J. Ind. Geophys. Union, 29(5) (2025), 321-338
https://doi.org/10.71122/JIGU.29(5)2025.0031

Geospatial assessment of groundwater quality and its suitability for drinking and irrigation in semi-arid regions of Andhra Pradesh (India) using water quality index approach

Ravi Kumar Pappaka[1], Srinivasa Gowd Somagouni[1*] Krupavathi Chinthala[1], and Pradeep Kumar Badapalli [2]
[1]Dept of Geology, Yogi Vemana University, YSR Kadapa- 516005, Andhra Pradesh (India)
[2]CSIR-National Geophysical Research Institute, Hyderabad-500007, Telangana (India)
*Corresponding author: ssgowd@gmail.com

ABSTRACT

Groundwater, a vital resource for drinking and irrigation in the semi-arid regions of Andhra Pradesh, is increasingly threatened by rapid depletion and quality deterioration due to growing demands from intensive agriculture and population expansion. In this study, a total of 92 groundwater samples were collected from boreholes during the pre-monsoon (PRM) and post-monsoon (POM) seasons, and their physicochemical properties were systematically analyzed. The major ion sequence in the groundwater was found to be Na^{+}> Ca^{2+}> Mg^{2+}> K^{+} for cations, and HCO_3^{-}> Cl^{-}> SO_4^{2-}> NO_3^{-} > F^{-} for anions. During the PRM season, only 19% of the samples met drinking water standards, with Water Quality Index (WQI) values ranging from 59.18 to 172.21. In the POM season, 22% of the samples were deemed safe for drinking, with WQI values ranging from 70.07 to 229.46. The majority of the samples were unsafe due to contamination from human activities, including improper sewage disposal and agricultural runoff. To assess the suitability of groundwater for agricultural and domestic use, Gibbs, USSL, and Wilcox diagrams were utilized. The Gibbs plot indicated that rock dominance governs the groundwater chemistry in the region. Most samples were highly suitable for irrigation, as evidenced by favorable Sodium Adsorption Ratio (SAR), %Na, Soluble Sodium Percentage (SSP), Kelly's Ratio (KR), Residual Sodium Carbonate (RSC), and Permeability Index (PI) values. The Piper diagram revealed a prevalence of Ca^{2+}-HCO_3^{-} and Ca^{2+}-Mg^{2+}-Cl^{-} water types. Using Geographic Information System (GIS) techniques, the spatial distribution of groundwater quality was mapped, showing that the majority of samples failed to meet drinking water quality standards, thus necessitating treatment before consumption. Groundwater with elevated concentrations of fluoride and nitrate is unsuitable for drinking purposes and should be avoided. The findings underscore the urgent need for sustainable aquifer management strategies to ensure the continued availability of safe groundwater for both domestic and agricultural use.

Keywords: Hydrogeochemistry, Water Quality Index (WQI), Drinking water and irrigation, Remote sensing and GIS, Spatial distribution maps, Semi-arid region, Pandameru River Basin

INTRODUCTION

Water is an essential resource that sustains life across ecosystems, supporting both plant and animal life. However, the quality of groundwater, an important source for drinking and irrigation, is deteriorating due to a combination of natural processes and anthropogenic activities. Factors such as rising temperatures, industrial discharge, and intensified agricultural practices are exacerbating water quality degradation, posing significant health risks to both aquatic and terrestrial ecosystems (Badapalli et al., 2024). These concerns highlight the need for comprehensive groundwater quality monitoring to protect ecological integrity and anticipate future environmental changes (Khatri et al., 2020; Parveen et al., 2025).

The purity of groundwater is influenced by both geogenic and anthropogenic factors. With increasing industrialization and the expansion of modern agricultural practices, untreated waste and surface runoff often enter the groundwater system, disrupting ecological balance (Gugulothu et al., 2022; Molagamudi et al., 2023). Groundwater quality is governed by multiple factors, including the chemical composition of surrounding rocks and soils, seasonal rainfall patterns, aquifer dynamics, and human activities such as the improper disposal of waste into poorly constructed wells. As groundwater percolates through weathered rock layers, its chemistry is altered by regional geology, flow patterns, and mineral interactions, all of which collectively shape its quality.

Understanding hydrogeochemical processes is essential for identifying and managing contamination sources in groundwater. Small amounts of metal ions are essential for health, yet excess exposure can be toxic or even carcinogenic. The rise of newly developed chemicals further threatens water resources, underscoring the urgent need to mitigate these contaminants (Asadi et al., 2019; Anusha et al., 2022). Innovative solutions, such as the use of nano-adsorbents, are under investigation to remove pollutants; however, local geochemical processes play a substantial role in defining groundwater chemistry and require careful analysis.

In India, the quality of groundwater, especially in hard rock terrains like Anantapur, Andhra Pradesh, is declining due to population growth, intensive groundwater extraction, and excessive fertilizer use. Numerous studies have analyzed the impact of human activities such as wastewater discharge, agricultural chemicals, and water-rock interactions on groundwater, highlighting the need for strategies to improve groundwater suitability for drinking, agricultural, and industrial use (Subba Rao et al., 2019; Nayak et al., 2023). In the semi-arid Pandameru River basin, Andhra Pradesh, groundwater accounts for 80-90% of water needs, necessitating immediate action to safeguard this essential resource (Pappaka et al., 2024).

Water Quality Index (WQI) is a widely recognized tool for assessing groundwater suitability. Unlike traditional evaluation

methods that may lack a comprehensive view of spatial and temporal water quality trends, the WQI provides a single metric representing overall water quality, making it an effective resource for policymakers (Dutta et al., 2022; Golla and Badapalli, 2022). This study underscores the significance of WQI as a reliable method for assessing groundwater quality for drinking, agricultural, and hydrochemical purposes in semi-arid regions of Andhra Pradesh, India.

This study aims to evaluate groundwater quality in the semi-arid Pandameru River Basin, Andhra Pradesh, India, with a focus on its suitability for drinking, agricultural, and industrial use. By integrating the Water Quality Index (WQI) with detailed hydrogeochemical analyses, the research identifies key contaminants and geochemical processes influencing groundwater quality. The novelty of this study lies in the combined application of WQI and localized hydrogeochemical data to offer a nuanced understanding of groundwater quality dynamics in a region critically reliant on this resource. The findings are intended to aid local communities and policymakers by providing actionable insights for sustainable groundwater management, protecting public health, and optimizing agricultural practices in an environment susceptible to contamination and resource depletion. These insights can further inform water quality monitoring initiatives, support the development of pollution mitigation strategies, and contribute to policy frameworks aimed at long-term groundwater conservation in arid and semi-arid regions.

STUDY AREA

The study area is situated in the central part of Anantapur district, Andhra Pradesh, South India, bounded by 14°16'N to 14°40'N and 77°20' E to 77°44' E. It is covered by Survey of India toposheets Nos. 56 F/6, F/7, F/10, and F/11. Geologically, the region falls within the Peninsular Gneissic Complex and comprises lithological units such as hornblende-biotite gneiss (HBN), Closepet granites, and schist formations (Reddy, 1998). This semi-arid region experiences moderate rainfall and significant evapotranspiration, with considerable seasonal temperature variation. The average annual rainfall is approximately 517.8 mm, which plays a crucial role in recharging the aquifers. Groundwater occurs at depths ranging from 10 to 30 meters below ground level (bgl), with the weathered zone extending to 5–15 meters and the fractured zone reaching to depths of 20–50 meters. Groundwater movement generally follows the natural topography, flowing from higher elevations toward lower-lying areas, predominantly in a southerly to south-easterly direction. The region is highly dependent on groundwater resources for both drinking and agricultural needs. However, declining groundwater levels due to seasonal variability and excessive extraction have raised serious concerns about long-term water resource sustainability. Figure 1 presents a detailed map of the study area, illustrating the sampling locations and key hydrogeological features.

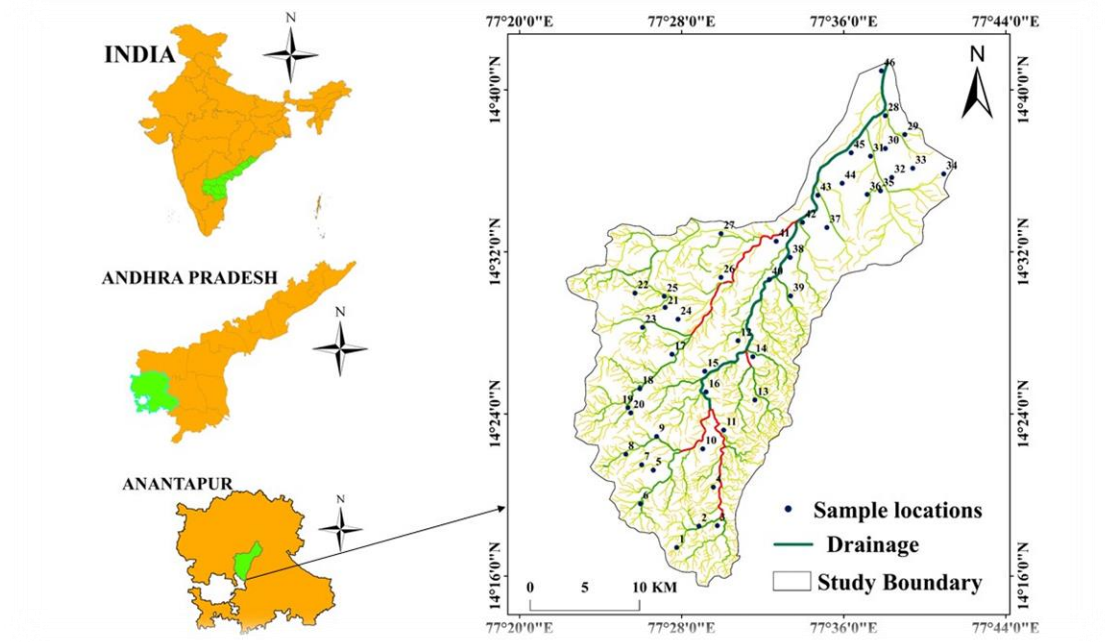


Figure 1. Sample site map of the investigated region in Anantapur district of Andhra Pradesh.

METHODOLOGY

Groundwater quality for drinking and irrigation

To assess the groundwater chemistry, 46 groundwater samples were collected from open wells and bore wells during the both pre-monsoon (March) and post-monsoon (December) seasons in 2023. The study area of the Pandameru River Basin is characterized by diverse lithological variations, and the availability of groundwater varies significantly across different locations. The entire study area is underlain by hard rock aquifers, which influences groundwater distribution and quality. The samples were collected in one-liter plastic bottles, which were pre-cleaned in the laboratory with diluted HNO_3 acid and distilled water to prevent contamination. Additionally, the sampling locations' latitude and longitude were recorded using a GPS device to ensure precise geo-referencing.

Key parameters such as pH, EC, TDS, total hardness (TH), Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^-, Na^+, K^+, SO_4^{2-}, NO_3^-, and F^- were determined using various analytical methods, including pH and conductivity meters, titration, flame photometry, and spectrophotometry. Sample compatibility with WHO, 2011 drinking water guidelines was assessed. The major cations and anions were graphed on a Piper Trilinear diagram, projecting to a shared diamond-shaped area to classify water types. The Gibbs diagram (Gibbs, 1970) was used to interpret the variables affecting groundwater chemistry quality criteria in the research region. Table 1 shows the irrigations parameters along with formulas.

Precision and Reliability Check

Using standard procedures, we analyzed the acquired samples for major and minor dissolved ions. The total cations and total anion balances were used to calculate the ionic charge balance error percentage, as outlined by Freeze and Cherry (1979). The error percentage in the samples is approximately ±5%, with a few outliers attributed to certain ions exhibiting significantly higher levels during different seasons. Errors in groundwater chemical analysis may arise from factors such as the use of reagents, limitations of the techniques and instruments employed the presence of pollutants in distilled water, and other potential sources.

$$\text{IBE (Ionic Balance Error)} = \frac{\sum Cations - \sum Anions}{\sum Cations - \sum Anions} \times 100 \quad (1)$$

Water Quality Index (WQI)

WQI is an essential statistic for assessing groundwater quality and evaluating whether it is fit for human consumption. WQI is a classification system that evaluates the broad acceptance of water for human consumption using a combination of various water quality parameters (Sharma and Bora, 2020; Kumar et al., 2022; Chinthala et al., 2023). WQI is determined using WHO (2011) drinking standards. The WQI is calculated in three steps. The constraints (pH, EC, TDS, HCO_3^-, Cl^-, F^-, SO_4^{2-}, NO_3^-, Ca^{2+}, Mg^{2+}, Na^+, and K^+) were each assigned a weight (wi) in the first phase depending on how important they were to the overall quality.

The parameters NO_3^-, TDS, Cl^-, F^-, and SO_4^{2-} have been assigned an extreme weight of 5, owing to their important character in influencing water quality (Table 2). Bicarbonate is assigned a weight of 1 since it has minimal effect on water quality assessment. The remaining variables, such as Ca^{2+}, Mg^{2+}, Na^+, and K^+, were weighted from 1 to 5 to indicate their respective relevance in defining water quality. The relative weight (Wi) is calculated in the initial stage using the formula 2,

$$Wi = \frac{wi}{\sum_{i=1}^{n}(\text{wi})} \quad (2)$$

The "quality rating (qi)" for the third stage is calculated using Equation 3

$$qi = \left(\frac{ci}{si}\right) \times 100 \ (3)$$

If Ci represents the attentiveness of each characteristic in each water sample, then Si represents the recommended WHO, (2011) value for each characteristic. The subsequent equations will calculate WQI because Wi and qi were combined to estimate the SIi for each characteristic independently following equations 4 and 5.

$$SIi = wi \times qi \quad (4)$$
$$WQI = \sum_{i=1}^{n} SIi (5)$$

The sub-index of each parameter is here designated as Sli.

RESULTS AND DISCUSSION

Tables 3 and 4 provide the values of physicochemical parameters measured in mg/L, except EC (µS/cm) for different seasons. The pH of groundwater is a vital hydrologic indicator, with values across both the PRM (7.4–8.3) and POM (7.1–8.3) seasons averaging within WHO's recommended 6.5–8.5 range for human consumption. Electrical Conductivity (EC), which indicates dissolved substances in water, recorded seasonal variations between 1473 and 3254 µS/cm, categorizing the water as moderate to poor quality (WHO threshold: 1500 µS/cm). Total Dissolved Solids (TDS), responsible for hardness and taste, ranged from 1030.8 to 2279 mg/L, classifying all groundwater samples as brackish per Freeze and Cherry standards (Freeze and Cherry, 1979).

Calcium (Ca^{2+}) concentrations, crucial for health, fluctuated between 107 and 277 mg/L, with most samples falling within WHO's acceptable range (85% PRM, 78% POM). Magnesium (Mg^{2+}), another essential mineral, showed pre- and post-monsoon concentrations from 20 to 142 mg/L, staying well

within the WHO standard. Sodium (Na^+) content, critical for individuals with health conditions, varied from 92 to 348 mg/L; only 74% (PRM) and 48% (POM) of samples were suitable per WHO's 200 mg/L limit, with elevated levels attributed to feldspar weathering.

Potassium (K^+), typically low due to its bond strength in minerals, ranged from 1.0 to 16.6 mg/L, with 74% (PRM) and 69% (POM) samples considered safe. Chloride (Cl^-) levels varied seasonally, with high concentrations suggesting potential pollution from anthropogenic sources and posing health risks for specific conditions. Sulfate (SO_4^{2-}) levels, driven by industrial emissions and mineral oxidation, remained acceptable in 78% (PRM) and 80% (POM) of samples (Table 5). Bicarbonate (HCO_3^-), indicating alkalinity, surpassed the WHO limit of 600 mg/L in around 40% of samples, likely due to organic matter decomposition(Table 5).

Table 1. Studied irrigational parameters .

Parameters	Formulae	References
Sodium adsorption ratio	$\mathrm{SAR} = \frac{\mathrm{Na^+}}{\frac{\sqrt{\mathrm{Ca^{2+}}+\mathrm{Mg^{2+}}}}{2}}$	Richards (1954)
Percentage sodium	$\%\mathrm{Na} = \frac{\mathrm{Na^+ + K +}}{\mathrm{Ca^{2+} + Mg^{2+} + Na^+ + K^+}} \times 100$	Wilcox (1955)
Sodium soluble percentage	$\mathrm{SSP} = \frac{\mathrm{Na^+}}{\mathrm{Ca^{2+} + Mg^{2+} + Na^+ + K^+}} \times 100$	Richards (1954)
Residual sodium carbonate	$\mathrm{RSC} = (\mathrm{HCO_3^-} + \mathrm{CO_3^{2-}}) - (\mathrm{Ca^{2+}} + \mathrm{Mg^{2+}})$	Eaton (1950)
Magnesium adsorption ratio	$\mathrm{MAR} = \frac{\mathrm{Mg^{2+}}}{\mathrm{Ca^{2+} + Mg^{2+}}} \times 100$	Szabolcs (1964)
Permeability index	$\mathrm{PI} = \frac{\mathrm{Na} + \sqrt{\mathrm{HCO_3^-}}}{\mathrm{Ca^{2+}} + \mathrm{Mg^{2+}} + \mathrm{Na^+}} \times 100$	Doneen (1964)
Kelley's Ratio	$KR = \frac{\mathrm{Na^+}}{\mathrm{Ca^{2+}} + \mathrm{Mg^{2+}}}$	Kelley (1940)

Table 2. The physiochemical parameters with their allotted and relative weights.

Chemical parameters	Standards (WHO, 2011)	Weight (wi)	Relative weight (Wi)
pH	8.5	4	0.10
TDS	500	5	0.12
Ca^{2+}	75	3	0.07
Mg^{2+}	30	3	0.07
Na^+	200	4	0.10
HCO_3^-	300	1	0.02
F^-	1.5	5	0.12
Cl^-	250	5	0.12
SO_4^{2-}	200	5	0.12
NO_3^-	45	5	0.12
TH	300	2	0.05
		∑wi=42	∑=Wi=1.0

All parameters are in Mg/L except for pH

Table 3. Physico-chemical analysis of groundwater sample for pre-monsoon season.

S. No	Sample locations	pH	EC (µS/cm)	TDS (Mg/L)	Ca^{2+} (Mg/L)	Mg^{2+} (Mg/L)	Na^{+} (Mg/L)	K^{+} (Mg/L)	HCO_3^{-} (Mg/L)	F^{-} (Mg/L)	Cl^{-} (Mg/L)	SO_4^{2-} (Mg/L)	NO_3^{-} (Mg/L)	TH (Mg/L)
1	Kangalakunta	7.9	2028.4	1420	197	24	207	7.2	584	1.27	254	121	34.6	590.9
2	Kanchikunta	7.9	2070.4	1449	216	20	231	10.3	610	1.06	235	112	22.2	622
3	Ramagiri	7.8	2210.5	1547	184	88	192	5.6	564	0.93	198	311	14.4	820.8
4	R. Kothapalli	8	1884.5	1319	136	64	184	6	422	1.96	189	271	45.2	602.4
5	Nasanakota	7.7	1979.7	1386	175	54	196	8	541	1.62	252	93	65.2	658.9
6	Muthyalanpalli	7.9	1540	1078	127	48	138	3	428	1.82	175	129	28.2	514.3
7	Venkatapuram	7.6	1849.3	1294	148	32	188	14	548	0.98	185	157	22.5	501.2
8	K G Kunta	8	1747.4	1223	165	66	102	10	540	1.71	213	87	38.5	683.1
9	Madapuram	8.2	1573.5	1101	129	76	104	8	427	1.98	238	89	28.5	634.1
10	Muthavakuntla	8	1644.2	1151	123	79	106	10	549	1.76	148	116	21.2	631.4
11	Thallimadugula	8	1472.7	1031	118	43	112	1	488	1.98	142	98.9	27	471.3
12	Balepalem	8	1788.9	1252	185	63	92	11	549	2.02	213	87	51.2	720.8
13	Konapuram	7.9	1861.3	1303	131	99	108	12	549	1.92	266	107	29	733.4
14	Kanaganapalli	7.9	1965.4	1376	166	97	102	7	671	1.78	190	107	34	812.7
15	Elakuntla	7.6	1799.8	1260	152	105	116	16.6	549	1.43	162	73.8	84	810.5
16	Nemalivaram	7.7	2032.5	1423	151	112	127	11	610	1.57	240	89	65.2	836.7
17	Bhadhalapuram	7.62	3094	2103	218	135	264	12.3	748	1.38	380	262	82.8	1099
18	Narasampalli	7.8	1773.7	1242	124	91	122	4	598	1.48	167	102	32.1	683.1
19	Somaravandlapalli	7.8	2250.9	1576	175	108	192	6	648	1.82	243	164	85.8	880.3
20	Gudivandlapalli	7.8	2195.3	1537	193	88	132	4	732	1.51	213	128	45.2	843.3
21	Thagarakunta	8	2044.5	1431	184	78	129	5	650	1.62	218	127	38.5	779.8
22	Gunthapalli	8	1624.5	1137	128	76	142	4	419	1.62	239	79	48.5	631.6
23	Patapalyam	8	2108.1	1476	158	82	197	8	629	1.74	208	126	65.9	731.2
24	Pullaiahkunta	7.6	1565.6	1096	124	57	138	2	428	0.72	213	98	35.2	543.7
25	Bhoginepalli	7.8	1516.1	1061	117	74	97	4	488	1.48	180	80	19.8	595.9
26	Palacherla	8.2	2595	1817	195	125	258	12	629	2.02	312	185	98.5	1000
27	Thopudurthi	8.3	3141	2096	212	142	311	9	784	1.96	328	214	94.2	1112
28	Upparapalle	7.7	2053.9	1438	185	101	94	4	640	1.56	228	134	50.2	876.6
29	Chinnakunta	8	1528.8	1070	132	65	112	10	478	2.14	146	73	52.2	596.5
30	Akuthotapalli	8	3102	2115	221	115	302	11	736	1.88	338	296	93.4	1024
31	Gangulakunta	8.1	2113.4	1479	174	67	191	7	529	2.01	242	192	75.4	709.7
32	Kandukur	7.86	2909.6	2037	227	104	328	9.6	718	1.78	318	240	90.7	993.9
33	Itikalapalli	8.1	3129	2116	268	96	310	8.8	740	1.9	322	311	58.2	1064
34	Krishnama reddy palli	7.7	1960.5	1372	198	70	134	10.4	589	1.44	186	145	38.5	782
35	Jangalapalle	8.2	1639.6	1148	163	69	103	10	448	2.93	203	87	62.5	690.4
36	Ramanepalli	8.1	2087.6	1461	159	127	126	5	549	1.73	249	106	98.6	918.2
37	Gondireddipalli	7.9	1494.3	1046	132	65	108	9	428	1.78	193	72	37.2	596.5
38	yerragunta	7.6	1704.3	1193	154	32	174	9	524	1.54	172	88	38.5	516.2
39	Bandameedapalle	7.4	1573.9	1102	112	85	122	6	419	1.75	182	96	78.5	628.5
40	Varimadugu	7.9	1562.5	1094	139	39	128	3	469	1.78	175	107	75.2	507.4
41	Gandlaparthy	7.5	1886.4	1321	163	77	118	10	489	1.01	155	250	58.2	723.2
42	Pullalarevu	7.4	1857.9	1301	193	70	138	8	589	1.05	186	68.2	68.5	769.5
43	Bommeparthy	7.8	2000.6	1400	185	59	202	12	529	1.44	258	102	72.5	704.4
44	Linganapalli	7.7	2308.6	1616	197	67	216	10	649	1.75	248	162	85.8	767.2
45	Rapthadu	8.09	2761	1822	196	110	244	9.3	632	1.89	320	206	59.1	941
46	Anantapur tank	7.8	3064	2104	218	129	268	12	672	1.79	287	284	103	1074

Table 4. Physico-chemical analysis of groundwater sample for post-monsoon season

S. No	Sample locations	pH	EC (µS/cm)	TDS (Mg/L)	Ca^{2+} (Mg/L)	Mg^{2+} (Mg/L)	Na^{+} (Mg/L)	K^{+} (Mg/L)	HCO_3^{-} (Mg/L)	F^{-} (Mg/L)	Cl^{-} (Mg/L)	SO_4^{2-} (Mg/L)	NO_3^{-} (Mg/L)	TH (Mg/L)
1	Kangalakunta	7.62	1840.6	1164.4	168	47	192	3.7	524	1.45	185	121	46.9	610.6
2	Kanchikunta	7.48	2380.1	1666.1	229	78	262	9.1	592	1.03	282	186.8	76.1	892.0
3	Ramagiri	8.07	2760.0	1932.0	194	95	293	9.4	672	2.72	222	212.5	95.4	874.4
4	R. Kothapalli	8.11	2189.4	1532.6	185	78	227	5.6	576	2.11	242	184.6	52.4	782.4
5	Nasanakota	7.61	2301.5	1483.1	197	86	186	6.6	648	1.93	262	155	70.2	846.6
6	Muthyalanpalli	7.59	1735.8	1215.1	153	75	188	3.2	440	1.06	212	162	30.9	689.5
7	Venkatapuram	7.34	1962.3	1373.6	196	69	207	7	489	0.78	244	187	28.9	775.7
8	K G Kunta	7.91	2045.1	1431.5	185	67	167	12	624	1.67	206	122	47.1	736.1
9	Madapuram	7.55	1846.5	1292.5	157	57	181	14	496	1.46	244	108	33.6	627.9
10	Muthavakuntla	7.32	1721.3	1204.9	149	62	184	10.8	448	1.45	194	162	50.8	626.3
11	Thallimadugula	7.48	1625.1	1137.6	127	76	126	1.5	498	1.34	184	106	28	628.6
12	Balepalem	8.2	1927.1	1349.0	198	73	128	12	529	3.12	242	118	45.7	794.5
13	Konapuram	7.99	2334.6	1634.2	169	125	186	12.8	660	1.89	324	148	51.3	935.7
14	Kanaganapalli	7.83	1873.6	1311.5	193	55	204	8.3	528	1.82	220	127	46.9	709.8
15	Elakuntla	7.99	1998.8	1345.2	159	78	194	13.4	596	2.02	188	104.4	94.2	717.3
16	Nemalivaram	7.77	3189.0	2233.0	198	96	264	9.3	724	2.14	254	216	89.1	890.0
17	Bhadhalapuram	7.62	2355.0	1728.5	168	105	184	8.3	748	0.88	240	142	62.8	849.3
18	Narasampalli	7.49	3106.0	2174.5	167	59	227	12.2	756	1.42	200	98.2	51.2	660.9
19	Somaravandlapalli	7.83	2449.0	1786.3	202	89	232	10.7	648	1.76	288	186	76.6	870.6
20	Gudivandlapalli	7.37	2748.0	1923.6	277	55	287	7.9	818	1.01	242	157	77.9	920.5
21	Thagarakunta	7.52	2312.1	1618.4	187	89	227	6.8	640	1.24	278	174	48.3	832.2
22	Gunthapalli	7.65	1953.5	1367.4	173	75	189	6.1	512	1.44	252	106	52.9	739.7
23	Patapalyam	7.05	2189.7	1602.8	189	78	242	7.8	620	1.18	306	122	67.5	790.3
24	Pullaiahkunta	7.59	1895.1	1326.6	162	67	161	4.1	514	1.67	246	127	43.8	679.8
25	Bhoginepalli	7.94	1738.8	1115.2	146	43	188	6	480	1.6	218	108	26.8	540.4
26	Palacherla	8.01	2078.2	1408.8	178	87	199	9.6	486	2.24	262	194	46.1	804.5
27	Thopudurthi	8.21	3126.6	2188.6	202	128	282	8.8	728	2.03	268	286	93.8	1030.3
28	Upparapalle	8.3	2061.6	1443.1	177	66	196.5	7.1	544	2.42	278	144	55.7	713.8
29	Chinnakunta	7.83	2848.7	1994.0	224	125	268	11.7	742	2.43	296	240	85.4	1070.8
30	Akuthotapalli	7.79	1792.1	1254.5	141	65	152	11	536	1.68	188	96	63.4	620.1
31	Gangulakunta	8.11	2271.7	1421.2	225	82	238	11.6	546	3.11	254	218	73.7	898.0
32	Kandukur	7.86	2079.6	1415.7	167	74	198	8.6	588	1.78	248	90	80.7	719.7
33	Itikalapalli	8.12	2053.9	1397.7	198	66	214	6.8	580	1.9	222	131	78.2	765.3
34	Krishnama reddy palli	7.6	2212.1	1508.5	203	68	247	7.7	552	1.57	226	196	87.1	786.6
35	Jangalapalle	7.69	3144.0	2108.0	219	131	260	10.7	792	1.56	356	248	90.1	1084.6
36	Ramanepalli	7.79	2015.1	1410.5	199	70	214.5	7.7	588	1.53	240	143	46.8	783.2
37	Gondireddipalli	7.86	3067.0	1993.6	255	132	328	9.7	748	1.87	345	220	62	1178.7
38	yerragunta	7.86	2333.0	1634.0	196	84	248	6.1	658	1.98	242	162	85.4	834.4
39	Bandameedapalle	7.69	3254.0	2278.8	119	131	190	10.7	712	1.56	226	148	90.1	834.6
40	Varimadugu	7.45	1826.3	1218.4	178	39	192	6.1	516	1.48	198	138	85.6	605.1
41	Gandlaparthy	7.49	1937.4	1356.2	189	80	217.2	9.8	425	0.91	201	208	95.4	799.3
42	Pullalarevu	7.65	1874.9	1312.4	194	55	158	7.8	580	1.73	212	86	105.4	712.1
43	Bommeparthy	7.82	3025.0	2118.0	187	103	222	9.4	690	1.79	246	128.8	97.9	888.5
44	Linganapalli	7.83	1647.8	1153.5	107	66	151	8.8	496	2.76	184	82	98.4	539.5
45	Rapthadu	7.49	2275.2	1466.6	156	90	214	7.3	628	0.89	232	126	102.5	757.1
46	Anantapur tank	7.83	3118.6	2183.0	245	122	348	10.2	724	1.79	368	246	118.5	1110.7

Table 5. Classification based on physicochemical parameters considering WHO (2011) limiting values.

Parameter	Range	Class	No. of Samples (PRM)	%	No. of Samples (POM)	%
pH	<6.5	Not potable	–	–	–	–
	6.5 - 8.5	Potable	46	100	46	100
	>8.5	Not potable	–	–	–	–
EC	<250	Excellent	-	-	-	-
	250-750	Good	-	-	-	-
	750-2250	Moderate	37	80	26	57
	2250-4000	Bad	9	20	20	43
	>4000	Very bad	-	-	-	-
TDS	0-1000	Fresh water	–	–	–	–
	1000-10000	Brackish water	46	100	46	100
	10000-100000	Saline water	–	–	–	–
	>100000	Brine water	–	–	–	–
Ca^{2+}	<75	Acceptable	–	–	–	–
	75 - 200	Allowable	38	85	36	78
	>200	Not potable	8	15	10	22
Mg^{2+}	<30	Acceptable	2	4	–	–
	30 - 150	Allowable	44	96	46	100
	>150	Not potable	–	–	–	–
Na^{+}	<50	Acceptable	–	–	–	–
	50 - 200	Allowable	34	74	22	48
	>200	Not potable	12	26	24	52
K^{+}	< 10	Acceptable	32	74	32	69
	10-Dec	Allowable	11	20	10	22
	> 12	Not potable	3	6	4	9
Cl^{-}	<250	Acceptable	34	74	30	65
	250 - 300	Allowable	5	11	11	24
	>300	Not potable	7	15	5	11
SO_4^{2-}	<200	Acceptable	36	78	37	80
	200 - 400	Allowable	10	22	9	20
	>400	Not potable	–	–	–	–
TH	< 75	Safe	–	–	–	–
	75 - 150	Moderate safe	–	–	–	–
	150- 300	Hard	–	–	–	–
	> 300	Very hard	46	100	46	100
F^{-}	< 0.5	Dental caries	-	-	-	-
	0.6-1.5	Required level for human	15	33	17	37
	1.6-2	Dental fluorosis	26	56	20	43
	2.1-3	Dental and skeletal fluorosis	5	11	7	16
	> 3	leads to skeletal fluorosis	-	-	2	4
NO_3^{-}	< 45	Low risk	6	13	4	8
	45 - 100	High risk	37	80	39	85
	> 100	Very high risk	3	7	3	7

Fluoride and Nitrate hotspots

Fluoride concentrations in the investigation region ranges from 0.72 mg/L and 0.8 mg/L to 2.93 mg/L and 3.1 mg/L during the PRM and POM season. Based on the WHO (2011) recommended limit of fluoride levels is 0.6 to 1.5 mg/L for human consumption. Levels below 0.6 mg/L may lead to dental caries, while levels exceeding 1.2 mg/L can result in fluorosis, which promotes proper bone growth and prevents tooth decay. In the pre-and post-monsoon seasons, 33% and 37% of groundwater samples were below the allowed limits (0.6 to 1.5 mg/L), while 56% and 43% were above the suggested limit of 1.5 mg/L, potentially causing dental fluorosis. Additionally,

11% and 16% of samples had concentrations between 2.1 to 3 mg/L, posing dental and skeletal fluorosis risks in both seasons. Furthermore, 4% of samples had concentrations exceeding 3 mg/L, which could lead to skeletal fluorosis, particularly during the POM season (Table 5, Figure 2).

Nitrate contamination in groundwater stems from various sources and origins. Human activities, such as home sewage leaks, poultry waste dumping, the application of animal manure, and nitrate displacement from garbage, municipal use, and commercial trash, are chiefly responsible for elevated nitrate levels in groundwater (Singh et al., 2022). Nitrate can enter groundwater through two pathways: geogenic and human-caused processes. During the pre-monsoon season, nitrate levels ranged from 14.4 to 103 mg/L, with an average of 55.50 mg/L, while during the post-monsoon season, it ranged from 26.8 to 119 mg/L, with an average of 68.20 mg/L. In the pre- and post-monsoon seasons, 13% and 8% of groundwater samples are inside the acceptable nitrate limit, 80% and 85% of samples belong to the danger zone, while the remaining 7% and 7% of samples fell in the extremely high-risk zone, as shown in Table 5 and Figure 3.

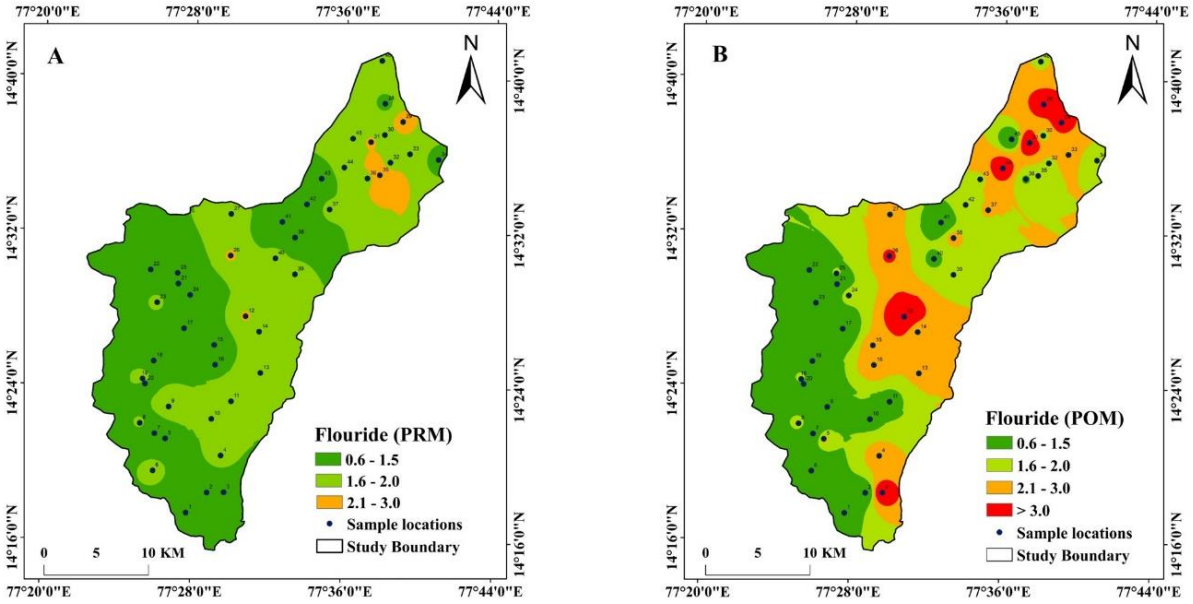


Figure 2. Spatial distribution map of F^- in the study area **(A)** Pre-monsoon, and **(B)** Post-monsoon.

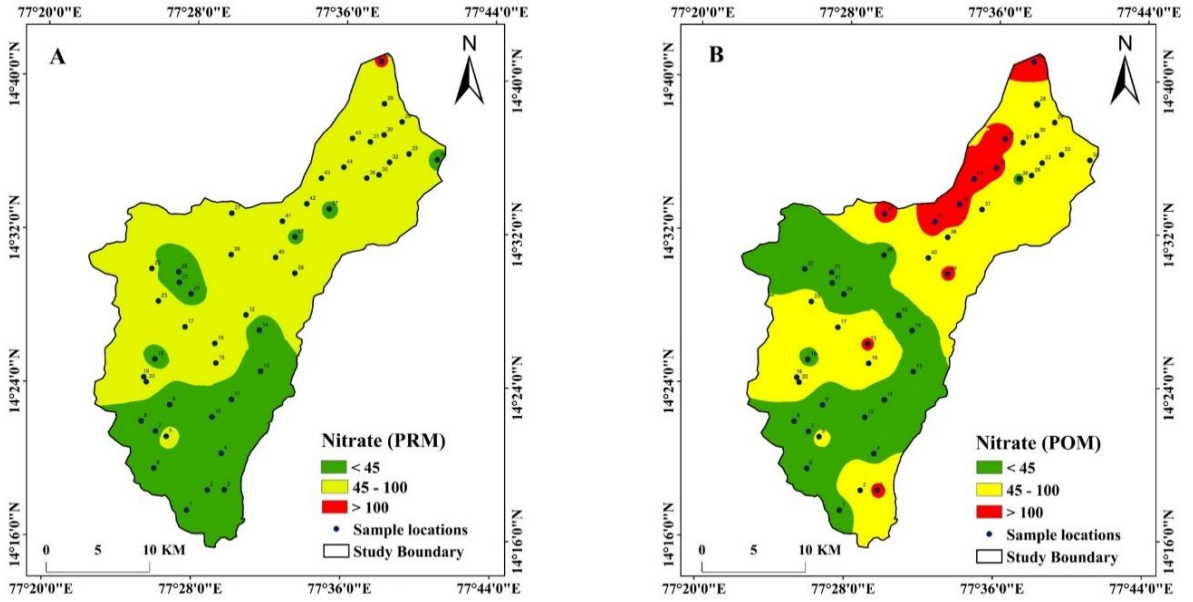


Figure 3. Spatial distribution map of NO_3^- in the study area **(A)** Pre-monsoon, and **(B)** Post-monsoon.

Total hardness (TH) of water is influenced by the presence of dissolved cations, predominantly calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions, as well as certain anions that cause either temporary or permanent hardness (Sawyer and McCarthy, 1967). Carbonates and bicarbonates produce temporary hardness that can be removed by boiling, while sulphate and chloride ions lead to permanent hardness. According to WHO standards, the maximum acceptable limit for total hardness in drinking water is 500 mg/L. In the PRM season, TH ranged from 214 mg/L to 658 mg/L (Table 3). During the POM season, it varied between 241 mg/L to 681 mg/L (Table 4). Based on these measurements, 57% and 61% of samples exceeded the recommended limit during the PRM and POM seasons, respectively (Table 5), indicating the prevalence of hard water in the region. Excessive hardness in water can lead to issues such as scaling in pipelines, reduced efficiency in soap usage, and potential health concerns when ingested over prolonged periods.

Correlation analysis

Correlation analysis helped in understanding the strength and direction of relationships between various groundwater quality parameters and their combined influence on the hadrochemical characteristics of the study area. Pearson correlation coefficients for both PRM and POM seasons are presented in Table 6 and Table 7, respectively.

EC shows a very strong positive correlation with TDS in both PRM (r = 0.998) and POM (r = 0.988) seasons, indicating a common source and mutual dependence. This suggests that an increase in ion concentration (as reflected in TDS), directly increases the EC of groundwater. EC also shows significant positive correlations with other major ions such as Na^+, Cl^-, and HCO_3^- in both seasons, implying their likely origin from the same lithological sources, mainly due to water-rock interactions (Wagh et al., 2020). TH shows strong positive correlations with Mg^{2+} (r = 0.871), HCO_3^- (r = 0.814), and Cl^- (r = 0.771) during the PRM season, and with Mg^{2+} (r = 0.835), Cl^- (r = 0.809), and SO_4^{2-} (r = 0.784) during the POM season. These results suggest that Mg^{2+}, Cl^-, and SO_4^{2-} are the key contributors to water hardness, particularly in the post-monsoon period. Calcium (Ca^{2+}) exhibits moderate to strong positive correlations with Mg^{2+} (r = 0.331 in PRM; r = 0.262 in POM), Na^+ (r = 0.749 in PRM; r = 0.750 in POM), and HCO_3^- (r = 0.802 in PRM; r = 0.503 in POM), indicating that these ions likely originate from the dissolution of carbonate and silicate minerals within the host rocks. Interestingly, Ca^{2+} also shows a weak negative correlation with fluoride (F^-) during the PRM season (r = -0.033), suggesting potential geochemical competition or different geochemical behaviour in fluoride mobilization. Magnesium (Mg^{2+}) shows significant positive correlations with NO_3^- (r = 0.594 in PRM; r = 0.389 in POM), HCO_3^- (r = 0.568 in PRM; r = 0.632 in POM), and F^- (r = 0.225 in PRM; r = 0.147 in POM), highlighting possible anthropogenic contributions and its role in groundwater buffering. These correlations emphasize that groundwater chemistry in the region is primarily controlled by natural geogenic processes with minor anthropogenic influences, especially during the post-monsoon season.

Table 6. Pearson correlation matrix of groundwater parameters for PRM season.

	pH	*EC*	*TDS*	*TH*	*Ca2+*	*Mg2+*	*Na+*	*K+*	*HCO3-*	*F-*	*Cl-*	*SO42-*	*NO3-*
pH	1.000												
EC	0.197	1.000											
TDS	0.184	**0.998**	1.000										
TH	0.182	0.898	0.899	1.000									
Ca2+	0.114	0.849	0.856	0.752	1.000								
Mg2+	0.176	0.652	0.648	0.871	0.331	1.000							
Na+	0.183	0.876	0.876	0.622	0.749	0.332	1.000						
K+	-0.067	0.343	0.347	0.345	0.366	0.220	0.299	1.000					
HCO3-	0.089	0.849	0.854	0.814	0.802	0.568	0.639	0.277	1.000				
					-		-						
F-	0.672	0.066	0.057	0.140	0.033	0.225	0.002	0.053	-0.035	1.000			
Cl-	0.300	0.861	0.856	0.771	0.710	0.574	0.784	0.302	0.645	0.145	1.000		
										-			
SO42-	0.117	0.778	0.778	0.619	0.611	0.430	0.728	0.163	0.502	0.032	0.549	1.000	
NO3-	0.039	0.590	0.597	0.645	0.442	0.594	0.512	0.306	0.401	0.289	0.547	0.312	1.000

Table 7. Pearson correlation matrix of groundwater parameters for POM season.

	pH	*EC*	*TDS*	*TH*	*Ca^{2+}*	*Mg^{2+}*	*Na^{+}*	*K^{+}*	*HCO_3^-*	*F^-*	*Cl^-*	*SO_4^{2-}*	*NO_3^-*
pH	1.000												
EC	0.123	1.000											
TDS	0.096	**0.988**	1.000										
TH	0.203	0.785	0.765	1.000									
Ca^{2+}	0.071	0.486	0.459	0.749	1.000								
Mg^{2+}	0.236	0.740	0.733	0.835	0.262	1.000							
Na^{+}	0.050	0.735	0.709	0.772	0.750	0.503	1.000						
K^{+}	0.232	0.353	0.360	0.308	0.155	0.318	0.165	1.000					
HCO_3^-	0.072	0.878	0.877	0.721	0.503	0.632	0.618	0.308	1.000				
F^-	0.772	0.094	0.064	0.138	0.063	0.147	0.013	0.311	0.027	1.000			
Cl^-	0.117	0.568	0.556	0.809	0.602	0.679	0.621	0.228	0.524	0.083	1.000		
SO_4^{2-}	0.183	0.598	0.575	0.784	0.609	0.637	0.751	0.146	0.382	0.137	0.581	1.000	
NO_3^-	0.100	0.497	0.484	0.420	0.270	0.389	0.463	0.265	0.457	0.182	0.176	0.303	1.000

Water Quality index (WQI)

The WQI values are categorized as follows: if the WQI is less than 50, the groundwater is considered excellent; between 50.1 and 100, good quality water; from 100.1 to 200, it is classified as poor; between 200.1 and 300, very poor; and if the values exceed 300, the water is deemed unfit for drinking. This information is summarised in Table 8. Based on the WQI classification, 9 groundwater samples are of good quality, while 37 samples are of poor quality, indicating that 19% of the study area has good-quality water, and 81% suffers from poor-quality water. In the post-monsoon season, 12 groundwater samples show good quality, whereas 34 samples demonstrate poor quality. This reveals that 26% of the study area has good-quality water, and 74% experiences poor-quality water. The elevated WQI values may be linked to higher levels of Total Dissolved Solids (TDS), Electrical Conductivity (EC), and Total Hardness (TH), suggesting that the groundwater is unsuitable for drinking purposes.

The IDW interpolation method was employed using ArcGIS software to create a spatial distribution map based on the WQI values of each sample. This study strongly advocates for using GIS to assess water quality and explore regional variations. The spatial distribution maps of the WQI in the research area, as depicted in Figure 4, provide valuable information to the public regarding water quality in specific areas and serve as a tool to raise awareness among local residents about the importance of safeguarding water quality in the region. A comprehensive classification of WQI for both the pre- and post-monsoon seasons is presented in Table 8**,** with higher WQI values observed in the post-monsoon season compared to the pre-monsoon season.

Irrigation Water Quality

To assess the suitability of groundwater quality for irrigation, several fundamental ratios such as SAR, RSC, Na%, MAR, SSP, KR, and PI were used for the interpretation.

Sodium Adsorption Ratio (SAR)

The Sodium Adsorption Ratio (SAR) is a measure that evaluates the relative and absolute concentration of sodium ions in comparison to calcium and magnesium ions. SAR values are directly correlated with the soil's sodium absorption capacity (Ahmed et al., 2020). During the pre-monsoon season, SAR values range from 1.38 to 4.53 meq/L (Table 9). In the post-monsoon season, 1.97 to 4.55 (Table 9). Based on Richards (1954) classification, all groundwater samples in this study area (100%) fall into the "excellent" category for irrigation during both seasons Table 10).

Residual sodium carbonate (RSC)

The RSC content in water reflects a notably high concentration of bicarbonate ions (HCO_3^-) relative to other negative ions, as observed in Table 9. Consequently, carbonate ions (HCO_3^- and CO_3^{2-}) influence water quality by precipitating alkaline earth ions (Ca^{2+} and Mg^{2+}) in areas where water concentration is higher. During the pre-monsoon (PRM) season, RSC values ranged from -10.50 meq/L to 2.91 meq/L **(**Table 9). In the post-monsoon (POM) season, it ranged from -11.38 meq/L to 3.20 meq/L **(**Table 9**).** According to Eaton (1950) classification, 96% and 94% of samples are classified as appropriate for farming, 2% and 2% are dubious, and 2% and 4% are unsuitable for irrigation in the PRM and POM seasons, respectively **(**Table 10**).**

Percent sodium (%Na)

Soil permeability is lowered when sodium replaces calcium. The %Na is significant for classifying irrigation water. Wilcox (1955) percentage Na values are used to classify the purity of water used for farming. Sodium mixes with carbonates and chlorides to form alkaline and saline soils. Plants develop poorly in alkaline or salty soils. A sodium level of 60% is allowed in groundwater for purposes of agriculture (Mukherjee et al., 2022). In the PRM, the %Na levels fluctuated between 19.29 meq/Land 46.67 meq/L (Table 9) and in POM, between

27.00 and 43.55 (Table 9). As per Wilcox (1955) categorization, 87% and 80% of samples are good, while 13% and 20% are permitted for irrigation during both seasons (Table 10).

Sodium Soluble Percentage (SSP)

The Sodium Soluble Percentage (SSP) ratio, proposed by Richards (1954), helps assess sodium-related hazards by comparing the concentration of sodium ions to total cations. During the PRM season, SSP values ranged from 18.82% to 45.48% at Thopudurthi and Kanchikunta **(**Table 9). In the POM season, SSP values ranged from 25.59% to 42.75% in Balepalem and Pullaiahkunta (Table 9**).**

Table 8. Classification of water quality types based on WQI (Karunanidhi et al., 2021)

WQI range	Water quality status	% of water samples (PRM)	% of water samples (POM)
< 50	Excellent	–	–
50.1-100	Good	19 (9 samples)	22 (10 Samples)
100.1-200	Poor	81 (37 samples)	74 (34 samples)
200.1-300	very poor	–	4(2 samples)
>300	Unsuitable for drinking	–	–

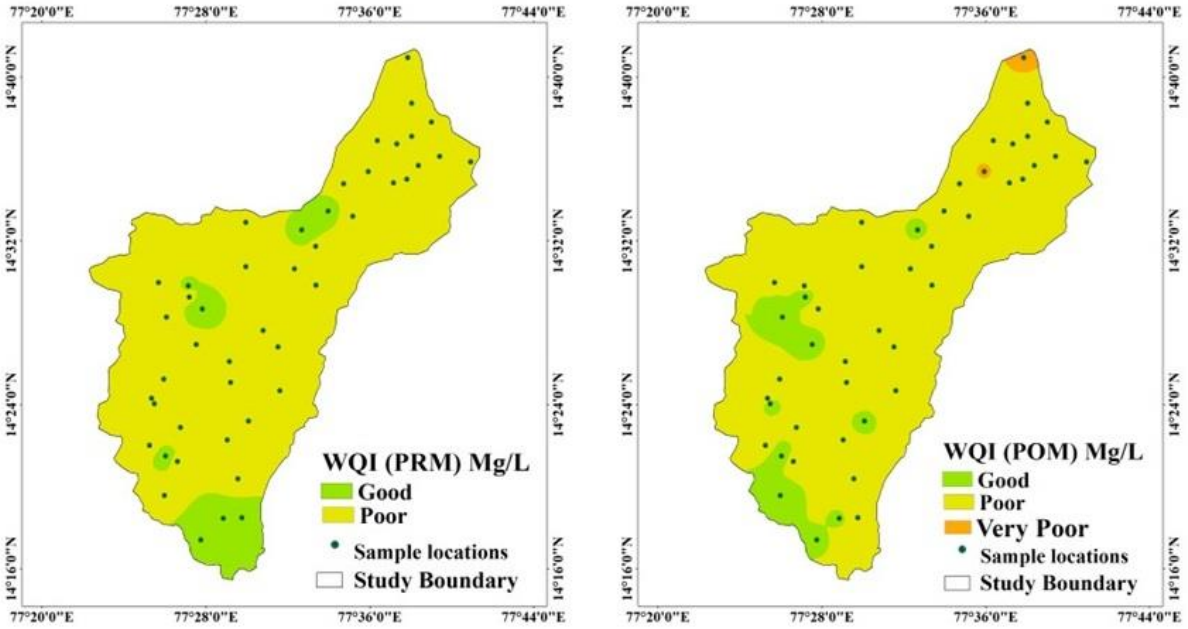


Figure 4. Spatial distribution map of Water quality index (WQI) in the study area during pre-monsoon and post-monsoon.

Table 9. Groundwater quality parameters for irrigation purposes for the pre-monsoon (PRM) and post-monsoon (POM) seasons.

Parameters	PRM				POM			
	Minimum	Maximum	Average	Std.Dev	Minimum	Maximum	Average	Std.Dev
SAR (meq/L)	1.38	4.53	2.66	0.88	1.97	4.55	3.3	0.53
RSC (meq/L)	-10.5	2.91	-4.9	2.9	-11.38	3.2	-5.6	2.99
%Na (meq/L)	19.29	46.67	32.86	6.98	27	43.55	37.44	3.41
SSP (meq/L)	18.82	45.48	31.91	7.02	25.59	42.75	36.56	3.46
MAR (meq/L)	12.77	56.82	42.92	9.74	39.66	57.97	49.52	3.55
KR (meq/L)	0.23	0.85	0.49	0.16	0.35	0.76	0.59	0.08
PI (meq/L)	33.85	61.44	46.43	6.68	24.76	64.56	41.61	7.37

Table 10. Classification of groundwater based on irrigational water quality parameters during pre-monsoon (PRM) and post-monsoon (POM) seasons

Parameter	Water quality	Ranges	% of groundwater samples (PRM)	% of groundwater samples (POM)
SAR (Richards, 1954)	Excellent	0 −10	100%	100%
	Good	10−18	Nil	Nil
	Doubtful	18-26	Nil	Nil
	Unsuitable	> 26	Nil	Nil
RSC (Eaton,1950)	Good	< 1.25	96%	96%
	Doubtful	1.25 – 2.50	2%	2%
	Unsuitable	> 2.50	2%	2%
%Na (Wilcox, 1955)	Excellent	< 20	Nil	Nil
	Good	20 – 40	87%	87%
	Permissible	40−60	13%	13%
	Doubtful	60−80	Nil	Nil
SSP (Richards, 1954)	Good	< 50	100%	100%
	Unsuitable	> 50	Nil	Nil
MAR (Szabolcs, 1964)	Suitable	< 50	74%	74%
	Unsuitable	> 50	26%	26%
KR (Kelley, 1940)	Suitable	<1	100%	100%
	Unsuitable	>1	Nil	Nil
PI (Doneen, 1964)	unsuitable	< 25 Class-III	Nil	Nil
	Good	25 – 75 class-II	100%	100%
	Excellent	>75 class- I	Nil	Nil

Based on Richards (1954) assessment, 100% of groundwater samples in both seasons fall within the "superior" range for farming suitability **(**Table 10**).**

Wilcox Diagram

Wilcox (1955) developed a diagram to determine the suitability of groundwater for irrigation by combining electrical conductivity (EC) and sodium percentage (%Na). This model divides the diagram into five distinct zones: excellent to good, good to permissible, permissible to doubtful, doubtful to unsuitable, and unsuitable, with increasing salinity and sodium content posing potential threats to agriculture. According to this categorization, 56% and 37% of groundwater samples fall within the good to permissible zone, while 33% and 46% are categorized as doubtful to unsuitable, and 11% and 17% are classified as unsuitable for irrigation during the PRM and POM seasons, respectively (Figure 5). These results highlight variations in the suitability of groundwater resources for agricultural use between the pre- and post-monsoon seasons.

USSL Diagram

The interpretations of the USSL (1954) for rating irrigation water are shown in Figure 6, where Sodium Adsorption Ratio (SAR) data is plotted against specific conductance (EC). In the pre-monsoon (PRM) season, the majority of samples (78%, 36 samples) fall within the C3S1 category, indicating moderate salinity and low sodium hazard. A smaller proportion (9%, 4 samples) falls within the C4S1 category, which represents high salinity and low sodium hazard, while 13% (6 samples) belong to the C4S2 category, indicating high salinity and moderate sodium hazard, according to the USSL (1954) classification.

In the post-monsoon (POM) season, the distribution shifts slightly: 58% (27 samples) are categorized as C3S1, 20% (9 samples) fall in the C4S1 category, and 22% (10 samples) are in the C4S2 category. These findings suggest that high saline and alkali levels in some areas may reduce the suitability of groundwater for agricultural use, especially in locations with poor drainage. Overall, the groundwater chemistry in the study area reflects moderate water quality, which is significantly influenced by the underlying host rock. This influence is evident in both the water type and chemical composition, with implications for its use in agriculture and human activities.

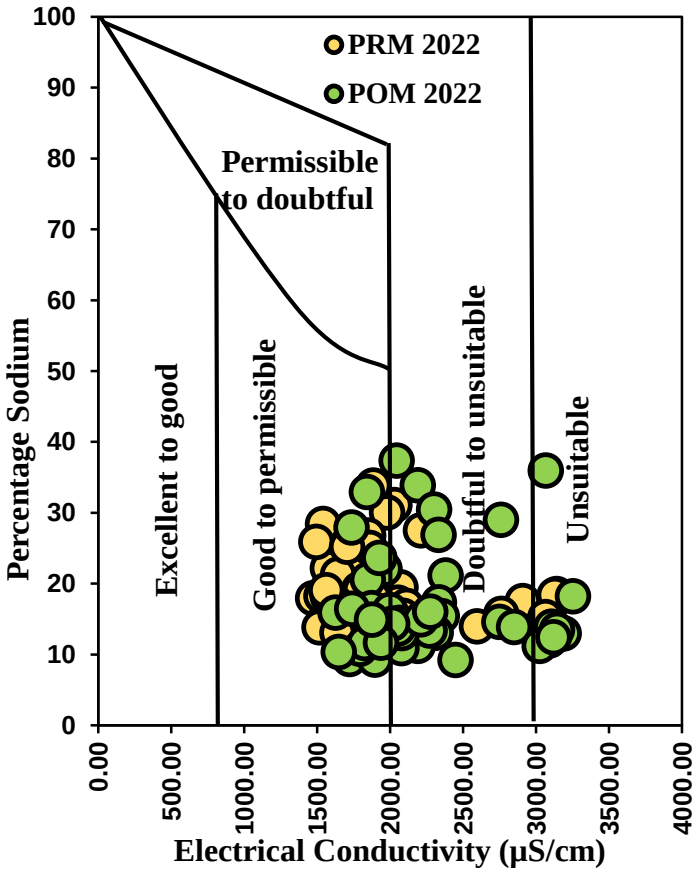


Figure 5. Wilcox diagram of the study area (Pre Monsoon and Post Monsoon)

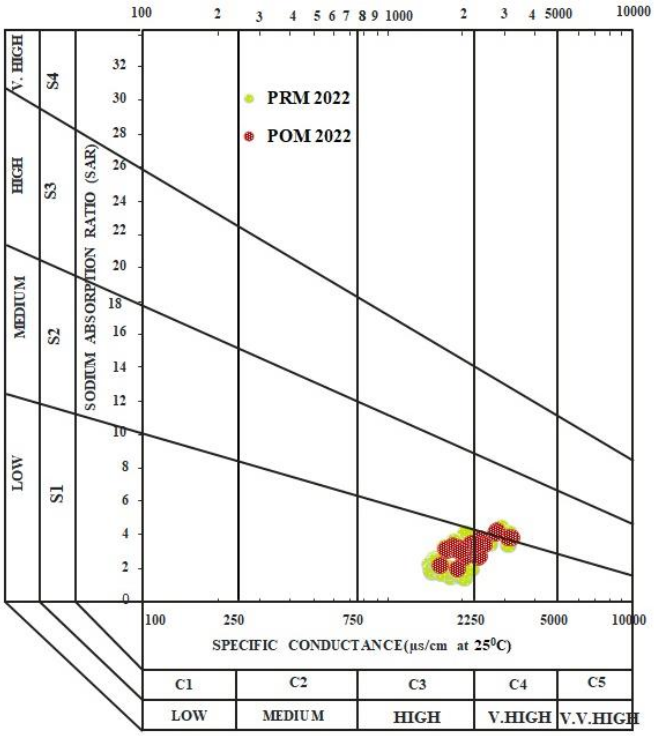


Figure 6. USSL (1954) diagram of the investigation region in PRM and POM seasons

Magnesium Absorption Ratio (MAR)

Magnesium concentration is a critical factor in evaluating the suitability of water for irrigation. The balance between calcium and magnesium in water is important, and increasing magnesium levels can harm crop yields, especially in saline soils (Szabolcs, 1964; Zhang et al., 2020). In the pre-monsoon (PRM) season, the MAR values ranged from 12.77 meq/L to 56.82 meq/L (Table 9). In the post-monsoon (POM) season, MAR values ranged from 39.66 meq/L to 57.97 meq/L (Table 9). Based on Szabolcs (1964) classification, 74% and 92% of the samples fall under the "suitable" category for irrigation, while 26% and 8% are categorized as "unsuitable" during the two seasons, respectively (Table 10).

Kelley's ratio (KR)

The Kelley Ratio (KR), introduced by Kelley (1940) evaluates the sodium concentration in water relative to calcium (Ca^{2+}) and magnesium (Mg^{2+}). A KR value exceeding 1 indicates high sodium levels, rendering the water unsuitable for irrigation. For acceptable irrigation standards, the KR value should be less than 1. In the pre-monsoon season, KR values ranged from 0.23 meq/L to 0.85 meq/L, while in post monsoon season KR values ranged from 0.35 meq/L to 0.6 meq/L (Table 9). According to this classification, all groundwater samples (100%) are categorized as "suitable" for irrigation during both the seasons (Table 10).

Permeability Index (PI)

The permeability of soil is an important factor for assessing the suitability of water for irrigation. The permeability index (PI) helps classify water into three categories: Class I and Class II waters are suitable for irrigation with high permeability (above 75%), while Class III waters are less suitable with lower permeability (below 25%) (Doneen, 1964). In the pre-monsoon season, PI ranged from 33.85 meq/L to 61.44 meq/L (Table 9) and in the post-monsoon season, 24.76 meq/L to 64.56 meq/L (Table 9). According to Doneen (1964) classification, all groundwater samples (100%) fall under the "good" category for irrigation during both seasons (Table 10).

Hydrogeochemical facies -Piper Trilinear Diagram Interpretation

Piper's classification, introduced in 1944 and refined in 1953, is a widely used method for characterizing the chemical composition of groundwater (Piper1944, 1953). It utilizes a trilinear diagram to classify ion dominance and provides a more accurate assessment of groundwater chemistry compared to other methods. The diagram consists of a central diamond-shaped field with six distinct subfields that represent different ion pairings viz.,

(i) Ca^{2+}- HCO_3^-

(ii) .Na^+-Cl^-

(iii) Mixed Ca^{2+}-Na^+-HCO_3^-

(iv) Mixed Ca^{2+}-Mg^{2+}-Cl^-

(v) Ca^{2+}-Cl^-

(vi) Na^+-HCO_3^-

Based on the results from this study (Figure.7a, b) the majority of groundwater samples from both the pre-monsoon (PRM) and post-monsoon (POM) seasons fall into the Ca^{2+}-HCO_3^- and Ca^{2+}-Mg^{2+}-Cl^- facies. These findings suggest that groundwater chemistry is predominantly influenced by ion exchange processes and the weathering of silicate rocks, particularly granite gneisses. The water chemistry typically results from the interaction between rainwater or groundwater and carbonate rocks.

The presence of high concentrations of Ca^{2+} contributes to water hardness, which, while not a health hazard, can reduce palatability. Elevated HCO_3^- levels increase water alkalinity, thereby enhancing its capacity to neutralize acids, which can impact the pH of the water. Furthermore, high alkalinity can affect the effectiveness of chlorine disinfection and lead to the precipitation of calcium carbonate in soils. This can reduce soil permeability and aeration, ultimately affecting plant growth by altering nutrient availability and increasing soil pH. High chloride (Cl^-) concentrations elevate the salinity of groundwater, which can impair water palatability and, if excessive, pose health risks for individuals with hypertension or kidney issues. Additionally, high salinity can inhibit plant growth, reduce crop yields, and be toxic to sensitive plant species. Elevated levels of calcium and magnesium can also alter soil structure, contributing to soil salinization, which makes the land unsuitable for agriculture.

The study suggests that high-salinity water, basically from surface contaminated sources such as irrigation return flow, domestic wastewater, and septic tank effluents, do mix with existing groundwater, which modifies the water chemistry, further influencing the observed facies in the Piper diagram. Understanding these interactions between surface contamination and groundwater is crucial for gaining insights into the regional hydrogeochemical profile (Ayyandurai and Venkateswaran, 2022).

Gibbs Diagram

In 1970, Gibbs introduced a diagram to explore the factors influencing the chemical composition of water, emphasizing the interaction between geological formations and water chemistry.

The Gibbs plot serves as a tool for identifying the primary mechanisms affecting groundwater composition, such as evaporation, precipitation, and rock-water interaction. Based on the analysis of the Gibbs diagram for both cations and anions, the results show that 100% of the water samples fall under the rock dominance category during both the pre-monsoon and post-monsoon seasons (Figure 8a,b). This indicates that the chemical composition of groundwater is primarily influenced by the weathering of rocks, such as silicate minerals, rather than by processes like evaporation or precipitation. The dominance of hornblende biotite gneiss rock during water interaction in this study, highlights the significant role of geological formations in shaping the groundwater's chemical profile, a pattern that remains consistent across both seasons. This finding reinforces the importance of understanding the geological context in hydrogeochemical studies, as the interaction between water and rock formations plays a key role in determining water quality in the region.

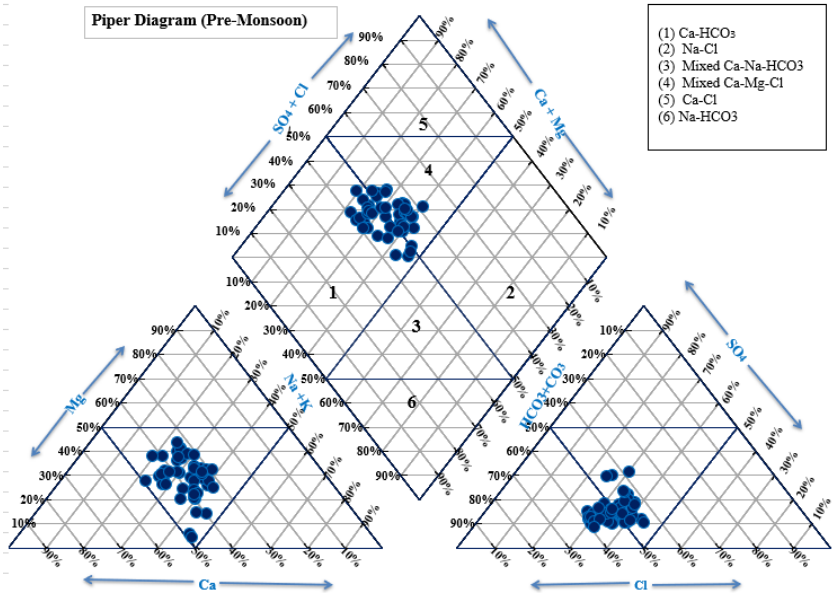


Figure 7a. Piper plot displaying water type in the investigation region during pre-monsoon (PRM) period.

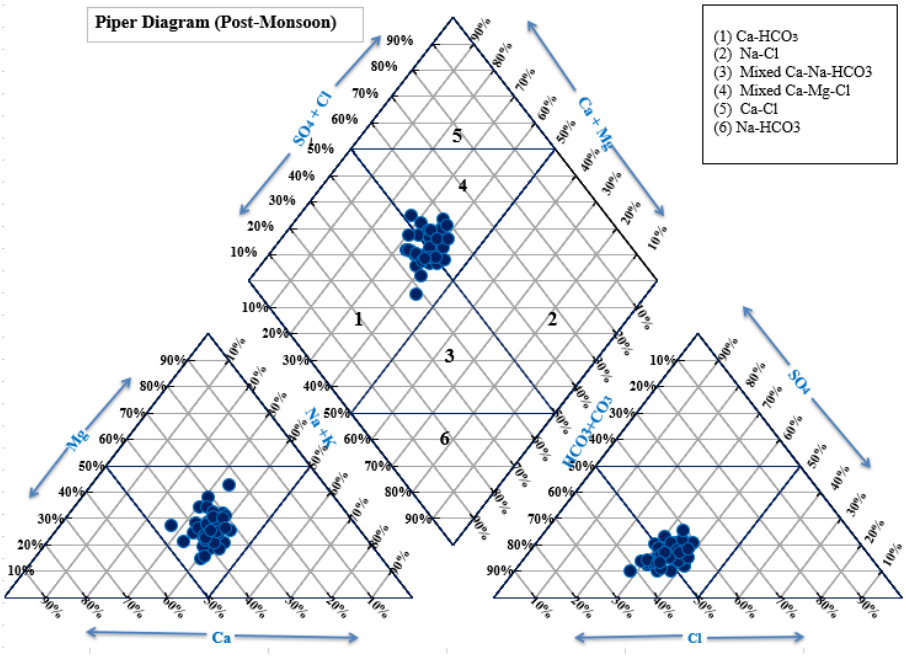


Figure 7b. Piper plot displaying water type in the investigation region during post-monsoon (POM) periods

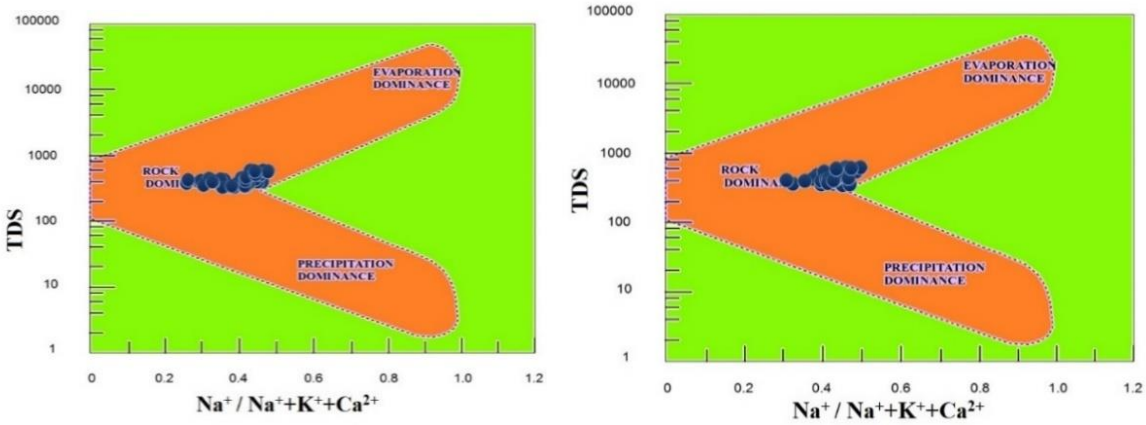


Figure 8a. Gibbs Plots for Cation. PRM season (left panel) and POM season (right panel)

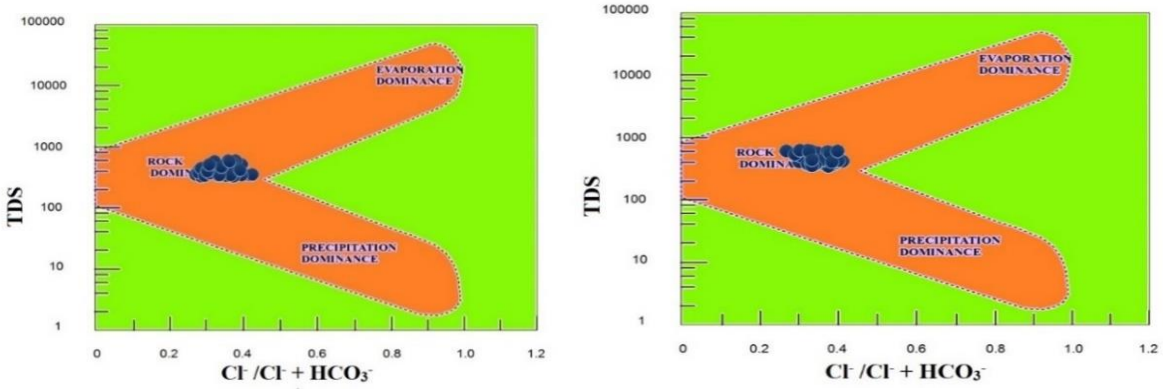


Figure 8b. Gibbs Plots for Anion. PRM season (left panel) and POM season (right panel)

CONCLUSIONS

This study assess the quality of groundwater for drinking and agricultural purposes in the semi-arid regions of Andhra Pradesh, India, based on samples collected during the Pre Monsoon (PRM) and Post Monsoon (POM) seasons of 2023. Geochemical analyses revealed that the predominant cation and anion composition of the groundwater samples was Na^+, Ca^{2+}, and Mg^{2+}, along with HCO_3^-, Cl^-, and SO_4^{2-}. Despite the samples remaining within the potable pH limits, 87% and 92% of the samples during the PRM and POM seasons, respectively, exceeded the desirable nitrate levels, and fluoride concentrations exceeded the permissible limit in 67% and 59% of samples, mainly due to agricultural and geogenic sources. The WQI indicated that only a small proportion of samples were safe for drinking, with the remaining samples deemed unsafe due to contamination from sewage, agricultural runoff, and poor groundwater management. The elevated WQI values in the POM season, compared to the PRM season, reflected deterioration in water quality over time, driven by rising TDS, EC, and TH. Piper's diagram showed the predominance of Ca^{2+}-HCO_3^- and Ca^{2+}-Mg^{2+}-Cl^- facies, highlighting the influence of high-salinity water due to surface contamination and interaction with silicate rocks, such as granite gneisses. Gibbs diagram analysis confirmed that groundwater chemistry is largely influenced by the weathering of geological formations. According to the US Salinity Laboratory and Wilcox's classification, most samples were suitable for irrigation purposes.

GIS-based spatial analysis also confirmed the partial suitability of groundwater for domestic use, with significant variations in quality across the study area. Groundwater quality issues persisted despite high rainfall during the NE monsoon season, suggesting that improper groundwater management and inadequate artificial recharge are key factors. The predominant lithology, particularly granitic rocks, contributes to high concentrations of calcium and magnesium, while basaltic formations may influence other ion concentrations. These variations in rock types play a critical role in groundwater quality concerns. To improve water quality and ensure sustainability, effective management strategies such as constructing artificial recharge structures, implementing rainwater harvesting systems, and improving groundwater management practices are essential, especially tailored to the region's lithological conditions.

Acknowledgement

The authors are thankful to the Department of Geology, Yogi Vemana University, for providing necessary facilities to carry out the research work. P. Ravi Kumar received financial support from the Department of Science and Technology (DST), Government of India, through the Inspire Program (Sanction Order No. DST/INSPIRE Fellowship/2018/IF180877).

Author Credit Statement

Ravi Kumar Pappaka: Manuscript preparation, sample collection, and methodology; Srinivasa Gowd Somagouni: Manuscript preparation and corrections; Krupavathi Chinthala: Sample collection, methodology; Pradeep Kumar Badapalli: Manuscript Corrections, revisions, and GIS mapping

Data Availability

Data will be made available on reasonable request from the corresponding author.

Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

References

Ahmed, S., Khurshid, S., Sultan, W. and Shadab, M. B., 2020. Statistical analysis and water quality index development using GIS of Mathura City, Uttar Pradesh, India. Desalination and Water Treatment, 177(12), 152-166.

Anusha, B. N., Babu, K. R., Kumar, B. P., Kumar, P. R. and Rajasekhar, M., 2022. Geospatial approaches for monitoring and mapping of water resources in semi-arid regions of Southern India. Environmental Challenges, 8 (8), 1-13.

Asadi, E., Isazadeh, M., Samadianfard, S., Ramli, M. F., Mosavi, A., Nabipour, N. and Chau, K. W., 2019. Groundwater quality assessment for sustainable drinking and irrigation. Sustainability, 12(1), 1-13.

Ayyandurai, R., and Venkateswaran, S., 2022. An Investigation of Groundwater Hydrochemistry in the Shallow Aquifers of the Cuddalore Coast, South India. In: Climate Change Impact on Groundwater Resources: Human Health Risk Assessment in Arid and Semi-arid Regions. Cham: Springer International Publishing. pp.117-138

Badapalli, P. K., Nakkala, A. B., Kottala, R. B. and Gugulothu, S., 2024. Geo environmental green growth towards sustainable development in semi-arid regions using physicochemical and geospatial approaches. Environmental Sci. Pollution Res., 31(41), 54089-54106.

Chinthala, K., Somagouni, S. G., Pappaka, R. K. and Gudala, H. V., 2023. Ground Water Quality Assessment Using Water Quality Index and Geographical Information System of Mogamureru River Basin, YSR Kadapa District, Andhra Pradesh, India. In: Emerging Technologies for Water Supply, Conservation and Management, Cham: Springer International Publishing. pp 291-313

Doneen, L. D., 1964. Notes on water quality in agriculture. Department of Water Science and Engineering, University of California, Davis.

Dutta, N., Thakur, B. K., Nurujjaman, M., Debnath, K. and Bal, D. P., 2022. An assessment of the water quality index (WQI) of drinking water in the Eastern Himalayas of South Sikkim, India. Groundwater for Sustainable Development, 17, 100735.

Eaton, F. M., 1950. Significance of carbonates in irrigation waters. Soil science, 69(2), 123-134.

Freeze, R. A. and Cherry, J. A., 1979. Groundwater. Prentice hall Inc. Englewood cliffs. New Jersey, 604.

Gibbs, R. J., 1970. Mechanisms controlling world water chemistry. Science, 170(3962), 1088-1090.

Golla, V. S. and Badapalli, P. K., 2022. Evaluation of water quality for drinking and irrigation purposes and Fluoride Health Hazard Risk Assessment (HHRA) in parts of semi-arid regions in the south-eastern part of India. Int. J. Energy and Water Resources, 6(4), 521-529.

Gugulothu, S., Subbarao, N., Das, R. and Dhakate, R., 2022. Geochemical evaluation of groundwater and suitability of groundwater quality for irrigation purpose in an agricultural region of South India. Applied Water Sci, 12(6), 1-13.

Karunanidhi, D., Aravinthasamy, P., Subramani, T. and Muthusankar, G., 2021. Revealing drinking water quality issues and possible health risks based on water quality index (WQI) method in the Shanmuganadhi River basin of South India. Environmental Geoch. and Health, 43, 931-948.

Kelley, W. P., 1940. Permissible composition and concentration of irrigation water. Proc. Am. Soc. Civil Engineers, 66, 607-613.

Khatri, N., Tyagi, S., Rawtani, D., Tharmavaram, M. and Kamboj, R. D., 2020. Analysis and assessment of ground water quality in Satlasana Taluka, Mehsana district, Gujarat, India through application of water quality indices. Groundwater for Sustainable Development, 10(4), 1-8.

Kumar, P.R., Gowd, S. S., Krupavathi, C. and Kumar, B.P., 2022. Groundwater quality assessment using Water Quality Index (WQI) in parts of Anantapur, A.P. (India). J. Ind. Geophys. Union, 26(2), 155-164.

Molagamudi, S. R., Uravakonda, S., Badapalli, P. K. and Golla, V. S., 2023. Evaluation of groundwater chemistry and its impact on drinking, irrigation, and human health hazard risk assessment (HHRA) in Pincha river basin, semi-arid region of Andhra Pradesh, India. Int. J. Energy and Water Res., 7(3), 347-353.

Mukherjee, I., Singh, U. K. and Chakma, S., 2022. Evaluation of groundwater quality for irrigation water supply using multi-criteria decision-making techniques and GIS in an agroeconomic tract of Lower Ganga basin, India. J. Environmental Manag., 309, 114691.

Nayak, A., Matta, G. and Uniyal, D. P., 2023. Hydrochemical characterization of groundwater quality using chemometric analysis and water quality indices in the

foothills of the Himalayas. Environ. Development and Sustainability, 25(12), 14229-14260.

Pappaka, R. K., Somagouni, S. G., Chinthala, K. and Nakkala, A. B., 2024. Appraisal of groundwater quality for suitability of drinking and irrigation purposes of Pandameru river basin, Anantapur district, AP, India. Arabian J. Geosci., 17(1), 1-16.

Parveen, N., Giri, S., Singh, A. K. and Tripathi, J. K., 2025. Fluoride and nitrate contamination in groundwater of Naini Industrial Area, Uttar Pradesh: Assessing non-carcinogenic human health risk. Groundwater for Sustainable Development, 28, 101388.

Piper, A. M., 1944. A graphic procedure in the geochemical interpretation of water-analyses. EOS, Trans. Am. Geophys. Union, 25(6), 914-928.

Piper, A. M., 1953. A graphic procedure in the geo-chemical interpretation of water analysis. USGS groundwater note, pp. 12

Reddy, K. V. S., 1998. Compilation of STM geological maps of the Peninsular gneissic complex, Anantapur district, A.P. Rec. Geol. Surv. India, 132(pt 5), 5-7.

Richards, L. A. (Ed.)., 1954. Diagnosis and improvement of saline and alkali soils (No. 60). US Government Printing Office.

Sawyer, C. N. and McCarty, P. L., 1967. Chemistry for sanitary engineers (Vol. 518). New York: McGraw-Hill.

Sharma, P. and Bora, P. J., 2020. Water quality assessment using water quality index and principal component analysis: A case study of historically important lakes of Guwahati City, North-East India. Appl. Ecology and Environmental Sci., 8(5), 207-217.

Singh, S., Anil, A. G., Kumar, V., Kapoor, D., Subramanian, S., Singh, J. and Ramamurthy, P. C., 2022. Nitrates in the environment: A critical review of their distribution, sensing techniques, ecological effects and remediation. Chemosphere, 287 (8), 1-18.

Subba Rao, N., Srihari, C., Deepthi Spandana, B., Sravanthi, M., Kamalesh, T. and Abraham Jayadeep, V., 2019. Comprehensive understanding of groundwater quality and hydrogeochemistry for the sustainable development of suburban area of Visakhapatnam, Andhra Pradesh, India. Human and Ecological Risk Assessment: An International Journal, 25(1-2), 52-80.

Szabolcs, I., 1964. The influence of irrigation water of high sodium-carbonate content on soils.

USSL., 1954. Diagnosis and improvement of salinity and alkaline soil. USDA Hand Book no. 60, Washington

Wagh, V. M., Panaskar, D. B., Mukate, S. V., Aamalawar, M. L. and Laxman Sahu, U., 2020. Nitrate associated health risks from groundwater of Kadava river basin Nashik, Maharashtra, India. Human and Ecological Risk Assessment: an international journal, 26(3), 654-672.

WHO, 2011. World Health Organization., Guidelines for drinking-water quality. World Health Organization.

Wilcox, L., 1955. Classification and use of irrigation waters. US Department of Agriculture, No. 969.

Zhang, Q., Xu, P. and Qian, H., 2020. Groundwater quality assessment using improved water quality index (WQI) and human health risk (HHR) evaluation in a semi-arid region of northwest China. Exposure and Health, 12(3), 4

Received on: 02-12-2024; Revised on: 24-06-2025 ; Accepted on: 29-06-2025