

Groundwater Quality Assessment for Drinking and Irrigation Purposes in Tadimarri Mandal, Sri Sathya Sai District, Andhra Pradesh Using Water Quality Index and Geospatial Techniques

N. Jagadeesh^{1*}, V. Gope Naik², K. Ramanaidu³

Abstract

Groundwater is the primary source of potable water and supports agriculture worldwide. Assessing its quality is vital to determine its suitability for various purposes, especially as a safe drinking water source. This study focuses on evaluating the quality of groundwater used for drinking and irrigation in Tadimarri Mandal, Anantapur district, Andhra Pradesh, India. During the pre-monsoon season, 30 groundwater samples were collected from boreholes and analyzed for physicochemical parameters. The analysis revealed that all water samples from the area were alkaline. To assess and explain the water quality, techniques such as the water quality index (WQI) and geographic information system (GIS)-based interpolation were employed. The WQI ranged from 66.87 to 171.65 mg/L, indicating that 33% of the samples were deemed safe for drinking, while 67% fell below the safe drinking water standards. To mitigate the potential health risks of consuming untreated groundwater, proper water treatment methods are recommended. The Gibbs plot results suggest that rock-water interaction is the dominant process affecting groundwater composition across the entire sample set. In terms of irrigation suitability, most groundwater samples showed favorable values for sodium absorption ratio, %Na, Kelley's ratio, residual sodium carbonate, and permeability index, making them appropriate for agricultural use. However, geospatial analysis revealed that a significant portion of the groundwater does not meet the required drinking water standards, highlighting the need for treatment before consumption. These findings underscore the necessity for effective aquifer management strategies to safeguard groundwater quality and ensure its safe use for both drinking and irrigation purposes.

Keywords: Groundwater quality, water quality index (WQI), drinking purposes, remote sensing, geographic information system (GIS), spatial distribution maps

INTRODUCTION

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Groundwater consumption for drinking and agriculture is rapidly growing in semi-arid locations around the world. According to the findings, around 150 million people worldwide rely on groundwater for consumption and cultivation [1, 2]. Groundwater accounts for little more than 45% of all irrigation water utilized on India's 39 million hectares of agricultural land, and it fulfils nearly 80% of domestic demands. A total of 90% of rural populations, both in urban and rural areas, use groundwater for domestic reasons, including drinking water. Fresh water is becoming increasingly scarce and polluted as a result of abuse, and continuous irrigation methods risk damaging groundwater [3]. Groundwater quality is influenced by both anthropogenic and geogenic activities. With

the rise of industrialization and modern agriculture, unprocessed waste products from these activities are released into the atmosphere, disrupting the balance of life. The quality of groundwater is also influenced by various geogenic processes such as weathering, groundwater flow, terrain, and geology. Groundwater chemistry in the area is not uniform and is influenced by various factors such as movement, geochemical operations, drying, and transpiration processes. The interaction of groundwater with different elements can cause water quality changes.

Therefore, understanding the chemical reactions involved is crucial, especially in worn rock layers. Groundwater quality is slowly declining as a result of human and natural activities like farming and industry, which have several negative effects on the environment's health [4, 5]. The purity of water is strongly related to public health; hence, regular monitoring is crucial. Fluoride and nitrate contamination of groundwater has been a significant public health problem globally over the past 20 years [6]. This research has been conducted around the world in semi-arid regions due to its significance [7, 8]. Fluoride concentration in water depends on factors such as water accessibility to fluoride-containing minerals, rock-water interaction, evaporation, and fluoride ion composition. Mixed fluoride hydroxide complexes with boron also play a role [9]. Approximately 90% of fluoride ingested through water is absorbed by the digestive system, with over 200 million people worldwide consuming fluoride-contaminated water [10]. Nitrate is often regarded as one of the most severe chemical contaminants in groundwater around the world. Nitrate levels in groundwater are increasing in India. Nitrate contamination in groundwater stems from various sources and origins [11]. Elevated nitrate concentrations in groundwater are primarily linked to human activities, including domestic sewage leaks, poultry waste disposal, the application of animal manure, and the migration of nitrates from sewage, municipal, and industrial waste. Over the past 30 years, the nitrate content of groundwater has increased in various countries due to excessive nitrate levels in drinking water, which have been associated with adult stomach cancer and methemoglobinemia in children [12]. Agriculture is the primary source of this contamination. Groundwater contaminated with toxic fluoride and nitrate can be harmful to crops and people [13].

The investigation aims to describe the impact of the water-rock interface and human-caused disturbances on the hydrogeochemistry and suitability of aquifers for consumption, cultivation uses in the Tadimarri Mandal in Sri Sathya Sai district of Andhra Pradesh, India. It is vital to understand the condition of the groundwater and its appropriateness for different uses to prevent further depletion of this crucial resource. A unified approach of water quality index (WQI) and the geographic information system (GIS) can be used to provide a simple and valuable tool for decision-making on groundwater excellence. WQI is a scientific tool that can convert an important quantity of data on water superiority into a single amount that signifies the level of water excellence. Several researchers have previously used the WQI as a tool to determine groundwater excellence [14–16]. A GIS is a vital instrument for gathering massive quantities of information that can be geographically connected and recovered to produce the necessary output for spatial study and processing. GIS is a helpful instrument for administering local or regional water supplies, dealing with water resource issues, assessing groundwater resources, reviewing water supplies, controlling flooding, and understanding neighboring ecosystems. Furthermore, several researchers have classified irrigation water excellence in various areas of the nation using electrical conductivity (EC), sodium absorption ratio (SAR), %Na, Kelley's ratio (KR), permeability index (PI), and residual sodium carbonate (RSC) [17, 18]. Finally, the study area depicts an exact recreation of harsh terrain with insufficient surface water; as a result, the majority of the district's people depend on groundwater to meet their daily needs. Groundwater quality research was more active in the past compared to recent years. As a consequence, an evaluation of current-state water quality is needed. The purpose of this study is to use geochemical and geospatial methods to conduct an initial evaluation and explain water quality in the research region to demarcate areas where groundwater is appropriate or inappropriate for drinking and agricultural uses.

STUDY AREA

The investigated region lies in the Sri Sathya Sai district of Andhra Pradesh, India, and encompasses an area of 269 km². This study area geographically lies between 14°28'00" and 14°40'00" N latitudes

and 77°48'00" and 78°0'00" E longitudes. It has an average elevation of 516 meters (1693 feet). Temperatures in the region range from 24°C to 46°C, and there is an average annual rainfall of 544 mm [19]. The research region falls under the Survey of India Toposheets 57F/14 and F/15.

Figure 1 depicts a sample location map of the research region (Toposheets 57F/14, and F/15). The primary rocks observed in the research region are hornblende biotite gneiss, Hornblende-Gneiss (HG), Biotite Gneiss (BG), migmatite, close pet granites, Gulchervu quartzites/arkose with conglomerate, Vempalle dolomites chert, and mudstone (Figure 2).

MATERIALS AND METHODS

During the pre-monsoon season in march 2024, 30 groundwater samples were taken from open and bore wells in several sites within the research zone. The laboratory analysis of the groundwater samples, which were taken in well-cleaned 1-L polyethylene bottles. The latitude and longitude of the sample locations are identified with a global positioning system. A pH meter and conductivity meter are used to measure pH and EC, respectively. A total dissolved solids (TDS) meter is used to estimate TDS and a titration method is used to measure total hardness (TH), Ca^{2+} , Mg^{2+} , HCO_3^- , and Cl^- . Flame photometry is used to measure Na^+ and K^+ , spectrophotometry for SO_4^{2-} and NO_3^- , and an ion-selective electrode for F^- . The spatial distribution maps are created using the interpolation method of the Arc GIS tool Inverse Distance Weight (IDW) to evaluate groundwater quality.

Water Quality Index

WQI is a significant tool for measuring aquifers' condition and suitability for drinking. It is a classification method that evaluates the overall acceptance of water for drinking by combining the effects of several different water quality guidelines [20–22]. WQI is determined using the World Health Organization (WHO) 2011 drinking water standards. The WQI is calculated in three steps. In the first phase, each of the (13) physicochemical parameters was assigned a weight (w_i) based on their significance to the overall condition.

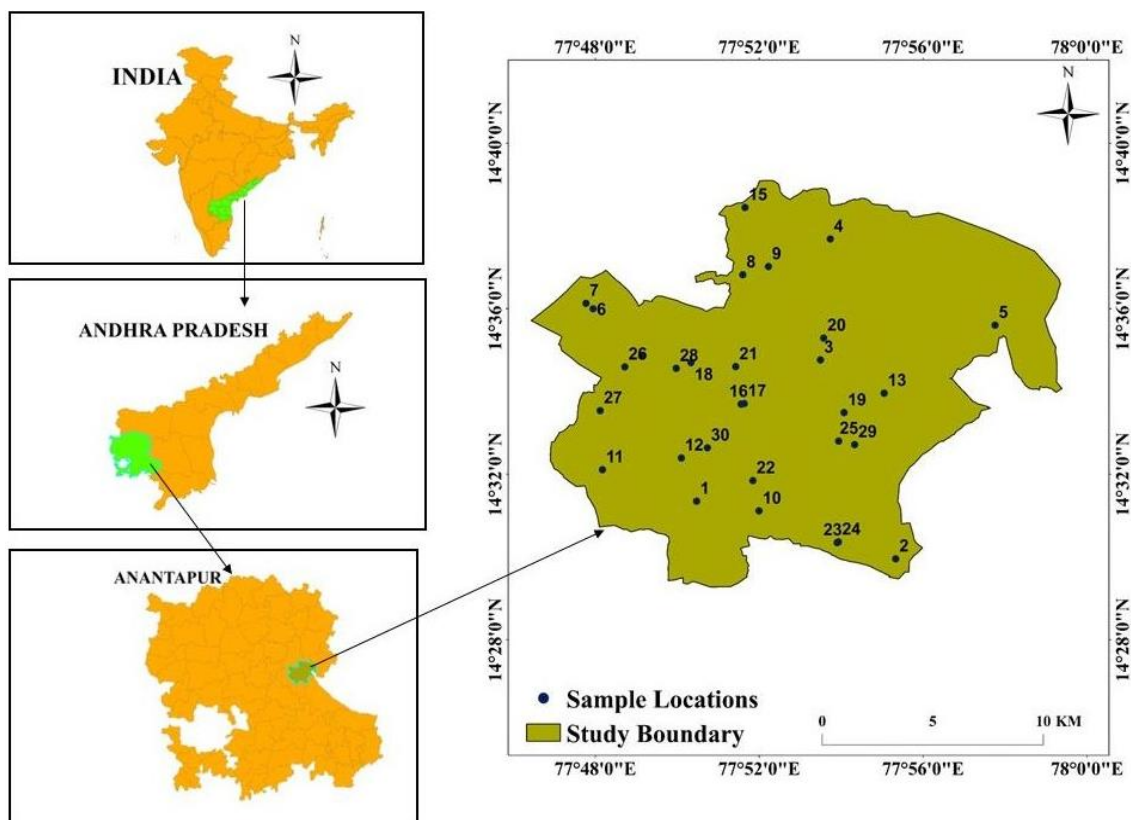


Figure 1. Sample location map of the investigation area.

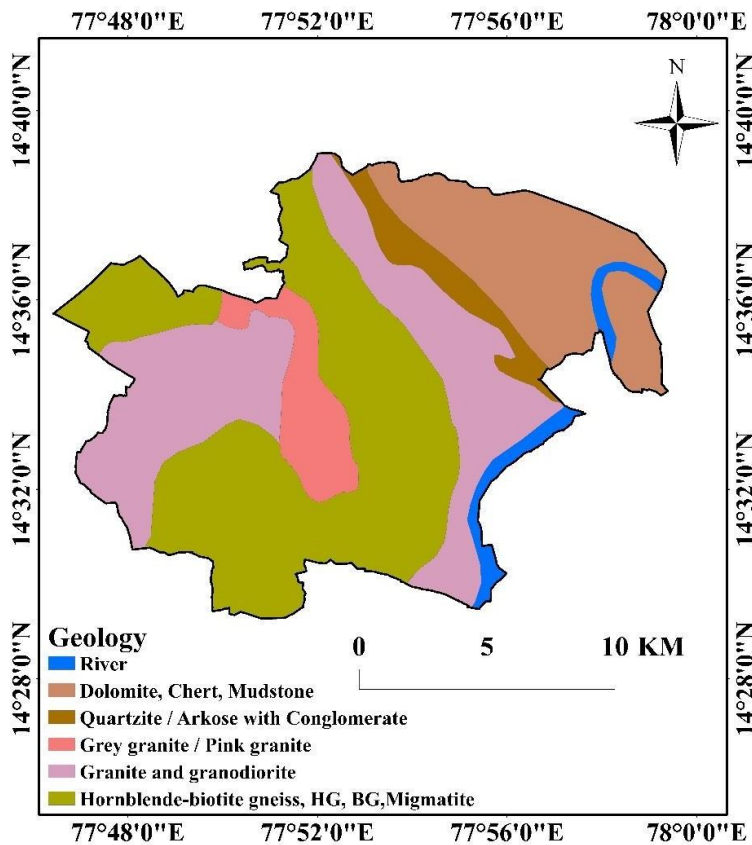


Figure 2. Geology map of the investigation region.

Because of their significance in assessing the purity of water, the parameters NO_3^- , TDS, Cl^- , F^- , and SO_4^{2-} have been owed a maximum weight of 5. Bicarbonate is allocated a lowest weight of 1 due to its small impact on water quality testing. Other factors such as Ca^{2+} , Mg^{2+} , Na^+ , and K^+ were assigned weights ranging from 1 to 5 to indicate their respective relevance in defining the water's quality. The relative weight (W_i) is obtained in the following stage using the following equation:

$$W_i = \frac{w_i}{\sum_{i=1}^n (w_i)} \quad (1)$$

The "quality rating (qi)" for the third stage is computed using the formula below.

$$qi = \left(\frac{c_i}{s_i} \right) \times 100 \quad (2)$$

If C_i is the level of concentration of all characteristics in each water sample, S_i denotes the WHO 2011 recommended value for that characteristic. Because W_i and qi were used to estimate the S_{li} for each characteristic individually, the following equations will calculate WQI.

$$S_{li} = w_i \times qi \quad (3)$$

$$WQI = \sum^n S_{li} \quad (4)$$

The sub-index of each parameter is here designated as S_{li} .

RESULTS AND DISCUSSION

Results of physicochemical parameters of the study area for post-monsoon and the statistical summary of physicochemical parameters and ion concentrations have been compared with the WHO

2011 as shown. Tables 1 and 2 provide the values of physicochemical parameters measured in mg/L, except EC ($\mu\text{S}/\text{cm}$) for different seasons.

The pH level of groundwater plays a vital role in influencing various hydrological processes, including carbon absorption, ion exchange, and flocculation, which are highly sensitive to pH variations. The pH of groundwater in the research area fluctuates between 7.05 to 8.21, with an average of 7.71, revealing a slightly acidic to alkaline nature (Table 1). Importantly, these pH levels fall within the recommended range of 6.5 to 8.5, as established by the WHO in 2011, ensuring the safety of groundwater for human consumption [23]. Maintaining suitable pH levels is not only crucial for human health but also essential for preserving the overall quality and ecological equilibrium of the water source.

Table 1. Physicochemical analysis of groundwater sample for post-monsoon season in the research region.

Sample No.	Sample Locations	pH	EC	TDS	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	HCO ₃ ⁻	F ⁻	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	TH
1	Atmakur	7.34	2056	1336	155.5	54.4	227	7	356	0.78	344	187	28.9	612
2	C.c revu	7.91	2598	1793	165.1	116.6	287	4.9	624	1.67	406	322	47.1	891
3	Chillakondaiahpalli	7.55	2569	1798	157.1	57.3	281	1.7	496	1.46	294	158	33.6	628
4	Chillavaripalli	7.32	2771	1773	235.7	62.2	240	2.8	448	1.45	394	302	50.8	844
5	Daditota	7.48	1982	1209	126.7	66.1	176	1.5	312	2.34	340	146	28	588
6	Ekapadampalli	7.68	2498	1399	128.3	72.9	328	1.9	468	3.12	420	168	45.7	620
7	Ekapadampalli (MPUP School)	7.62	2862	1860	267.7	46.7	258	3.7	400	1.45	548	221	46.9	861
8	Kunukuntla	7.48	2981	1848	229.3	77.8	320	4.1	592	1.03	482	186.8	76.1	892
9	Kunukuntla ZPH School	8.07	2971	1872	163.5	95.3	293	9.4	572	2.72	422	196.4	23.4	799
10	M. agraharam	8.11	3056	1864	264.5	58.3	347	5.6	576	2.11	400	236	52.4	900
11	Narsimpalli	7.61	2943	2001	246.9	54.4	386	6.6	600	1.93	362	255	80.2	840
12	Nidigallu	7.59	1946	1304	133.1	74.8	198	3.2	400	1.06	292	262	30.9	640
13	Peddakotla	7.99	2641	1796	149.1	135.1	262	7.9	660	1.89	368	288	51.3	927
14	Pinnadari	7.83	2487	1691	133.1	55.4	301	5.3	428	1.82	400	167	46.9	560
15	Ramapuram	7.86	3055	2108	166.7	73.9	458	3.6	588	1.78	418	220	60.7	720
16	Tadimarri	8.12	3589	2512	267.7	66.1	480	6.8	720	1.9	622	311	58.2	940
17	Tadimarri ZPHS	7.6	2612	1750	133.1	68.0	337	7.7	452	1.57	466	196	47.1	612
18	Beemraopeta	8.01	3898	2612	243.7	61.2	622	9.4	744	1.45	680	356	78.1	860
19	Guddampalli	7.79	2478	1561	62.5	70.0	411	3.7	288	1.53	440	203	46.8	443
20	Kondamanayanipalem	7.37	3698	2626	277.4	55.4	587	7.9	888	2.01	602	200	77.9	921
21	Madhalacheruvu	7.52	2934	1878	184.4	78.7	387	4.8	640	1.24	478	174	48.3	784
22	Maravapalle	7.65	2901	2089	173.1	74.8	489	6.1	712	1.44	512	206	52.9	740
23	Marrimakulapalle	7.05	3678	2464	288.6	77.8	592	7.8	920	1.78	606	262	67.5	1040
24	Medimakulapalle	7.59	2811	1771	161.9	67.1	361	4.1	544	0.67	346	197	43.8	680
25	Modugulakuntla	7.94	1974	1303	44.9	42.8	245	6	280	1.6	248	138	26.8	288
26	Pulaobaiahpalli	8.01	2573	1750	168.3	87.5	199	1.6	440	2.24	262	194	46.1	780
27	Pullampalli	8.21	3965	2815	251.7	128.3	682	8.8	928	2.03	712	286	93.8	1155
28	Pullanarayanapalli	7.44	2884	1875	157.1	66.1	268	7.1	444	1.06	378	204	55.7	664
29	Shro thirumalapura	7.83	3011	2198	194.0	71.9	418	11.7	656	2.43	460	340	60.9	780
30	Sivampalli	7.79	3434	2301	221.2	65.1	602	11	736	1.68	538	296	63.4	820

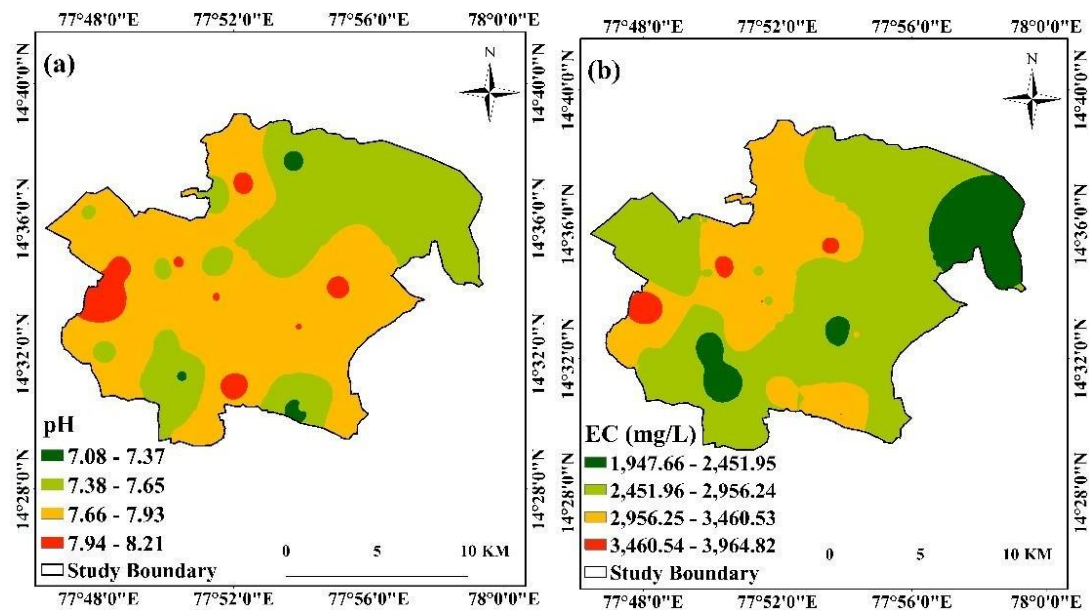
Table 2. Concentrations of physicochemical constraints and their comparison with the WHO 2011 standards.

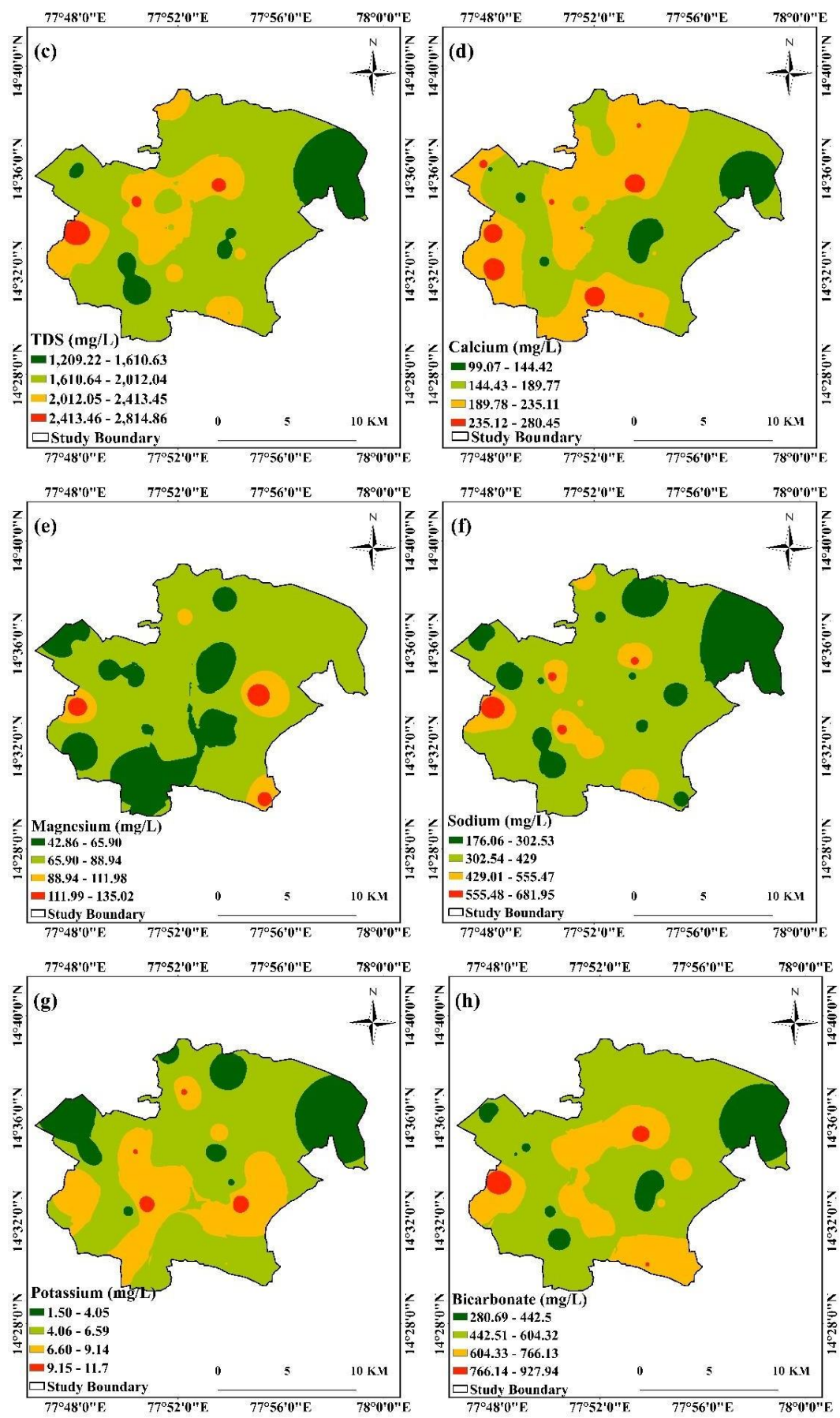
Parameter	Minimum	Maximum	Average	WHO (2011)	
				<i>Desirable Limit</i>	<i>Allowable Limit</i>
pH	7.05	8.21	7.71	6.5-8.5	9.2
EC	1946	3965	2861.87	500	1500
TDS	1209.02	2815.15	1905.22	500	1500
Ca ²⁺	98.89	288.57	185.06	75	200
Mg ²⁺	42.76	135.10	72.74	50	150
Na ⁺	176	682	368.07	50	200
K ⁺	1.5	11.7	5.79	10	12
HCO ₃ ⁻	280	928	563.73	–	–
F ⁻	0.67	3.12	1.71	0.6- 1.5	1.5
Cl ⁻	248	712	441.33	250	600
SO ₄ ²⁻	138	356	229.27	250	400
NO ₃ ⁻	23.4	93.8	52.34	–	45
TH	287.57	1155.30	760.88	100	500

Additionally, monitoring pH levels in groundwater aids in identifying potential environmental impacts and implementing appropriate measures for sustainable water resource management. EC is a vital indicator to evaluate the quality of water. EC provides an indirect assessment of the dissolved components within the water. Specifically, EC is defined as the reciprocal of electrical resistance in ohms (R) concerning a cube of water with a 1 cm edge length at 25°C. In practical terms, EC is commonly expressed in micro-Siemens (μS). In the study region, groundwater exhibits EC values ranging from 1946 to 3965 $\mu\text{S}/\text{cm}$, with an average of 2861.87 $\mu\text{S}/\text{cm}$. The presence of higher EC levels in post-monsoon samples can be attributed to increased salinity and mineral content at the sampling site. It is important to note that EC is influenced by factors such as temperature, ion concentration, and the types of ions present in the groundwater. According to EC classification, 60%, and 30% of samples belong to high salt enrichment [23]. High electrical conductivity may be due to the black cotton soil of this area. In the research region, the TDS values range from 1209.02 mg/L to 2815.15 mg/L, with a mean value of 1905.22 mg/L. According to Freeze and Cherry [24], 100% of the groundwater samples exceeded the permissible limit (1000 mg/L) of total dissolved solids in the study region. Water contamination by anthropogenic activities such as sewage disposal and agricultural practices also affects TDS. The hardness of groundwater is primarily determined by the presence of dissolved cations, with calcium and magnesium being the most commonly considered ions [25]. TH in the investigated area ranges from 287.57 to 1155.30 mg/L, with a mean value of 760.88 mg/L. According to Sawyer and McCarthy [26], TH groundwater classification denotes that 100% of the groundwater sample belongs to very hard types in the study region. Calcium is a vital nutrient that plays a crucial role in promoting human health, growth, and overall preservation.

It is particularly associated with the development and strength of bones and teeth, as well as supporting cardiovascular functions [27]. Calcium concentrations in this research region range between 98.89 and 288.57 mg/L, with a mean of 185.06 mg/L. All of the samples are within the permitted limits and safe to drink (200 mg/L). Magnesium in groundwater is derived partly from silicates and partly from minerals like magnesium calcite or dolomite [28]. Silicates are produced through intensive weathering of mafic rocks, as well as the breakdown of pyroxene and amphiboles. Weathering of igneous and metamorphic rocks results in soluble carbonates, clay, and silica. In the study area, Mg concentration varies from 42.76 and 135.10 mg/L with a mean value of 72.74 mg/L. Values at all the locations are within the permissible limits of WHO 2011 standards (30–150 mg/L). Sodium is the predominant alkali metal found in groundwater, and it generally remains dissolved since it does not significantly participate in precipitation reactions. It is recommended to have a sodium concentration

of less than 200 mg/L for water quality, as per the WHO 2011 standards. Exceeding this concentration renders the water unsuitable for domestic use, as it can lead to severe health issues like hypertension. High levels of sodium pose a risk, particularly for individuals with cardiac, renal, and circulatory diseases [29]. In the research area, Na^+ values fluctuated between 176 and 682 mg/L, with a mean of 368.07 mg/L. Potassium content in water exceeding a few tens of parts per million (ppm) serves as an indicator of pollution. Among the cations, potassium is present in the lowest concentration in groundwater during both seasons. For drinking water, a potassium concentration of less than 10 ppm is considered acceptable according to the WHO guidelines of 2012. K^+ concentrations ranged from 1.5 to 11.7 mg/L with a mean value of 5.79 mg/L. The relatively low potassium concentration in water can be attributed to the difficulty in dissociating potassium from silicate minerals. Bicarbonate serves as an indicator of overall alkalinity in water, reflecting its capacity to neutralize acidity [30]. The presence of dissolved carbon species, particularly bicarbonate and carbonate, contributes to the alkaline nature of most natural waters. In the study region, the attentiveness of HCO_3^- varies from 280 to 928 mg/L, with a mean value of 563.73 mg/L. Fluoride is a naturally occurring element found in varying concentrations in drinking water sources. It is a chemical component that is spontaneously present in many types of rock. In groundwater, fluoride is primarily derived from the breakdown of minerals and sediments or the weathering and accumulation of volcanic particles from the atmosphere [31]. In the study region, the fluoride content ranges from 0.67 to 3.12 mg/L, with a mean value of 1.71 mg/L. Cl^- is the second most abundant anion in the study region. In the research area Cl^- content ranged from 248 to 712 mg/L, with a mean value of 441.33 mg/L. High concentrations of Cl^- can have detrimental effects on individuals with pre-existing heart or kidney conditions. Although chlorides are not directly involved in corrosion, they can accelerate the corrosion process. Sulfate is abundant in both natural and human-made water systems. Sulfate is mostly produced naturally by atmospheric precipitation, the decomposition of sulfate minerals, and the oxidation of sulfide minerals. In the study region, SO_4^{2-} concentrations varied from 138 to 356 mg/L with a mean value of 229.27 mg/L. Nitrate in groundwater is primarily derived from various nonpoint sources, including leaching from chemical fertilizers and livestock waste, as well as contamination from septic and sewage discharges. Differentiating between natural and anthropogenic sources of nitrogen contamination in groundwater poses a challenge. Nitrate concentrations in groundwater are influenced by chemical and microbial processes such as nitrification and denitrification [32]. Nitrate serves as an indicator of pollution in water systems. Nitrate in drinking water should not exceed 45 mg/L, according to the WHO 2011 standards. In the research area, NO_3^- concentrations in groundwater ranged from 23.4 to 93.8 mg/L, with a mean value of 52.34 mg/L. Figure 3 shows the spatial distribution maps of pH (a), EC (b), TDS (c), Ca^{2+} (d), Mg^{2+} (e), Na^+ (f), K^+ (g), HCO_3^- (h), F^- (i), Cl^- (j), SO_4^{2-} (k), NO_3^- (l), and TH (m).





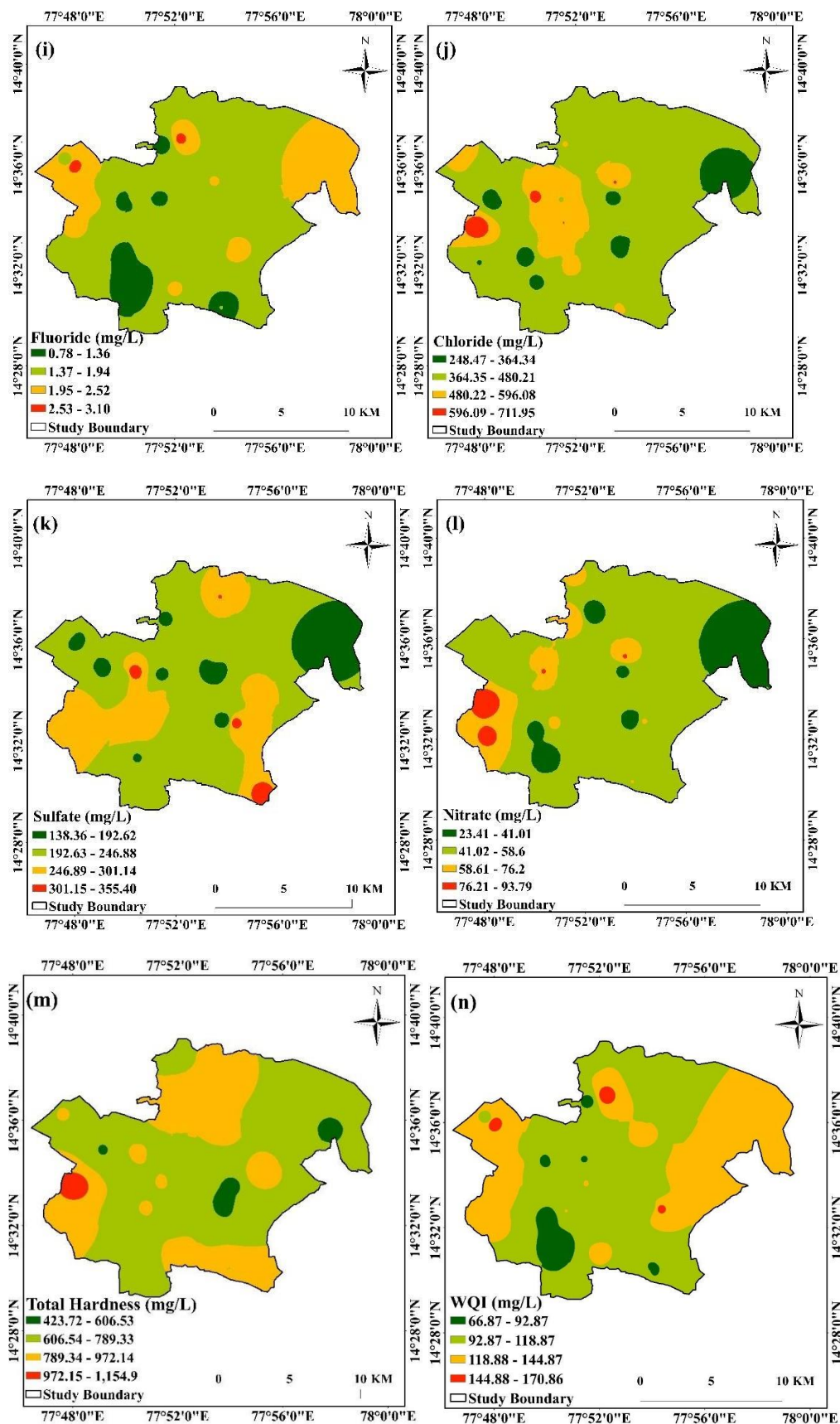


Figure 3. Spatial distribution of Maps (a) pH, (b) EC (c) TDS (d) Ca^{2+} (e) Mg^{2+} (f) Na^+ (g) K^+ (h) HCO_3^- (i) F, (j) Cl- (k) SO_4^{2-} (l) NO_3^- (m) TH. (n) water quality index (WQI).

Water Quality Index

The WQI values are categorized as follows: if it is less than 50, the groundwater is considered excellent; if it falls between 50.1 and 100, it is regarded as good quality water; if the values range from 100.1 to 200, the groundwater is classified as poor; if it falls between 200.1 and 300, it is labeled as very poor; and if the values exceed 300, the water is deemed unfit for drinking [33]. Regarding the WQI classification, 33% of groundwater samples are good, while the other 67% are poor, owing to groundwater abuse, direct sewage release, and agricultural influence (Table 4). Table 3 shows the WQI at specific sampling locations. Figure 3n depicts the spatial distribution map of WQI.

Table 3. Water quality index (WQI) at individual sampling stations.

Sample No.	Sample Locations	Latitude	Longitude	WQI	Water Quality Status
1	Atmakur	N 14° 31' 21.00"	E 77° 50' 28.37"	66.8700	Good water
2	C.c revu	N 14° 29' 57.53"	E 77° 55' 20.01"	115.65	Poor water
3	Chillakondaiahpalli	N 14° 34' 46.19"	E 77° 53' 29.94"	93.65	Good water
4	Chillavaripalli	N 14° 37' 41.41"	E 77° 53' 44.29"	97.46	Good water
5	Daditota	N 14° 35' 36.47"	E 77° 57' 45.61"	132.86	Poor water
6	Ekapadampalli	N 14° 36' 00.25"	E 77° 47' 56.97"	171.65	Poor water
7	Ekapadampalli (MPUP School)	N 14° 36' 08.09"	E 77° 47' 46.63"	97.52	Good water
8	Kunukuntla	N 14° 36' 49.55"	E 77° 51' 36.14"	83.13	Good water
9	Kunukuntla zphs school	N 14° 37' 01.38"	E 77° 52' 13.64"	164.23	Poor water
10	M. agraharam	N 14° 31' 07.18"	E 77° 51' 59.82"	132.04	Poor water
11	Narsimpalli	N 14° 32' 06.76"	E 77° 48' 10.65"	124.9	Poor water
12	Nidigallu	N 14° 32' 23.74"	E 77° 50' 06.35"	78.2	Good water
13	Peddakotla	N 14° 33' 57.68"	E 77° 55' 03.04"	130.75	Poor water
14	Pinnadari	N 14° 34' 51.53"	E 77° 49' 08.17"	114.2	Poor water
15	Ramapuram	N 14° 38' 26.89"	E 77° 51' 39.29"	115.19	Poor water
16	Tadimarri	N 14° 33' 42.02"	E 77° 51' 33.74"	126.33	Poor water
17	Tadimarri ZPHS	N 14° 33' 42.65"	E 77° 51' 38.36"	106.78	Poor water
18	Beemraopeta	N 14° 34' 42.15"	E 77° 50' 20.34"	108.91	Poor water
19	Guddampalli	N 14° 33' 29.74"	E 77° 54' 04.67"	99.76	Good water
20	Kondamanayanipalem	N 14° 35' 17.61"	E 77° 53' 34.74"	131.53	Poor water
21	Madhalacheruvu	N 14° 34' 36.28"	E 77° 51' 25.83"	91.43	Good water
22	Maravapalle	N 14° 31' 51.08"	E 77° 51' 54.44"	102.16	Poor water
23	Marrimakulapalle	N 14° 30' 20.93"	E 77° 53' 54.38"	123	Poor water
24	Medimakulapalle	N 14° 30' 22.01"	E 77° 53' 56.14"	62.39	Good water
25	Modugulakuntla	N 14° 32' 48.18"	E 77° 53' 56.40"	99.89	Good water
26	Pulaobaihpalli	N 14° 34' 35.83"	E 77° 48' 43.44"	133.91	Poor water
27	Pullampalli	N 14° 33' 35.40"	E 77° 48' 07.32"	141.81	Poor water
28	Pullanarayanapalli	N 14° 34' 33.68"	E 77° 49' 58.76"	83.16	Good water
29	Shro thirumalapura	N 14° 32' 43.22"	E 77° 54' 20.00"	153.8	Poor water
30	Sivampalli	N 14° 32' 38.58"	E 77° 50' 44.47"	119.38	Poor water

Table 4. Water quality categorization based on water quality index (WQI) value [33].

Quality of Water	WQI	Percentage of Water Samples
Excellent	<50	–
Good	50–100	33%
Poor	100–200	67%
Very poor	200–300	–
Unsuitable	>300	–

Irrigation Water Quality

The appropriateness of groundwater for irrigation is determined by the effects of inorganic substances on soil and vegetation, as demonstrated by Wilcox [36] and Richards [34]. To determine the irrigation appropriateness of groundwater in this research region, many essential ratios such as SAR, RSC, Na%, magnesium absorption ratio (MAR), and KR were used for groundwater understanding. These ratios provide valuable insights into the overall quality of the groundwater and its potential impact on irrigation practices. By analyzing these ratios, it is possible to determine the level of suitability and make informed decisions regarding the use of groundwater for irrigation purposes.

Sodium Absorption Ratio

The SAR is determined by comparing the absolute and relative amounts of sodium ions to calcium and magnesium ions. SAR levels have a direct impact on the soil's sodium absorption. When groundwater includes a high sodium and low calcium content, the soil's cation exchange complex may become saturated with sodium. The SAR is often used to determine the appropriateness of groundwater for irrigation. The SAR can be calculated using Equation 5:

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad (5)$$

Richards [34] assigned the levels of SAR into four categories depending on Na⁺, Ca²⁺, and Mg²⁺ concentrations in mEq/L. SAR concentrations in the research area ranged from 3.10 to 9.23 mEq/L, with an average of 5.82 mEq/L (Table 5). Based on Richards's classification all the samples (100%) fell within the excellent limit category for water quality in the research region (Table 6).

Residual Sodium Carbonate

The RSC content in water indicates a notably high concentration of HCO₃⁻ when compared to other negative ions, as seen in Table 5. Consequently, carbonate ions (comprising HCO₃⁻ and CO₃²⁻) exert an influence on water quality, leading to the precipitation of alkaline earth ions (Ca²⁺ and Mg²⁺) in regions where water is more concentrated. As a result, estimating RSC is critical for irrigation suitability and can be done using Equation 6:

$$RSC = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+}) \quad (6)$$

This displays each ionic level in mEq/L. The observed RSC levels in groundwater were -10.68 to -1.19 mEq/L with a mean value of -6.02 mEq/L in the research region. According to the irrigational classification, the 100% observed in the research region (Table 6).

Percentage Sodium

When the percentage of Na⁺ in the soil rises, it decreases the permeability of the soil and, as a result, plant development. In general, the percentage of Na⁺ in irrigation water should not exceed 60. The percent Na⁺ can be determined by Equation 7. The percent Na⁺ in the subsurface ranges from 35.81 to 66.95 mEq/L, with an average of 50.62 mEq/L in the research region (Table 5). According to irrigational classification, 87% ground water samples are suitable for irrigation, and 13% of samples are unsuitable for irrigation (Table 6).

$$\%Na = \frac{Na^+ + K^+}{(Ca^{2+} + Mg^{2+} + Na^+ + K^+)} \times 100 \quad (7)$$

Table 5. Groundwater quality indices of irrigation water samples in the research area.

Sample No.	SAR	RSC	%Na	PI	KR	MAR	Gibbs Ratio I	Gibbs Ratio II
1	4.00	-6.43	45.11	55.56	0.81	36.57	0.63	0.56
2	4.18	-7.66	41.43	51.71	0.70	53.78	0.53	0.60

Sample No.	SAR	RSC	%Na	PI	KR	MAR	Gibbs Ratio I	Gibbs Ratio II
3	4.87	-4.47	49.42	60.80	0.97	37.55	0.51	0.61
4	3.60	-9.57	38.38	48.11	0.62	30.30	0.60	0.47
5	3.16	-6.67	39.56	51.09	0.65	46.23	0.65	0.55
6	5.73	-4.76	53.60	63.87	1.15	48.36	0.61	0.69
7	3.83	-10.68	39.69	48.47	0.65	22.30	0.70	0.46
8	4.66	-8.18	44.02	53.63	0.78	35.85	0.58	0.55
9	4.50	-6.67	44.81	54.97	0.80	48.97	0.56	0.61
10	5.03	-8.61	45.85	54.87	0.84	26.64	0.55	0.53
11	5.79	-7.01	50.24	59.31	1.00	26.64	0.51	0.58
12	3.40	-6.27	40.46	52.15	0.67	48.09	0.56	0.56
13	3.74	-7.79	38.48	49.02	0.61	59.88	0.49	0.61
14	5.52	-4.22	54.17	64.78	1.17	40.68	0.62	0.66
15	7.43	-4.81	58.17	67.09	1.38	42.19	0.55	0.71
16	6.80	-7.06	52.84	61.28	1.11	28.91	0.60	0.61
17	5.94	-4.87	54.84	64.59	1.20	45.72	0.64	0.69
18	9.23	-5.07	61.35	69.01	1.57	29.28	0.61	0.69
19	8.47	-4.18	66.95	74.94	2.02	64.84	0.73	0.85
20	8.43	-3.92	58.32	66.78	1.39	24.76	0.54	0.65
21	6.01	-5.24	51.97	61.73	1.07	41.30	0.56	0.65
22	7.82	-3.19	59.16	68.44	1.44	41.59	0.55	0.71
23	8.00	-5.80	55.52	63.64	1.24	30.74	0.53	0.64
24	6.02	-4.73	53.77	63.77	1.16	40.56	0.52	0.66
25	6.27	-1.19	65.26	77.97	1.85	61.08	0.61	0.83
26	3.10	-8.42	35.81	46.75	0.56	46.12	0.51	0.51
27	8.73	-7.98	56.40	63.59	1.28	45.64	0.57	0.70
28	4.52	-6.04	47.14	57.55	0.88	40.93	0.60	0.60
29	6.52	-4.90	54.24	63.52	1.17	37.92	0.55	0.65
30	9.16	-4.40	61.75	69.63	1.60	32.66	0.56	0.70
min	3.10	-10.68	35.81	46.75	0.56	22.30	0.49	0.46
max	9.23	-1.19	66.95	77.97	2.02	64.84	0.73	0.85
average	5.82	-6.02	50.62	60.29	1.08	40.54	0.58	0.63

Table 6. Classification based on different geophysical parameters.

Parameter	Water Quality	Ranges	Samples Numbers	% of Groundwater Samples
SAR [34]	Excellent	0–10	1–30	100%
	Good	10–18		
	Doubtful	18–26		
	Unsuitable	> 26		
EC	Excellent	< 250	–	
	Good	250 - 750	–	
	Permissible	750 - 2000	5,12,25	10%

Parameter	Water Quality	Ranges	Samples Numbers	% of Groundwater Samples
	Doubtful	2000 - 3000	1-4,6-9,11,13,14,17,19-22,24,26,28	60%
	Unsafe	> 3000	10,15,16,18,23,27,29,30	30%
TDS	Fresh	<1000		
	Brackish	>1000	Jan-30	100%
	Saline	>10,000		
	Braine	>100,000		
TH	Safe	<75		
	Moderately hard	75 -150		
	Hard	150 -300		
	Very hard	>300	Jan-30	100%
RSC [35]	Suitable	< 1.25	Jan-30	100%
	Marginal	1.25 - 2.50		
	Unsuitable	> 2.50		
%Na [36]	Suitable	< 60	1-17,20-24,26-29	87%
	Unsuitable	> 60	18,19,25,30	13%
KR [37]	Suitable	<1	1-26, 28-30	97%
	Marginal	>1	6,14-25,27,29,30	3%
MAR [38]	suitable	< 50	1,3-11,13-18,20-24,26-30	87%
	Unsuitable	> 50	2.12,19,25	13%
PI [39]	unsuitable	< 25 Class-III	Nil	Nil
	Good	25 – 75 class-II	1-18,20-24,26-30	100%
	Excellent	>75 class- I	19,25	7

United States Salinity Laboratory – Diagram Interpretation

The interpretations of United States Salinity Laboratory (USSL) diagrams [40] for rating irrigation water are illustrated in Figure 4. SAR data is shown against specific conductance (EC). Based on the USSL classification, in the study region, 70% of groundwater samples fall in the C4S2 field, 17% in the C4S3 field, 10% in the C3S1 field, and 3% in the C4S2 fields which denotes very high salinity and medium sodium hazard limit its moderate suitability for irrigation, particularly in soils with limited drainage in the study region.

Wilcox Graphical Interpretation

Wilcox [36] established a model for measuring the efficacy of irrigated farming by combining EC and %Na⁺ (Figure 5). The diagram's five zones are excellent to good, good to permissible, permitted to questionable, doubtful to unsuitable, and unsuitable, with rising salinity and sodium levels endangering farming. According to the Wilcox categorization, 7% of groundwater samples are good to acceptable, 60% are uncertain to inappropriate, 3% are permissible to doubtful, and 30% are unsuitable for irrigation.

Kelley's Ratio

Kelley's ratio (KR) serves as an important metric to categorize the aquatic environment of irrigated agriculture, specifically about the balance between Na⁺, Ca²⁺, and Mg²⁺ ions. KR can be determined by applying Equation 8.

$$KR = \frac{Na^+}{(Ca^{2+} + Mg^{2+})} \quad (8)$$

The ion concentrations used in KR calculation are measured in mg/L. In the research area, the KR values ranged from 0.56 to 2.02 mEq/L, with a mean value of 1.08 mEq/L observed (Table 5). According to Kelley’s [37] classification, majority (97%) of the samples are suitable for irrigation (Table 6).

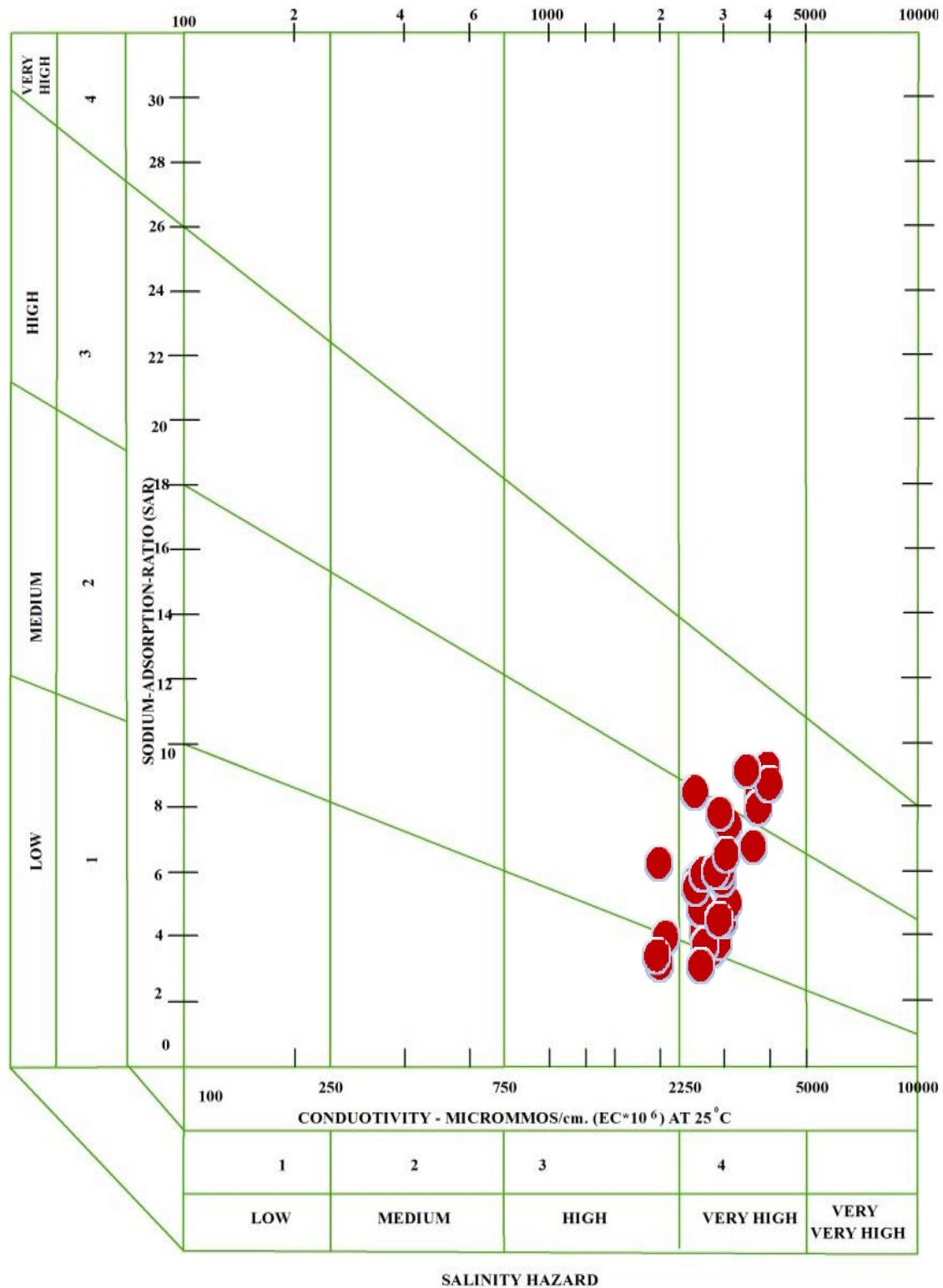


Figure 4. United States Salinity Laboratory (USSL) (1954) diagram of the study region.

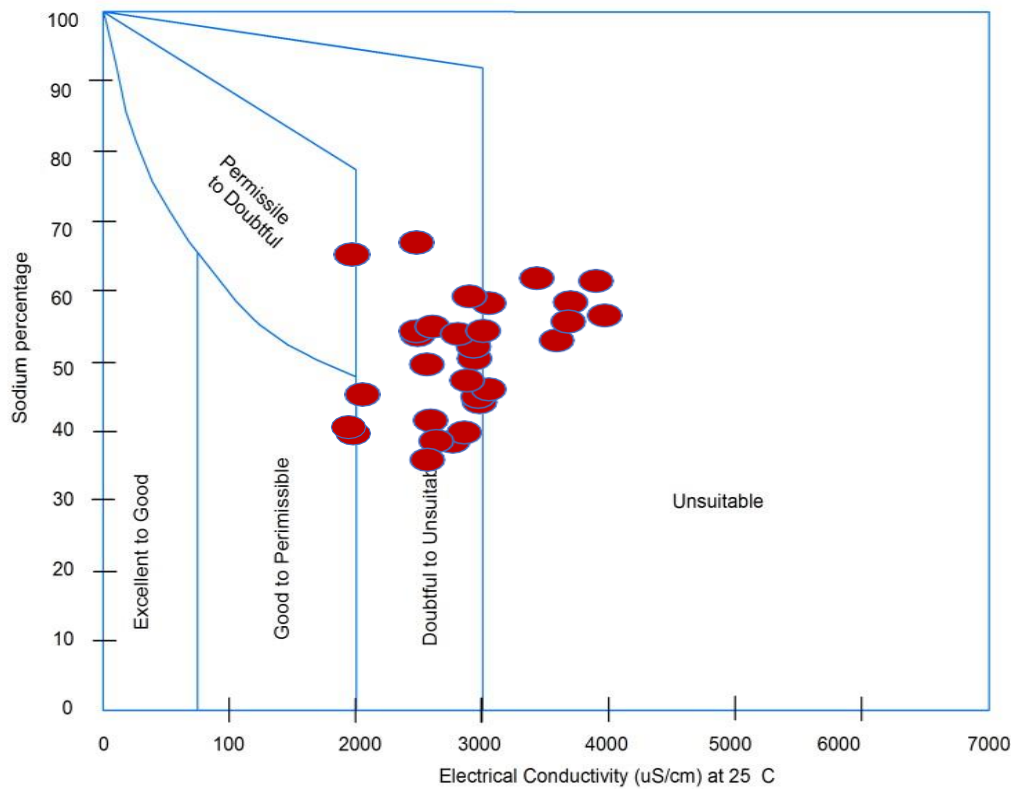


Figure 5. Wilcox diagram of the study region.

Magnesium Absorption Ratio

The magnesium content is a crucial qualitative parameter when assessing the suitability of irrigation water. In most cases, water contains a balanced ratio of calcium and magnesium (Equation 9). However, as soil salinity increases, higher levels of magnesium in water can have detrimental effects on crop production. In the research area, MAR values observed ranged from 22.30 to 64.84 mEq/L, with a mean value of 40.54 mEq/L.

$$MAR = \frac{Mg^{2+}}{(Ca^{2+}+Mg^{2+})} \times 100 \quad (9)$$

According to the irrigational classification, the unsuitable category limit for the magnesium adsorption ratio is set at 53%, indicating water with excessive levels of magnesium may hinder irrigation suitability. On the other hand, the suitable limit is determined to be 87% in the research region, while the remaining 13% samples are unsuitable for irrigation (Table 6).

Permeability Index

PI is a critical factor in determining the suitability of water for agricultural use. Traditionally, soil permeability has been influenced by the concentrations of sodium, calcium, magnesium, and bicarbonate as per the equation [41], with all ions measured in mEq/L.

$$PI = \frac{Na + \sqrt{HCO_3^-}}{Ca^{2+} + Mg^{2+} + Na^+} \times 100 \quad (10)$$

The analysis reveals that 7% of the collected groundwater samples are categorized as Class I and 93% as Class II, demonstrating that the groundwater is highly suitable for agriculture.

Gibbs Diagram Interpretation

In 1970, Gibbs developed a diagram aimed at elucidating the factors that govern the chemical composition of water, shedding light on the intricate interplay between geological formations and water

chemistry [42]. The Gibbs plot effectively delineates various mechanisms that influence groundwater composition. The outcomes of this analysis are presented in Table 5. Analyzing Gibbs plot interpretation for cation and anion demonstrates that 100% of the water samples have rock dominance during the pre-monsoon season (Figure 6).

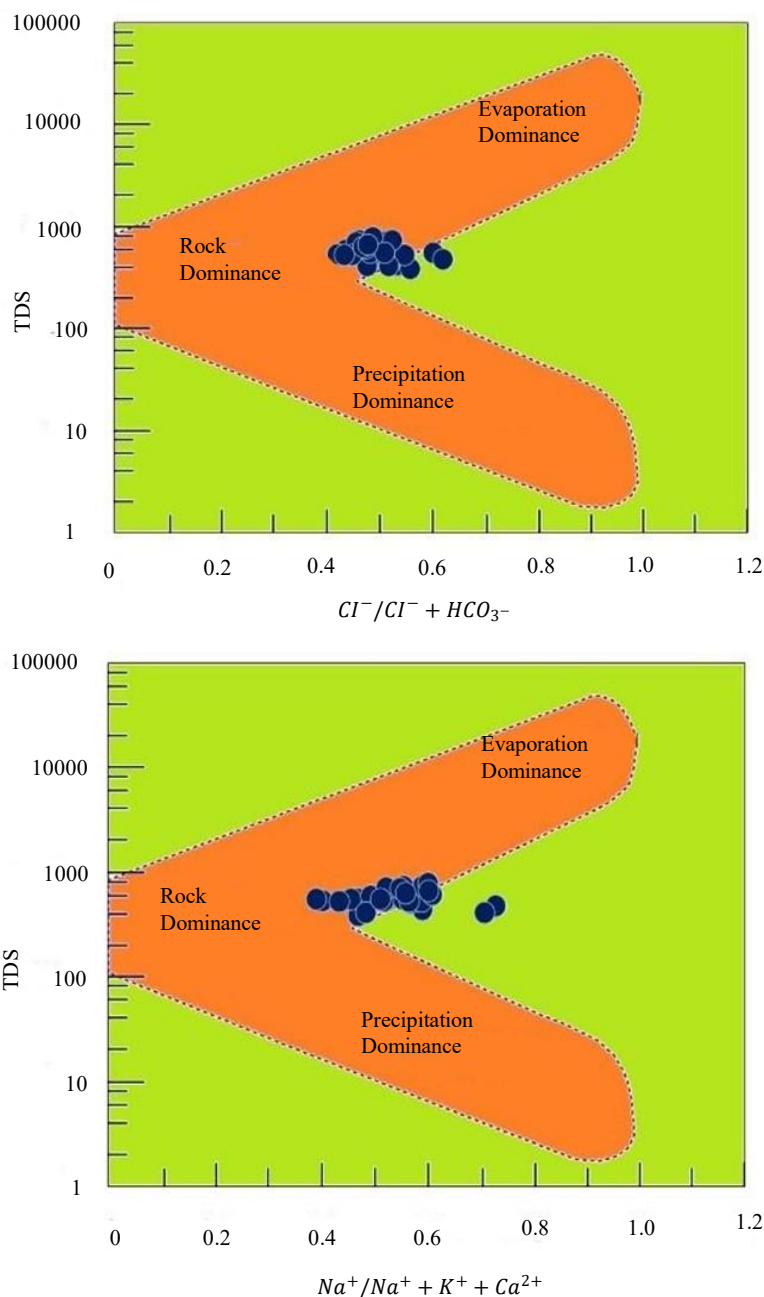


Figure 6. Gibbs plots for anions and cations versus total dissolved solids (TDS).

CONCLUSION

The study aimed to evaluate the quality of groundwater for drinking and irrigation in Tadimarri Mandal, Anantapur district of Andhra Pradesh, India. Water samples were analyzed physiochemically and compared with WHO 2011 standards for drinking water. The findings demonstrated that all of the water samples are naturally alkaline. The majority of samples that test over the acceptable range for EC, TDS, TH, and fluoride require treatment before being used for ingestion water. The groundwater geochemistry in the study region reveals that the most dominant anions are $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$

> F⁻ and the most dominant cations are Na⁺ > Ca²⁺ > Mg²⁺ > K⁺. The WQI indicates that 33% of groundwater samples are "good," while the remaining 67% are "unsuitable" for consumption. As a result, proper prevention and remediation methods are required before human consumption. The majority of groundwater samples are moderately acceptable for irrigation, as indicated by USSL and Wilcox diagrams, as well as the SAR, %Na, RSC, MAR, PI, and KR. To improve the quality of groundwater, they advise employing suitable management techniques, such as restricting the number of living things, putting in place water storage technology, treating soils for moisture, raising awareness, and starting a groundwater quality control program. According to the geographical variation of groundwater quality study performed using the GIS approach, most of the groundwater samples in this area slightly satisfy the standards.

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