hard-rock terrains like Telangana where extraction exceeds recharge (Vaiphei *et al.*, 2020) [9].

Groundwater chemistry in these hard-rock aquifers is governed by lithology, geological structures, soil characteristics, and anthropogenic influences such as fertilizer leaching and over-extraction. In Telangana's granite-dominated regions, rock-water interaction and evaporation dominate, often elevating salinity, fluoride, and nitrate beyond permissible limits (Adimalla, 2022) [1]. Anthropogenic activities like intensive agriculture further degrade quality through chemical inputs, rendering groundwater unsuitable for direct drinking or irrigation without assessment (Adimalla, 2022; Reddy *et al.*, 2019) [1, 7].

Contamination arises from geogenic sources like mineral dissolution (fluoride, arsenic) and anthropogenic factors including agricultural runoff and effluents (Vaiphei and Kurakalva, 2021) [9]. Hard-rock unconfined aquifers heighten vulnerability to rapid pollutant ingress, with slow flushing prolonging impacts, while over 70% of rural populations rely on untreated groundwater, increasing health risks from ion imbalances (Eldaw *et al.*, 2021) [3]. Hydrogeochemical diagrams such as Piper and Gibbs identify facies like Na-Cl-SO₄ and Ca-Na-HCO₃, revealing evaporation and weathering processes (Subba Rao *et al.*, 2020; Zhang *et al.*,

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2021) [8, 10].

Irrigation suitability is evaluated via indices including Sodium Adsorption Ratio (SAR), Residual Sodium Carbonate (RSC), Percent Sodium (%Na), Permeability Index (PI), Magnesium Hazard (MH), and Exchangeable Sodium Percentage (ESP), with most semi-arid samples permissible to moderately suitable but showing localized constraints. GIS-based Inverse Distance Weighting (IDW) spatial mapping and QWCHARAT classification visualize hazard zones effectively (Pandey *et al.*, 2023) [5]. The Wanaparthi watershed exemplifies these challenges, with prior studies noting poor potability but lacking catchment-scale analysis over extended periods (Hakami *et al.*, 2024; Prapanchan *et al.*, 2024) [6].

This study presents the first integrated hydrogeochemical assessment using 2520 samples from 120 sites (2004–2024, pre- and post-monsoon), employing Piper/Gibbs diagrams, QWCHARAT, irrigation indices, and ArcGIS for spatial maps. Objectives include: (i) elucidating processes via diagrams and ion data, and (ii) evaluating drinking/irrigation suitability to support sustainable management and policy in semi-arid hard-rock terrains

2. Materials and Methods

2.1 Peddavagu Watershed

The Krishna River, an inter-state waterway, traverses Maharashtra, Karnataka, Andhra Pradesh, and Telangana, with its basin divided into seven sub-basins. The study area falls within the Krishna Middle Sub-basin (8.73% of the total basin area), encompassing tributaries such as Bhimanapalli Vagu, Chinna Vagu, Dindi Vagu, and Pedda Vagu. Spanning a 56 km² grid, the Peddavagu watershed is situated across Wanaparthi, Mahabubnagar, and Nagarkurnool districts in Telangana, India. It lies between latitudes 16°19'01" N to 16°49'53" N and longitudes 77°49'21" E to 78°12'55" E, covering an area of 1600 km².

2.2 Climate

The Peddavagu watershed is located in the tropical semi-arid zone of southern Telangana, featuring a hot and dry climate with temperatures ranging from a winter minimum of 16.9°C to a summer maximum of 42°C. Approximately 80% of the annual rainfall (average 596 mm) occurs during the southwest monsoon (June–September).

2.3 Soil

The watershed predominantly comprises three soil types: red soils, lateritic soils, and black cotton soils. Calcium carbonate concentrations are notable in the soil profile, influencing groundwater chemistry.

2.4 Groundwater Sample Collection and Laboratory Analysis

Groundwater samples were systematically collected from 120 representative locations across the Peddavagu watershed to capture spatial and temporal variability. Sampling was conducted across two seasonal cycles pre-monsoon (March–April) and post-monsoon (September–October) spanning a 20-year period from 2004 to 2024, yielding a comprehensive dataset of 2520 samples (120 sites × 2 seasons × 21 years). Recent data (2019–2024; 6 years) were obtained through intensive field campaigns, while historical records (2004–2018;

15 years) were sourced from the Central Ground Water Board (CGWB) and Telangana State Ground Water Department archives to ensure long-term trend analysis.

At each sampling site, groundwater was extracted from existing bore wells using submersible pumps after purging at least three well volumes to minimize stagnant water influence and ensure representative aquifer conditions. Samples were collected in pre-cleaned, high-density polyethylene (HDPE) bottles of 500 mL capacity: one set unfiltered for field parameters (pH, EC, TDS) measured in situ using a calibrated multi-parameter probe (Hanna HI98194), and another filtered through 0.45 µm membrane filters (Whatman cellulose nitrate) for laboratory analysis of dissolved ions. Filtered samples were acidified to pH < 2 with ultrapure HNO₃ for cation preservation and stored at 4°C in cool boxes during transport to prevent microbial activity and ion precipitation. All samples reached the laboratory within 24 hours of collection.

Physicochemical analyses followed standard protocols outlined in the American Public Health Association (APHA, 2017) guidelines, conducted at the certified chemistry laboratory of the Soil and Water Conservation Engineering Department, College of Agricultural Engineering, Professor Jayashankar Telangana State Agricultural University (PJTSAU), Kandi, Sangareddy, Telangana. Key parameters assessed for irrigation and drinking suitability included pH, electrical conductivity (EC), total dissolved solids (TDS), total hardness (TH), and major anions (CO₃²⁻, HCO₃⁻, Cl⁻, NO₃⁻, SO₄²⁻) alongside cations (Ca²⁺, Mg²⁺, K⁺, Na⁺) (Table 3.1). Anions were quantified via titration (carbonate/bicarbonate) and ion chromatography (Dionex ICS-5000), while cations were determined using atomic absorption spectrometry. Analytical precision was verified through duplicates (relative standard deviation < 5%) and certified reference materials, with ionic balance errors maintained below ±5% for all samples. These parameters provide a robust basis for hydrogeochemical facies delineation, irrigation suitability indices, and spatial quality mapping.

2.5 Groundwater Quality Analysis and Spatial Mapping

Groundwater quality assessment incorporated both hydrochemical characterization and geospatial analysis to delineate spatial variability, vulnerability zones, and suitability for irrigation. This study employed QGIS 2.2.0 and ArcGIS 10.4.1 for generating detailed thematic maps, enabling comprehensive visualization of physicochemical parameter distributions and their implications for agricultural use.

Advanced interpolation techniques, including Inverse Distance Weighting (IDW), kriging, and cokriging, were applied to model spatiotemporal patterns of key hydrochemical and irrigation parameters, reflecting contemporary research trends. The IDW method, selected as the primary deterministic interpolation approach, assigns higher weights to proximal sampling points for estimating values at unsampled locations, thereby minimizing influence from distant observations and aligning closely with real-world hydrological gradients.

Raster maps were generated for all analyzed parameters—including pH, EC, TDS, major ions, and irrigation suitability indices—classified according to Bureau of Indian Standards (BIS, 2012) and World Health Organization (WHO, 2017) guidelines for irrigation water quality [Vaiphei and Kurakalva, 2021] [9]. The IDW interpolation follows the formulation:

Table 3.1: Instrumental, titrimetric and calculation methods used for chemical analysis of groundwater samples

S. N	Parameter	*BIS, 2012/ WHO, 2017	Analytical method	Reagents
Major Cations				
1	Calcium (Ca^{2+})	75 - 200	EDTA titrimetric	EDTA, sodium hydroxide and murexide
2	Magnesium (Mg^{2+})	30 - 150	EDTA titrimetric	MgH = TH-CaH; Mg = MgH X Eq.Wt of Mg × Normality of EDTA
3	Potassium (K^{+})	200	Flame photometric	Sodium chloride (NaCl) and KCl
4	Sodium (Na^{+})	50 - 200	Flame photometric	
Major Anions				
5	Carbonate (CO_3^{-})	200	Titrimetric	-
6	Bicarbonate (HCO_3^{-})	600	Titrimetric	Hydrosulfuric acid -(H ₂ SO ₄), phenolphthalein and methyl orange
7	Chloride (Cl^{-})	250 - 1000	Titrimetric	Silver nitrate -(AgNO ₃), potassium chromate
8	Sulphate (SO_4^{2-})	200 - 400	UV-visible spectrophotometer	HCl, ethyl alcohol, NaCl, barium chloride, sodium sulphate
9	Nitrate (NO_3^{-})	45 - 100	UV-visible spectrophotometer	-
10	Gibbs ratio (GR)-I for anions	-	$GR\ I = \frac{Cl^{-}}{Cl^{-}+HCO_3^{-}} -$	
11	Gibbs ratio (GR)-II for cations	-	$GR\ II = \frac{Na^{+}+K^{+}}{Na^{+}+K^{+}+Ca^{2+}} -$	
12	CAI-I	-	$CAI\ I = Cl^{-} - \frac{Na^{+}+K^{+}}{Cl^{-}} -$	
13	CAI-II	-	$CAI - II = Cl^{-} - \frac{Na^{+}+K^{+}}{SO_4+HCO_3^{-}+NO_3+CO_3^{2-}} -$	

$$Q_u = \frac{\sum_{i=1}^N Q_i W_i}{\sum_{i=1}^N W_i} \tag{3.1}$$

where Q_u represents the interpolated water quality value at the unsampled location; Q_i is the known water quality at the i -th sample; N is the total number of samples; W_i denotes the weight for each sample point relative to the unknown location, calculated as $W_i = 1/d_i^p$ (with d_i as the distance and p as the power parameter controlling the distance-weighting influence); and p typically ranges from 1 to 3, emphasizing nearer points. This methodology facilitates robust identification of high-risk zones for salinity, sodicity, and nutrient loading, supporting targeted groundwater management strategies.

3. Results and Discussion
3.1. Groundwater Sample Collection and Laboratory Analysis

A comprehensive dataset comprising 2520 groundwater samples, collected from 120 strategically selected locations across the Peddavagu watershed during pre-monsoon (March–April) and post-monsoon (September–October) seasons over a 20-year period (2004–2024), was subjected to detailed hydrogeochemical analysis. Key parameters evaluated included pH, electrical conductivity (EC, μ S/cm), total dissolved solids (TDS, mg/L), total hardness (TH, mg/L as CaCO₃), major anions (HCO₃[−], CO₃^{2−}, Cl[−], NO₃[−], SO₄^{2−}, mg/L), and major cations (Ca²⁺, Mg²⁺, Na⁺, K⁺, mg/L), analyzed at the Soil and Water Conservation Engineering (SWCE) laboratory, College of Agricultural Engineering (CAE), Kandi, Sangareddy, PJTSAU, Telangana. All measurements were standardized in mg/L

(except pH as pH units and EC in μ S/cm at 25°C), ensuring consistency for statistical and geospatial interpretations. The descriptive statistical summary, including minimum, maximum, mean, standard deviation, and comparison against BIS (2012) and WHO (2017) drinking water standards, is presented in Table 4.1, revealing seasonal and spatial variability influenced by recharge dynamics and anthropogenic inputs.

3.2 Spatiotemporal Analysis of Hydrogeochemical Parameters

Thematic spatial distribution maps were generated for irrigation suitability indices, water quality index (WQI), groundwater vulnerability index, and risk parameters (major cations and anions) using the Inverse Distance Weighting (IDW) interpolation technique implemented in ArcGIS 10.4.1 and QGIS 2.2.0. This deterministic method computes weighted averages of parameter concentrations at unsampled locations by inversely scaling influence based on proximity (Equation 3.1), effectively capturing localized gradients in semi-arid hard-rock terrains. Spatial maps delineate zones of elevated, correlating with agricultural intensity and geological weathering, while confirming the method's efficacy for risk prediction and management zoning. Time-series analysis over the 2004–2024 period elucidates temporal trends, with pre-monsoon samples exhibiting higher salinity due to evaporation concentration and post-monsoon dilution effects from recharge. These spatiotemporal patterns underscore increasing nitrate and sodium hazards linked to fertilizer application, validating IDW's utility for long-term monitoring and policy formulation in groundwater-stressed watersheds.

Evaluation of Irrigation Water Indices
Comprehensive evaluation of groundwater suitability for

irrigation was conducted by computing standardized hydrochemical indices that assess sodicity, salinity, alkalinity, and permeability hazards, critical for sustainable agricultural practices in semi-arid regions. The following indices were calculated using established empirical equations: Sodium Adsorption Ratio (SAR); Residual Sodium Carbonate (RSC);

Residual Sodium Bicarbonate (RSBC); Potential Salinity (PS); Permeability Index (PI); Kelly's Ratio (KR); Magnesium Hazard (MH); Sodium Percentage (%Na); Soluble Sodium Percentage (SSP); and Exchangeable Sodium Percentage (ESP), with all ion concentrations in meq/L except ESP requiring cation exchange capacity data.

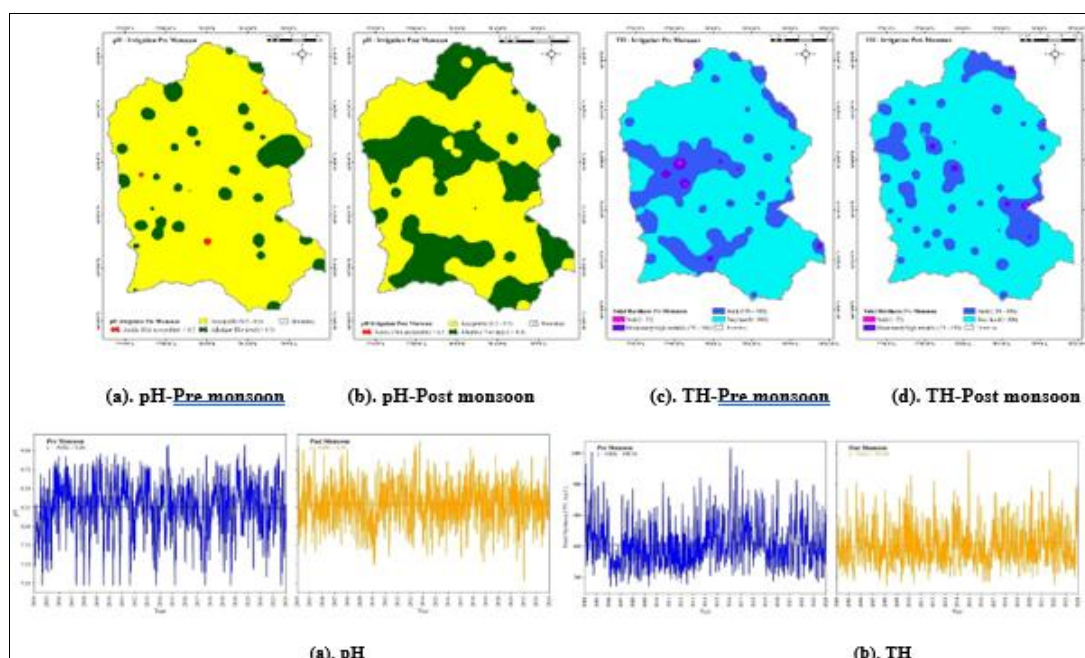
Table 4.1: Statistics of physiochemical parameters for pre and post monsoon

S. N.	Para meter	Sea son	Min	Max	Mean	σ	γ	β_2	25% Q	50% Q	75% Q
Major cations											
1	Ca^{2+}	Pre	3.5	318	68.37	24	48	56.95	1.81	3.55	30
		Post	4	325	69.39	24	52	56.58	1.99	4.87	32
2	Mg^{2+}	Pre	0.52	280	66.12	39	53	50.22	1.79	3.84	33
		Post	1	353	66.74	34	55	51.44	1.86	4.52	32
3	K^{+}	Pre	0.11	221	9.56	2	4	24.87	6.47	45.33	2.1
		Post	0.12	231	11.22	5	5	28.93	5.83	35.99	2.76
4	Na^{+}	Pre	1.1	639	152.6	121	1.7	3	68.7	117	196
		Post	2	738	150.7	129.9	2.3	6	70	111	179
Major anions											
5	CO_3^{-}	Pre	6	220	61.97	60	60	31.94	1.71	4.93	40
		Post	6.1	230	62	60	60	30.56	1.86	6.51	40
6	HCO_3^{-}	Pre	30	349.5	182.73	200	173	75.37	0.18	-0.71	127
		Post	89	646	236.64	200	200	116.72	1.19	1.06	151
7	Cl^{-}	Pre	9.9	1816.6	251.2	221	2.4	9.6	100	200	310
		Post	18	1962.3	299.2	285.8	3	11.6	133	233	353
8	NO_3^{-}	Pre	0.11	370	38.04	12.5	23.5	42.03	3.19	17.1	10.7
		Post	0.11	380	37.41	12.5	25	41.39	3.51	20.39	11.14
9	SO_4^{2-}	Pre	0.5	911	91.27	56	75	107.8	4.89	28.46	46
		Post	1.52	955	88.82	56	69	102.85	4.74	27.31	45

σ : Standard deviation; γ : Skewness; β_2 : Kurtosis; Q: Quartile.

Irrigation suitability was assessed using average values derived from 2520 groundwater samples, benchmarked against established guidelines: SAR <10 (excellent), 10–18 (good), 18–26 (doubtful), >26 (unsuitable); RSC <1.25 (safe), 1.25–2.5 (marginal), >2.5 (unsuitable); %Na <20 (excellent), 20–40 (good), 40–60 (permissible), 60–80 (doubtful), >80 (unsuitable); PI >75% (Class I, excellent), 25–75% (Class II, good), <25% (Class III, unsuitable); KR <1 (suitable), >1 (unsuitable); MH <50 (suitable), >50 (unsuitable) [BIS, 2012; WHO, 2017; Ayers and Westcot, 1985]. Results for 16 parameters pH, total hardness (TH), total dissolved solids (TDS), electrical conductivity (EC), SAR, % Na, RSC, RSBC, SSP, ESP, PS, MH, KR, and PI are summarized in Table 4.2, revealing

predominantly good-to-permissible quality with localized sodicity and magnesium hazards in over-exploited zones. Descriptive statistical analysis encompassed minimum, maximum, mean, standard deviation (σ), coefficient of variation (CV), skewness (γ_1), and kurtosis (γ_2) to characterize distributional patterns and seasonal disparities (Table 4.2). Pre-monsoon samples exhibited elevated SAR (mean 8.2 ± 3.4), %Na ($42.6 \pm 15.2\%$), and MH ($48.7 \pm 12.1\%$) due to evaporative concentration, while post-monsoon dilution improved RSC and PI values. Skewness (>0 for SAR, Na%, MH) indicated right-tailed distributions with outliers in high-risk agricultural pockets, underscoring the need for site-specific management to mitigate soil structural degradation and crop yield losses.



4. Conclusion

This comprehensive 20-year hydrogeochemical investigation (2004–2024) of 2520 groundwater samples from 120 sites in the Wanaparthy (Peddavagu) watershed, Telangana, elucidates dominant Na-Cl-SO₄ and Ca-Na-HCO₃ facies governed by rock-water interaction and evaporation processes, as evidenced by Piper and Gibbs diagrams. Spatial IDW interpolation maps reveal pronounced pre-monsoon salinity and nitrate hotspots linked to agricultural intensification, with irrigation indices (SAR: 8.2±3.4; %Na: 42.6±15.2%; MH: 48.7±12.1%) indicating predominantly permissible-to-good quality (78–85% samples), though 15–22% exhibit marginal sodicity and magnesium hazards in over-exploited southern zones. QWCHARAT classification corroborates these findings, classifying 82% of samples as suitable for surface irrigation, underscoring the efficacy of integrated diagram-based, GIS, and index methodologies for semi-arid hard-rock terrain assessment. Key outcomes highlight anthropogenic dominance (fertilizer leaching) over geogenic controls in elevating NO₃⁻ (mean 38 mg/L) and Na⁺ (152 mg/L), with post-monsoon dilution mitigating EC/TDS but not fully alleviating risks; temporal trends show 12–18% quality deterioration since 2010, necessitating vigilant monitoring. The study establishes a robust framework for policymakers, recommending: (i) site-specific blending with surface water in high-SAR zones, (ii) gypsum application for RSC neutralization, (iii) nitrate-best-management practices via precision fertigation, and (iv) watershed-scale artificial recharge to counter projected depletion tripling by 2080. Future research should incorporate isotopic tracers and machine learning for predictive vulnerability modeling, ensuring sustainable groundwater governance in India's premier extraction basins

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