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Hydrogeochemical Evaluation of Groundwater Quality for Drinking and Irrigation Purposes using Water Quality Index, and Geospatial Techniques in Parts of Semi-arid Regions, Andhra Pradesh, India

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ABSTRACT

The present study's primary goal is to assess drinking and irrigation water quality in semi-arid areas of Andhra Pradesh, India. Thirty groundwater samples have been taken from bore wells and dug wells and analyzed for physicochemical parameters. The results revealed that all the water samples in this research area are alkaline. The water quality index (WQI) and a spatial appraisal of groundwater using a geographic information system-based interpolation method are some of the techniques used to examine and explain water quality in the study area. WQI levels range from 53.34 mg/L to 129.14 mg/L, suggesting that 67% of samples are safe to drink and 33% are not. To improve the health consequences of drinking groundwater, adequate water purity treatment is required before use. Based on the USSL diagram, the majority of the samples 83% fall in the C3S1 field, 14% in the C4S1 field, and 3% in the C4S2 fields which denotes very high salinity and medium sodium hazard limit its moderate suitability for irrigation. Regarding the Wilcox categorization, 77% of groundwater samples are good to acceptable, 17% are uncertain to inappropriate, 3% are permissible to doubtful, and 3% are unsuitable for irrigation. Furthermore, according to sodium absorption ratio, percentage sodium, residual sodium carbonate, magnesium adsorption ratio, and Kelley's ratio, the majority of groundwater samples are moderately appropriate for irrigation.

Key words: Drinking and irrigation suitability, Hydrogeochemistry, Remote sensing and geographic information system, Semi-arid regions, Spatial distribution maps, Water quality index.

1. INTRODUCTION

Groundwater is a natural and vital resource for life on the planet. Water pollution and contamination have become major sources of disease in recent decades. Protected and non-polluted water for drinking is essential for a healthy life [1-15]. Contamination of natural freshwater remains a significant environmental issue in many parts of the world, especially in developing countries such as India. The majority of the population in rural areas depends on natural water sources, particularly groundwater, which is relatively safer than surface water [10]. This situation poses a significant challenge as ensuring the availability of safe drinking water is crucial for maintaining public health. According to Adimalla [1], around 2 billion people get drinking water directly from aquifers, and 40% of global food production comes from groundwater-dependent irrigated agricultural lands. In many Indian states, about 90% of the population depends on underground water supplies for consumption and farming. However, major developing nations' populations rely on shallow and bore wells, which are highly polluted [16-38] due to excess usage of fertilizers and pesticides for farming in rural areas and industrial effluents from urban areas. A unified approach of the 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 [13,22,23]. 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), percentage sodium (%Na), Kelley's ratio (KR), and residual sodium carbonate (RSC) [5,16]. 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.

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1.1. Study Region

The research region is situated in the northern part of the Anantapur district in the state of Andhra Pradesh and covers 305 km^2. Anantapur has a tropical environment, with temperatures varying from 24°C to 46°C from March to May. Agriculture is the primary source of income for most Anantapur residents [4]. The research area is located between 14° 45’ 00” and 14° 55’ 00” N and 77°25’ 00” and 77°40’ 00” E, with an average elevation of 516 m [Figure 1]. The study area is located on Survey of India topography maps 57 F/5 and 57 F/9. The lithology of the study area consists of hornblende biotite gneiss, migmatite, metabasalt, grey granite, and pink granite.

2. MATERIALS AND METHODS

2.1. Sample Collection

In November 2023, throughout the post-monsoon season, a study was led to appraise the excellence of groundwater in a selected investigation zone. To ensure accurate results, 30 samples were collected from various bore wells and hand pumps in 1-L plastic bottles. Before collecting the samples, each bottle was thoroughly washed with diluted HNO3 acid and rinsed with distilled water to maintain the purity of the samples. This careful approach was taken to avoid any potential issues and guarantee precise and reliable analysis of the groundwater samples.

2.2. Analysis

pH and EC are determined by pH meters and conductivity meters, TDS is determined by a TDS meter, and TH, Ca^{2+}, Mg^{2+}, HCO_3^-, and Cl^- are evaluated by the titration method. Na^+ and K^+ are determined by flame photometry; SO_4^{2-} and NO_3^- are measured by spectrophotometry; and F^- is determined using an ion-selective electrode. The spatial distribution maps are created using the interpolation method of the Arc GIS tool inverse distance weight to evaluate groundwater quality [2,3,8].

2.3. WQI

WQI is an essential statistic for judging groundwater eminence and evaluating whether it is fit for human consumption. WQI is a classification system that evaluates the overall appropriateness of the water for drinking purposes based on the combined effects of several different water quality guidelines. WQI is determined using World Health Organization (WHO) [38] drinking standards. The WQI is calculated in three steps. The (13) parameters (pH, 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, due to their significant role in influencing water quality [21,24]. Bicarbonate is given a minimum weight of 1 due to its minimal impact on the assessment of the water quality. To reflect their relative importance in defining the water’s quality, other variables including Ca^{2+}, Mg^{2+}, Na^+, and K^+ were assigned weights ranging from 1 to 5. In the following stage, the relative weight (Wi) is determined using the following equation 1:

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

The “quality rating (qi)” for the third stage is calculated using the calculation below Eq. 2.

$$qi = \left(\frac{ci}{si}\right) \times 100 \quad (2)$$

If Ci represents the attentiveness of each characteristic in each water sample, then Si represents the recommended WHO 2012 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 3 and 4.

$$SIi = wi \times qi \quad (3)$$

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

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

3. 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 [38] and are shown in Table 1.

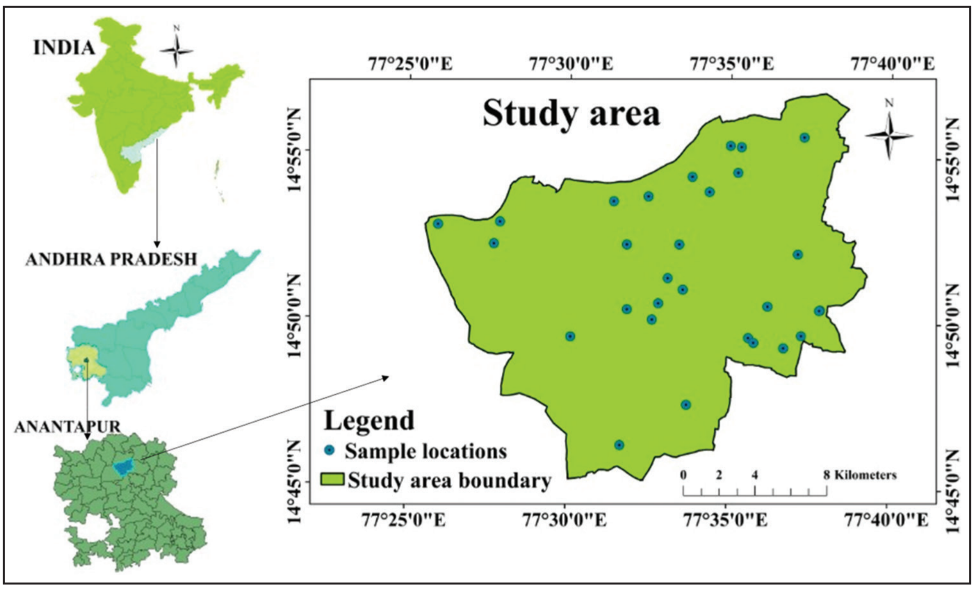

Figure 1: Sample location map of the investigation area.

Table 1: Concentrations of physicochemical parameters and their comparison with the WHO [38].

Parameter	Minimum	Maximum	Mean	SD	WHO (2012)
pH	7.1	8.3	7.71	0.35	6.5-8.5
EC	890	3040	1719	556.91	–
TDS	480	2048	1047	402.87	500
Ca^{2+}	52	182	35.44	29.58	75
Mg^{2+}	23	112	62	21.36	30-150
Na^{+}	58	201	124	31.68	200
K^{+}	1	12	5.74	2.92	–
HCO_3^-	236	732	491.87	123.02	–
F^-	0.38	1.6	0.97	0.32	1.5
Cl^-	90	308	197.13	57.32	250
SO_4^{2-}	21	97	54.80	24.24	250
NO_3^-	15	110	40.87	25.51	45
TH	227	762	500.32	132.52	–

EC: Electrical conductivity, WHO: World Health Organization

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 studied area ranges between 7.1 and 8.3, with a mean 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 2012, ensuring the safety of groundwater for human consumption. 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. In addition, 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). The research region's groundwater has EC values that fluctuate between 890 and 3040 µS/cm, with a mean of 1719 µS/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, 20%, and 3% of samples belong to high salt enrichment [11]. High EC may be due to the black cotton soil of this area. In the research region, the TDS values range from 480 mg/L to 2048 mg/L, with a mean value of 1047 mg/L. According to Freeze and Cherry [12], 40% 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 [6,12]. Total hardness in the investigated area ranges from 227 to 762 mg/L, with a mean value of 500.32 mg/L. Based on Sawyer and McCarthy [32], the TH groundwater categorization indicates that 97% of the subsurface sample in the research region is of extremely hard type. 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. Calcium concentrations in this research region range between 52 and 182 mg/L, with a mean of 35.44 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 such as magnesium calcite or dolomite [33]. 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 23 to 112 mg/L with a mean value of 62 mg/L. All the locations are within the permissible limits of WHO [38] (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 <200 mg/L for water quality, as per the WHO [38]. Exceeding this concentration renders the water unsuitable for domestic use, as it can lead to severe health issues such as hypertension. High levels of sodium pose a risk, particularly for individuals with cardiac, renal, and circulatory diseases. In the research area, Na^+ values fluctuated between 58 mg/L to 201 mg/L, with a mean of 59.66 mg/L. Potassium content in water exceeding a few tens of parts per million (ppm) serves as an indicator of pollution [26,29]. 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 62.5 to 174.1 mg/L with a mean value of 5.74 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 [24]. 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 236 mg/L to 732 g/L, with a mean value of 491.8 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 [7,16,21]. In the study region, the fluoride content ranges from 0.38 mg/L to 1.6 mg/L, with a mean value of 0.97 mg/L. Cl^- is the second most abundant anion in the study region. In the research area Cl^- content ranged from 90 mg/L to 308 mg/L, with a mean value of 197.13 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 [25]. Sulfate is abundant in both natural and human-made water systems [22,27]. 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 21 mg/L to 97 mg/L with a mean value of 54.80 mg/L. Nitrate in groundwater is primarily derived from various non-point sources, including leaching from chemical fertilizers and livestock waste, as well as contamination from septic and sewage discharges [14,20]. 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 [23]. Nitrate serves as an indicator of pollution in water systems. Nitrate in drinking water should not exceed 45 mg/L, according to the WHO [38]. In the research area, NO_3^- concentrations in groundwater ranged from 15 mg/L to 110 mg/L, with a mean value of 40.87 mg/L.

3.1. WQI

The WQI is divided into five categories: excellent type (0–50), good type (50–100), poor type (100–200), extremely poor type (200–300), and unfit for consumption (>300). The range of the WQI is 53.34 to 131.21 [Table 3] [30]. Based on the WQI, 67% of groundwater samples are suitable for drinking, whereas the remaining 33% are unsuitable due to high concentrations of TDS, EC, and TH [Table 4]. Figure 2 shows the spatial distribution map of WQI. The WQI of relative weights for each parameter is given in Table 2.

3.2. Irrigation Water Quality

Wilcox (1955) and Richards (1954) show that the impacts of inorganic compounds on the soil and plant life determine the suitability of groundwater for farming. To determine the irrigation appropriateness of groundwater in this research region, many essential ratios such as SAR, RSC, Na%, magnesium adsorption 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 groundwater use for irrigation purposes.

3.3. SAR

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 the following equation 5:

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

Richards [30] assigned the levels of SAR into four categories depending on Na^{+}, Ca^{2+}, and Mg^{2+} concentrations in meq/L. SAR concentrations in the research area ranged from 1.55 to 3.78 meq/L, with an average of 2.46 meq/L [Table 5]. Based on Richards's classification all the samples (100%) fell within the fit for irrigation purposes in the research area [Table 6].

3.4. RSC

To find the RSC, subtract the alkaline earth quality (Ca^{2+} + Mg^{2+}) from the carbonate (CO_3^{2-} + HCO_3^{-}). When the sum of carbonates exceeds that of calcium and magnesium, calcium and magnesium may precipitate completely [19,35]. As a result, estimating RSC is critical for irrigation suitability and can be done using the following equation 6 [9]:

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

The observed RSC levels in groundwater were −6.30 to 6.45 meq/L with a mean value of -1.99 meq/L in the research region. Based on RSC findings 86% of groundwater samples are appropriate, 7% are marginal suitable, and 7% as inadequate for farming [Table 6].

3.5. %Na

When the percentage of Na^{+} in the soil rises, it decreases the permeability of the soil and, as a result, plant development [37]. In general, the percentage of Na^{+} in irrigation water should not exceed 60. The percent Na^{+} can be determined by following Eq. (7).

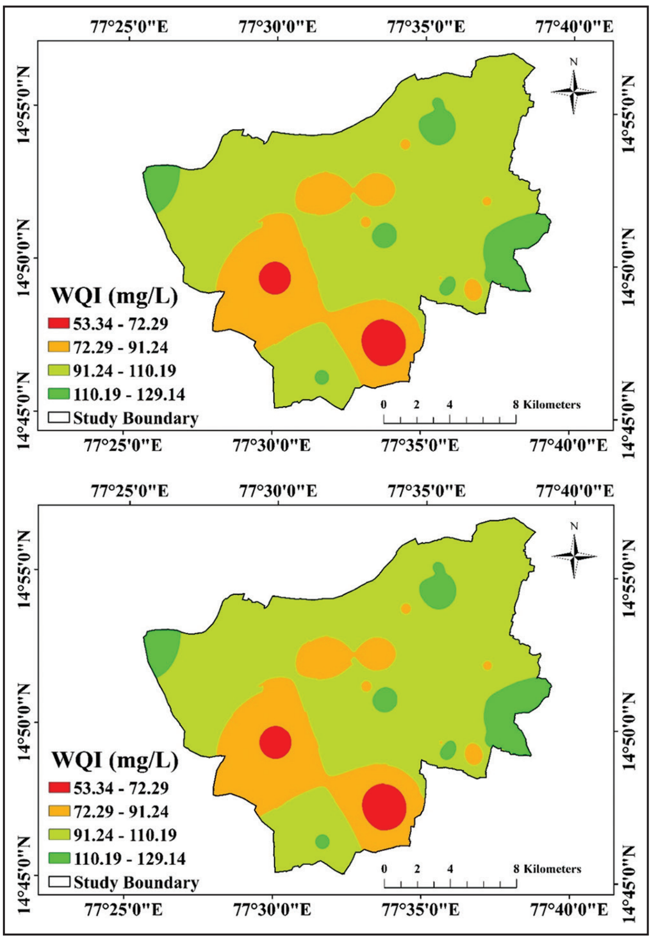

Figure 2: Spatial distribution map of water quality index.

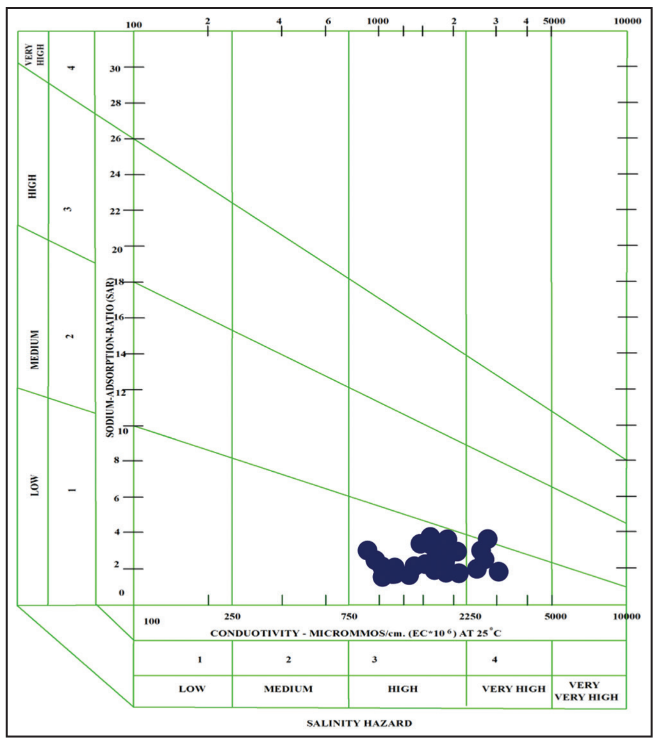

Figure 3: USSL, (1954) diagram of the study region.

Table 2: Relative weights for each parameter.

S. No.	Chemical parameters	wi	Wi	Wi=wi/∑ wi	C*i*	S*i*	q*i* = (C*i*/S*i*) *100	SIi=Wi*qi	∑SIi
1	pH	3	34	0.0882	7.2	8.5	84.71	7.47	102.85
2	TDS	3	34	0.0882	825	500	165.00	14.56	
3	Ca^{2+}	3	34	0.0882	84	75	112.00	9.88	
4	Mg^{2+}	3	34	0.0882	65	30	216.67	19.12	
5	Na^{+}	2	34	0.0588	86	200	43.00	2.53	
6	HCO_3^{-}	1	34	0.0294	287	300	95.67	2.81	
7	F^{-}	4	34	0.1176	1.42	1.5	94.67	11.14	
8	Cl^{-}	5	34	0.1471	131	250	52.40	7.71	
9	SO_4^{2-}	5	34	0.1471	38	200	19.00	2.79	
10	$N0_3^{-}$	5	34	0.1471	76	45	168.89	24.84	
		34	∑Wi	1				102.850	

Table 3: WQI individual sampling stations.

S. No	Sample locations	Lattitude	Longitude	WQI	WQI Status
1	Penakacherla	N 14° 52' 17.04"	E 77° 27' 41.04"	102.85	Good water
2	Penakacherla dam	N 14° 52' 50.52"	E 77° 25' 56.28"	128.69	Poor water
3	Kottapalli	N 14° 52' 56.64"	E 77° 27' 51.84"	94.11	Good water
4	Mukundapuram	N 14° 49' 30.72"	E 77° 30' 6.12"	64.88	Good water
5	Kamalapuram	N 14° 52' 18.48"	E 77° 31' 49.08"	84.08	Good water
6	Yarragutala	N 14° 50' 21.48"	E 77° 31' 50.88"	94.67	Good water
7	Thimampeta	N 14° 50' 29.76"	E 77° 36' 12.96"	92.22	Good water
8	Garladinne (ZPHS)	N 14° 49' 32.52"	E 77° 35' 37.68"	88.82	Good water
9	Garladinne	N 14° 49' 23.88"	E 77° 35' 47.76"	128.44	Poor water
10	Marthadu	N 14° 47' 30.12"	E 77° 33' 43.92"	53.34	Good water
11	Muntimadugu	N 14° 54' 22.32"	E 77° 33' 49.68"	97.18	Good water
12	Kalluru (RBK)	N 14° 55' 17.4"	E 77° 35' 20.76"	112.25	Poor water
13	Kalluru	N 14° 55' 19.56"	E 77° 35' 0.24"	98.59	Good water
14	Illuru	N 14° 55' 36.48"	E 77° 37' 17.76"	99.01	Good water
15	Kanampalli	N 14° 52' 4.8"	E 77° 37' 8.4"	90.44	Good water
16	Krishnapuram	N 14° 51' 18.72"	E 77° 33' 6.12"	88.19	Good water
17	Sirivaram	N 14° 52' 19.92"	E 77° 33' 27"	82.19	Good water
18	Kotanka	N 14° 46' 15.6"	E 77° 31' 40.8"	111.15	Poor water
19	Jambuladinne	N 14° 49' 14.88"	E 77° 36' 43.56"	78.06	Good water
20	Guddalapalli	N 14° 33' 57.6"	E 77° 22' 12.72"	98.26	Good water
21	Sangivapuram	N 14° 50' 3.48"	E 77° 32' 37.68"	105.01	Poor water
22	Koppalakonda	N 14° 53' 36.24"	E 77° 31' 23.88"	93.17	Good water
23	Sanjeevapuram	N 14° 50' 33	E 77° 32' 49.2"	96.61	Good water
24	J.D. Kottala	N 14° 49' 37.2"	E 77° 37' 16.32"	113.36	Poor water
25	Budedu	N 14° 50' 58.2"	E 77° 33' 34.56"	126.79	Poor water
26	Yeguvapalli	N 14° 54' 30.96"	E 77° 35' 15"	126.12	Poor water
27	Kalluru Agraharam	N 14° 53' 55.68"	E 77° 34' 22.08"	89.51	Good water
28	Kesavapuram	N 14° 53' 45.96"	E 77° 32' 28.32"	99.96	Good water
29	Papinepalyam	N 14° 50' 24"	E 77° 37' 50.88"	129.14	Poor water
30	Obulapuram	N 14° 50' 23.28"	E 77° 37' 49.44"	122.97	Poor water

WQI: Water quality index

Table 4: Water quality categorization based on WQI value [28].

WQI value	Water quality status	Percentage of water samples
<50	Excellent	–
50–100	Good	67%
100–200	Poor	33%
200–300	very poor	–
>300	Unsuitable	–

WQI: Water quality index

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

The percent Na^{+} in the subsurface ranges from 23.67 to 56.01 meq/L, with an average of 36.13 meq/L in the research region [Table 5]. According to Wilcox's [37] classification, 100% of samples fall under the suitable for irrigation [Table 5].

3.6. USSL – Diagram Interpretation

According to the analytical findings from the US Salinity Laboratory (1954), salinity hazards are measured using EC, whereas alkalinity

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

S. No.	SAR (meq/L)	RSC (meq/L	KR (meq/L)	MAR (meq/L)	%Na (meq/L)
1	1.72	−4.86	0.39	56.04	28.4
2	2.96	−3.16	0.71	46.2	42.21
3	1.7	−3.27	0.45	63.53	31.69
4	1.55	0.33	0.47	49.4	33.02
5	2.45	−0.06	0.64	42.41	40.21
6	2.3	−2.59	0.51	51.03	34.5
7	2.15	−4.26	0.47	59.2	33.51
8	3.01	0.78	0.81	43.19	45.94
9	3.66	−2.52	0.76	55.99	43.65
10	2.69	1.54	0.65	54.62	40.22
11	3.64	2.29	0.83	35.81	45.76
12	2.3	−0.88	0.53	56.71	35.32
13	1.93	−4.19	0.38	50.1	28.19
14	2.25	−4.21	0.46	55.34	32.35
15	3.07	−0.96	0.74	43.07	43.19
16	2.46	0.94	0.57	42.96	36.65
17	3.01	0.53	0.73	31.24	43.02
18	1.77	−5.06	0.34	32.83	26.05
19	2.48	−2.23	0.6	44.11	38.48
20	1.64	−6.08	0.3	60.39	23.67
21	3.39	−2.23	0.67	58.39	40.29
22	2.12	−3.74	0.44	59.04	31.44
23	2.07	−3.36	0.46	58.92	31.62
24	3.35	3.13	0.86	48.73	46.42
25	1.83	−6.31	0.35	42.57	25.88
26	2.51	−3.81	0.47	47.49	31.98
27	3.77	6.45	1.26	41.69	56.01
28	2.43	−0.68	0.59	50.19	37.71
29	1.99	−5.56	0.41	53.36	29.72
30	1.74	−5.72	0.36	65.14	26.91
Minimum	1.55	−6.30	0.297	31.24	23.67
Maximum	3.78	6.45	1.256	65.13	56.01
Average	2.46	−1.99	0.57	49.99	36.13
Std. Dev.	0.655	3.055	0.205	8.803	7.575

SAR: Sodium absorption ratio, %Na: Percentage sodium, RSC: Residual sodium carbonate, MAR: Magnesium adsorption ratio, KR: Kelley's ratio

Table 6: Classification based on different irrigational parameters.

Parameter	Water quality	Ranges	Samples numbers	% of groundwater samples
SAR [30]	Excellent	0−10	1−30	100%
	Good	10−18		
	Doubtful	18–26		
	Unsuitable	>26		
EC [38]	Excellent	<250	–	
	Good	250–750	–	
	Permissible	750–2000	1, 3–7, 10–24, 27, 28	77%
	Doubtful	2000–3000	2, 8, 9, 26, 29, 30	20%
	Unsafe	>3000	25	3%
TDS [12]	Fresh	<1000	1, 3–7, 11, 13–23	60%
	Brackish	>1000	2, 8–10, 12, 24–30	40%
	Saline	>10,000		
	Braine	>100,000		
TH [32]	Safe	<75		
	Moderately hard	75–150		
	Hard	150–300	4	3%
	Very hard	>300	1–3, 5–30	97%
RSC [9]	Suitable	<1.25	1–9, 12–23, 25, 26, 28–30	86%
	Marginal	1.25–2.50	10, 11	7%
	Unsuitable	>2.50	24, 27	7%
%Na [37]	Suitable	<60	1−30	100%
	Unsuitable	>60	–	
KR [17]	Suitable	<1	1–26, 28–30	97%
	Marginal	>1	27	3%
MAR [34]	suitable	<50	2, 4, 5, 8, 11, 15–19, 24–27	47%
	Unsuitable	>50	1, 3, 6, 7, 9, 10, 12–14, 20–23, 28–30	53%

SAR: Sodium absorption ratio, %Na: Percentage sodium, RSC: Residual sodium carbonate, MAR: Magnesium adsorption ratio, KR: Kelley's ratio

hazards are measured using SAR [Figure 3]. The results show that 83% of the water samples fall into the category of C3S1, which means that the water has high salinity but low alkalinity. This type of water can be safely used to irrigate most soils and crops, with little risk of exchangeable sodium. Fourteen percent of the samples fall into the C3S1 class, which means that they have a high salinity and low alkalinity risk. However, 3% of the samples fall into the C4S2 category, which indicates a high salinity and medium sodium risk. This suggests that the salinity and salt hazards linked with irrigation will gradually increase. Therefore, it is recommended to select semi-tolerant to salt-resistant crops using certain soil treatment approaches.

3.7. Wilcox Graphical Interpretation

The quality of groundwater samples was studied by analyzing the data obtained from the Wilcox diagram [37]. The analysis was based on the relationship between the EC and the percentage of sodium (%Na) in the water [Figure 4]. Out of the 30 groundwater samples, 77% were found to have good to permissible quality, 17% were doubtful to unsuitable, and 3% were unsuitable for agriculture [Table 6]. It is a well-known fact that irrigating lands with unsuitable water could result in low farming production. This is mainly due to the high concentration of sodium salts present in the water, which negatively affects the soil-plant interaction through osmotic pressure.

3.8. KR

KR serves as an important metric to categorize the aquatic environment of irrigated agriculture, specifically about the balance between Na^+, Ca^{2+}, and Mg^{2+} ions [17]. Kelley's ratio can be determined by applying the following equation 7.

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

The KR was computed from the groundwater samples and ranged from 0.29 to 1.256 meq/L. It represents the KR of 97% of the samples in the research area, which is less than unity, indicating that these samples are ideal for agriculture, whereas the remaining 3% of the samples are inappropriate [Table 6].

3.9. MAR

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 (Eq. 8). However,

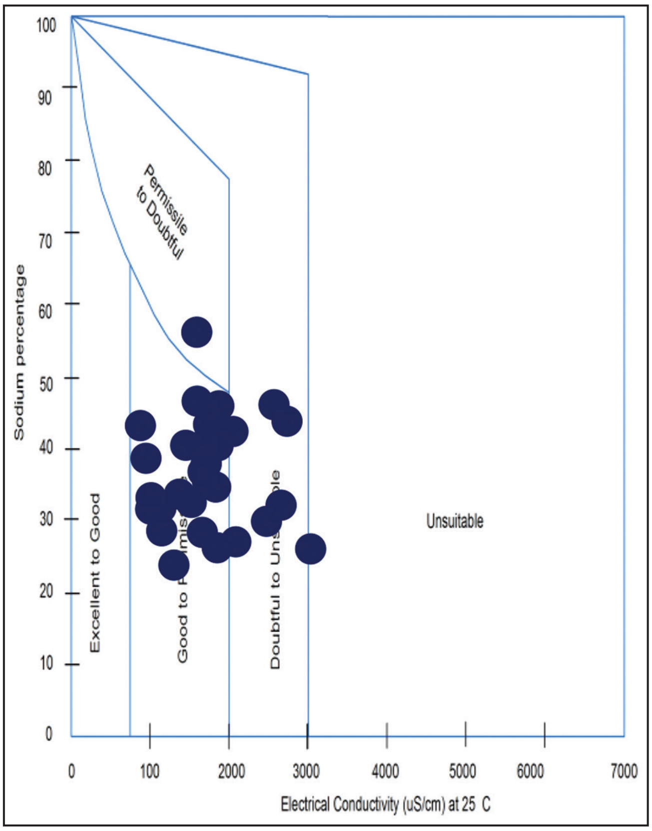

Figure 4: Wilcox diagram of the study region.

as soil salinity increases, higher levels of magnesium in water can have detrimental effects on crop production [31,34].

$$MAR = \frac{Mg^{2+}}{\left(Ca^{2+} + Mg^{2+}\right)} \times 100 \quad (8)$$

A magnesium ratio > 50 is regarded to be hazardous and inappropriate for agriculture usage. As soils grow more alkaline, crop yields will be reduced. The magnesium hazardous values in the research area fluctuate between 31.24 and 65.13, with a mean of 49.99 meq/L. The majority of groundwater samples (53%) were below the magnesium danger of 50, whereas the other 47% were exceeding 50, which is regarded as unfavorable and inappropriate for agricultural use [Table 6].

4. CONCLUSION

The study aims to evaluate the quality of groundwater for drinking and irrigation in semi-arid regions of Andhra Pradesh, India. Water samples were analyzed physiochemically and compared with WHO standards for drinking water. The findings demonstrated that all of the water samples are naturally alkaline. The groundwater geochemistry in the study region reveals that the most dominant anions are $HCO_3^->Cl^->NO_3^->SO_4^{2-}>F^-$ and the most dominant cations are $Na^+>Ca^{2+}>Mg^{2+}>K^+$. Based on the WQI 67% of groundwater samples are suitable for drinking purposes, whereas the remaining 33% are unsuitable for drinking. High concentrations are primarily caused by water-rock interaction and human activities. As a result, appropriate treatment and maintenance measures must be applied before human ingestion. According to the USSL diagram, 83% of the water samples fall into the category of C3S1, which means that the water has high salinity but low alkalinity. This type of water can be safely used to irrigate most soils and crops, with little risk of exchangeable sodium. Fourteen percent of the samples fall into the C3S1 class, which means that they have a high salinity and low alkalinity risk. However, 3% of the samples fall into the C4S2 category, which indicates a high salinity and medium sodium risk. Regarding the Wilcox categorization, 77% of groundwater samples are good to acceptable, 17% are uncertain to inappropriate, 3% are permissible to doubtful, and 3% are unsuitable for irrigation. Furthermore, according to SAR, %Na, RSC, MAR, and KR, the majority of groundwater samples are moderately appropriate for irrigation. People are advised not to drink groundwater where EC, TDS, TH, and F^- concentrations exceed permitted limits, and to rely on alternative sources for drinking and household water. The study utilized advanced and sophisticated techniques such as GIS and remote sensing to accurately calculate the WQI for drinking purposes and create geographical maps displaying the distribution of chemical elements in the research area. These maps are essential for the general public to comprehend the severity of groundwater pollution. In some regions, groundwater use for farming was restricted, resulting in the immediate implementation of salt-tolerant crops and improved drainage systems. We strongly recommend that the government and non-governmental organizations (NGOs) work collaboratively to construct additional structures for precipitation harvesting, such as infiltration canals, control barriers, replenishment trenches, farming ponds, and artificial recharge systems.

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