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GROUNDWATER QUALITY ASSESSMENT FOR DRINKING AND IRRIGATION ON HINDUPUR MANDAL, ANANTAPUR DISTRICT, ANDHRA PRADESH STATE, SOUTH INDIA

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ABSTRACT

Groundwater serves as a critical resource for drinking and irrigation, particularly in arid and semi-arid regions like Hindupur Mandal, Andhra Pradesh, where surface water availability is limited. This study assesses the hydrogeochemical characteristics and seasonal variations in groundwater quality using 25 samples collected during pre- and post-monsoon periods. Physicochemical parameters including pH, EC, TDS, major cations and anions, and various irrigation indices such as SAR and %Na were analyzed and compared against WHO and BIS standards. Spatial distribution maps, Piper plots, and USSL diagrams were utilized to interpret water chemistry, facies distribution, and irrigation suitability. Results indicate that groundwater is predominantly of Na–Cl type during the pre-monsoon and shifts partially toward Ca–Mg–HCO_3 type post-monsoon, reflecting seasonal dilution from rainfall recharge and carbonate weathering. While the majority of samples fall within acceptable limits for both drinking and irrigation, elevated concentrations of Na^+, K^+, and Cl^- in certain locations point to anthropogenic impacts such as agricultural runoff and domestic wastewater infiltration. The study concludes that groundwater quality in the area is generally acceptable for domestic and agricultural use, though periodic monitoring is essential to manage contamination risks and ensure sustainable use.

Keywords: Groundwater Quality, Pre-and Post-Monsoon, Physicochemical Parameters, Irrigation Suitability, Piper Plot, USSL Diagram, Agricultural Runoff

1. INTRODUCTION

Groundwater is essential for domestic water supply and agricultural irrigation, particularly in arid and semi-arid regions where precipitation and surface water resources are limited (Rao et al., 2020; Singh et al., 2020; Balasubramani et al., 2021; Laurent, R. 2022). The quality of groundwater, defined by its physical, chemical, and biological properties, must comply with the permissible limits established by agencies such as the WHO, BSI, and other regulatory bodies to ensure its safety for drinking, irrigation, and industrial applications.

Excessive use of groundwater can lead to a decline in water quality and a reduction in groundwater potential. The frequent failure of monsoon seasons and high dependence on rainfall make it imperative to understand the hydrogeochemical characteristics of the study area. Groundwater chemistry is influenced by interactions with environmental, climatic, biological, and anthropogenic processes. Various factors impact groundwater chemistry, including regional geology, the degree of chemical weathering of different rock types, the quality of recharge water, and contributions from sources beyond simple water-rock interactions (Toth et al., 1984; Schuh et al., 1997).

To ensure that groundwater is suitable for drinking, its quality must be evaluated against specific measures and compared to established standards. Similarly, the quality of water used for irrigation and industrial purposes should be assessed based on different parameters in accordance with standard guidelines. Understanding groundwater chemistry is critical for evaluating its suitability for residential and agricultural applications. High-quality groundwater, combined with effective soil and water management, enhances crop production. The utility of irrigation water in agriculture depends on various factors, including water quality, soil type, the salt tolerance of crops, climate, and drainage conditions (Nagaraj et al., 2016). Major challenges affecting groundwater quality include overexploitation, reduced precipitation, and declining groundwater levels.

Water is a vital resource for both biotic and abiotic factions to survive (Bari & Yeasmin, 2014; Etikala et al. 2021). The phrase "water quality" refers to the physical, chemical, and biological qualities of water, whether it is t for potable, irrigation, and other industrial uses (Golla et al, 2020; Akhtar, et al, 2021). Especially for drinking purposes, which may have an impact on human health (Li, P & Wu, 2019; Balaji et al, 2019). The primary source of drinking water is groundwater. In comparison to surface water, underground water is clean and pollution-free (Arveti, et al, 2019). The overuse of pesticides and fertilizers, rising human activity, and the fast development of industry have all contributed to the contamination of groundwater. Groundwater must undergo quality testing before being used as portable water for home purposes because it has a high concentration of different ions, salts, etc. Otherwise, it can result in water-borne illnesses. Keeping groundwater in a state for human consumption is therefore crucial. (Golla, et al. 2021)

2. STUDY AREA

Hindupur Mandal, located in the southern part of Anantapur district in Andhra Pradesh, lies between 13°40' to 13°56' North latitude and 77°26' to 77°39' East longitude (Fig 1). The region falls under the semi-arid zone of the Rayalaseema region and is geologically characterized by Archaean crystalline formations, primarily composed of granites, gneisses, and migmatites, which form the principal aquifers in the area. The soils are predominantly red loamy and lateritic, influencing both agriculture and groundwater recharge. The climate is semi-arid tropical, with hot summers (temperatures reaching up to 43°C) and moderate winters, while the average annual rainfall ranges from 550 to 600 mm, mostly received during the southwest monsoon (June–September). The natural vegetation comprises dry deciduous and thorny scrub forests, with common flora including species such as Acacia, Prosopis juliflora, Ziziphus mauritiana, Cassia auriculata, and Crotalaria. Faunal diversity, though limited due to human activity, includes Indian hare, mongoose, peafowl, partridges, reptiles, and occasional sightings of blackbuck and wild boar in less disturbed area. Hindupur is well connected by road via National Highway 544E, linking it to Anantapur and Bengaluru. It has good state and district road networks connecting nearby towns and villages. Hindupur railway station, located on the Guntakal–Bengaluru line, ensures reliable rail connectivity to major cities.

Figure 1

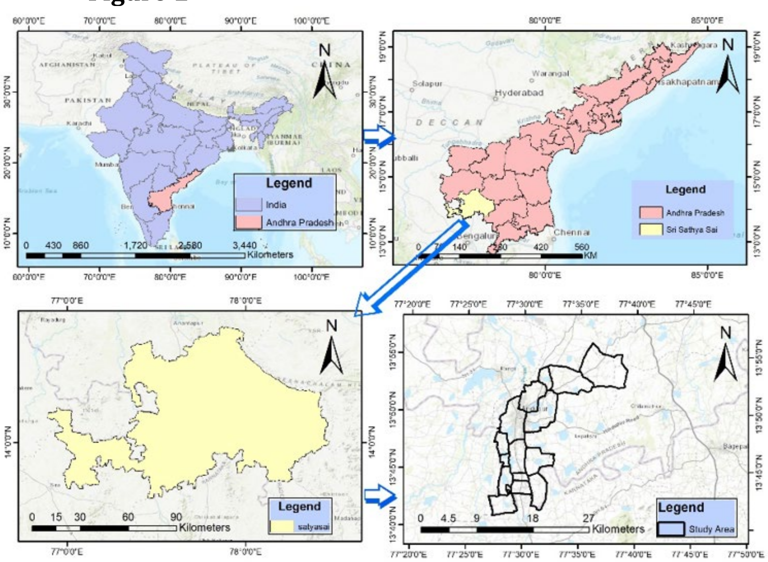


Figure 1 Location Map of the Study Area

Figure 2

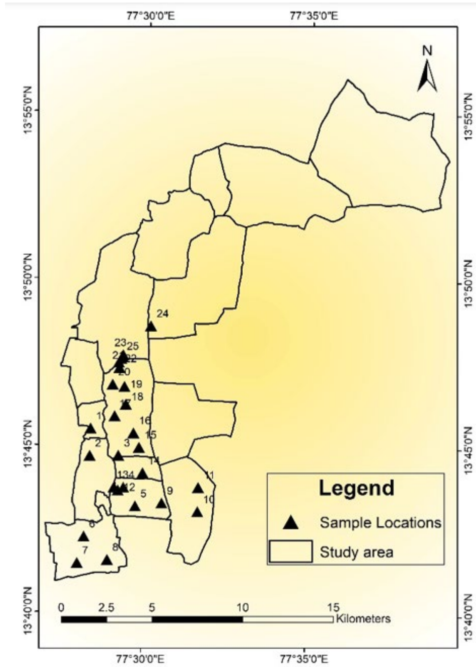


Figure 2 Samples location map in the study area

3. MATERIALS AND METHODOLOGY

To obtain more accurate data 25 water samples were collected for analysis during the pre-monsoon and post-monsoon periods (Table 1& 2) (Figure 2). The samples were analyzed promptly to maintain result accuracy. The pH, electrical conductivity (EC), and total dissolved solids (TDS) of the water samples were measured immediately after collection using a portable meter (H1991300P). Nitrate (NO_3^-) and sulfate (SO_4^{2-}) were analyzed using a UV-visible spectrophotometer. Carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), and chloride (Cl^-) were determined using volumetric methods. Sodium (Na^+) and potassium (K^+) concentrations were measured using a flame photometer, while fluoride content was determined using the zirconium-alizarin photometric method (Nagaraju and Balaji, 2016). High-purity analytical reagents and chemical standards were used consistently throughout the study (APHA, 1995).

Spatiotemporal maps were created using ArcGIS 10.3 with the inverse distance weighted (IDW) interpolation tool. The chemical analysis data for the pre-monsoon and post-monsoon periods are presented in Tables 1 and 2. Additionally, Piper diagram classifications were employed to evaluate groundwater hydrogeochemistry. Various irrigation indices, including the sodium absorption ratio (SAR), and percentage sodium (%Na) were calculated. Graphical representations such as the Wilcox diagram and USSL plot were developed to assess the suitability of the water for irrigation purposes. All concentrations are expressed in milligrams per liter (mg/l). The chemical analysis of pre- and post-monsoon is in Tables 1.0.

Table 1 Analysis of Physico-Chemical Parameters and Major ions in pre monsoon (mg/L)

S.No	pH	EC (µS/cm)	TDS (mg/l)	NO_3 (mg/l)	Ca^{2+}	Mg^{2+}	Na^+	K^+	CO_3^{2-}	HCO_3^-	Cl^-	SO_4	F	%Na	RSC	T.H	Kelless Ratio	SAR
1	6.4	298	156	42	81	57	213	13	28	302	423	109	0.65	52	-2.856	436	1.06	4.43
2	6.2	480	240	57.1	143	104	123	21	21	324	541	39	0.84	32	-6.688	634	0.42	2.12
3	6.9	210	310	34.1	110	86	72	26	23	332	339	59	0.46	19	-6.36	628	0.17	0.88

4	7.3	360	160	26.1	123	85	109	17	36	395	235	85	1.33	28	-5.47	656	0.36	1.85
5	7.5	630	310	92	116	77	166	16	36	379	334	139	1.21	38	-4.72	606	0.59	2.93
6	6.5	392	190	68.6	177	39	195	14	30	433	416	146	0.94	42	-3.95	602	0.7	3.45
7	6.2	360	180	47.6	90	69	118	70	33	427	167	167	1.47	41	-2.08	508	0.5	2.27
8	8	650	350	85.5	53	59	87	11	28	505	125	83	1.43	35	1.705	375	0.5	1.95
9	6.9	350	180	56.7	83	59	126	22	48	162	137	164	0.76	40	-4.76	449	0.6	2.58
10	7.8	392	228	22	122	160	142	16	25	204	372	135	1.24	10	-15.08	962	0.09	0.58
11	8.4	426	226	1.94	84	50	84	9	29	242	168	92	0.42	32	-3.36	415	0.43	1.79
12	8.2	251	131	0.16	96	64	137	14	30	292	230	78	1.15	39	-3.36	502	0.59	2.65
13	6.7	224	108	0.52	94	56	98	13	27	277	209	88	1.07	33	-4.27	464	0.45	1.97
14	7.5	276	103	0.22	92	69	99	10	28	266	218	94	0.29	31	-3.86	513	0.41	1.9
15	6.9	297	162	0.46	94	62	104	13	29	288	215	94	0.36	33	-4.98	489	0.46	2.04
16	6.6	432	219	0.1	113	59	135	20	18	305	289	105	0.15	38	-4.11	524	0.55	2.41
17	7.7	521	269	0.3	99	78	126	22	30	511	148	51	0.78	35	-10.49	568	0.48	2.28
18	8	476	273	0.23	78	70	183	26	24	290	328	53	1.43	47	-1.98	482	0.82	3.62
19	8.2	502	246	0.35	121	64	146	14	36	202	381	87	0.28	37	-4.11	565	0.56	2.67
20	7.9	560	267	0.49	60	67	102	10	28	477	122	49	1.7	36	-6.81	425	0.52	2.15
21	8.2	556	260	0.09	64	36	143	18	22	383	166	114	0.26	52	0.24	307	1.01	3.54
22	7.6	592	320	0.15	80	51	129	31	26	438	122	90	0.22	44	0.85	409	0.68	2.77
23	7.7	290	140	12.4	82	62	112	16	35	548	248	56	0.5	37	1.021	456	0.53	2.28
24	8.3	448	247	0.11	94	56	136	16	32	292	220	76	1.05	40	-3.46	465	0.63	2.74
25	6.6	220	110	4.9	83	59	122	22	50	162	177	144	0.7	40	-4.691	449	0.58	2.5

Table 2 Analysis of Physico-Chemical Parameters and Major ions in Post monsoon (mg/L)

S.No	pH	EC (µS/cm)	TDS (mg/l)	NO_3 (mg/l)	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	F	%Na	RSC	T.H	Kelless Ratio	SAR
1	6.2	273	142	20.8	63	112	321	18	17	529	502	157	0.43	54	-3.0	613	1.13	5.63
2	6.1	350	180	17.3	127	129	251	26	30	365	659	128	0.68	40	-10.0	847	0.64	3.74
3	6.6	300	150	44.3	124	94	138	23	20	302	434	104	0.36	32	-8.3	696	0.43	2.26
4	6.8	220	110	54	44	49	124	22	29	266	256	51	1.26	49	-3.9	311	0.86	3.05

5	7.4	640	352	49.5	68	62	200	28	43	385	486	137	1.16	52	-0.8	424	1.02	4.22
6	6	280	130	24.8	36	55	212	17	34	284	359	158	0.52	60	-0.5	316	1.45	5.18
7	5.7	2800	138	49.1	164	158	175	29	52	336	611	132	1.37	28	-14.0	1059	0.35	2.33
8	7.5	680	340	91.3	47	31	137	53	22	554	144	70	1.4	60	4.9	244	1.21	3.8
9	6.4	420	230	55.8	85	64	143	36	67	275	240	134	0.68	39	-2.7	475	0.54	2.39
10	7.1	360	180	12.7	287	207	225	83	15	301	472	242	0.21	27	-25.9	1567	0.31	2.47
11	8.1	368	201	1.93	55	44	168	11	16	383	247	86	0.25	54	0.4	318	1.14	4.09
12	8	140	134	0.18	94	44	156	10	16	417	353	65	0.92	46	-0.9	415	0.81	3.32
13	6.5	228	114	0.48	48	59	152	20	17	343	240	106	0.67	49	-1.1	362	0.91	3.47
14	7.4	263	142	0.2	65	45	139	43	14	355	232	76	0.21	51	-0.7	347	0.87	3.24
15	6.7	288	147	0.42	35	41	140	13	19	262	202	92	0.69	56	-0.2	256	1.18	3.8
16	6.6	428	213	0.13	72	63	185	48	19	362	362	102	0.18	51	-2.2	438	0.91	3.84
17	7.4	212	324	0.23	26	33	139	32	67	275	240	134	0.68	63	2.7	200	1.5	4.26
18	7.9	373	209	0.18	84	124	354	89	24	550	580	90	1.61	55	-4.6	719	1.06	5.73
19	7.8	403	228	0.34	72	38	318	28	57	238	295	77	0.24	68	-0.9	336	2.05	7.54
20	7.8	446	244	0.48	50	31	142	26	21	422	163	45	1.52	57	2.6	252	1.22	3.88
21	8	448	246	0.07	62	35	145	28	31	433	171	134	0.32	54	2.2	298	1.05	3.64
22	7.8	475	259	0.17	81	43	301	38	28	458	134	105	0.21	65	0.9	379	1.72	6.72
23	7.9	300	150	36.4	92	52	160	24	42	569	420	68	0.16	46	1.8	443	0.78	3.3
24	7.8	320	180	0.05	98	54	158	30	36	427	343	68	0.92	45	-1.1	466	0.73	3.18
25	6.3	150	80	0.92	95	66	146	38	64	245	240	134	0.68	42	-7.0	508	0.62	2.81

4. RESULT AND DISCUSSION

The groundwater in the Hindupur area has been examined in terms of physicochemical properties, and the drinking, irrigation, and human health hazard indexes have been derived as a result. These parameters are described more below:

4.1. HYDROGEN–ION CONCENTRATION (PH)

The pH of water is very important indication of its quality and provides information regarding types of geochemical equilibrium or solubility calculation. In the samples under study the pH varies from 6.2 to 8.4 with an average of 7.4 in pre-monsoon season. Likewise, post-monsoon groundwater samples show variations from 5.7 to 8.1 with an average of 7.1. some groundwater samples in the study area exceed the recommended pH limits. The interaction of groundwater with the surrounding minerals and rock formations indicates that the groundwater is slightly alkaline, as reflected in the spatial distribution of pH values (Fig 3. a &b).

4.2. EC AND TDS

In this study, Pre-monsoon EC values varied from 210 to 650 with a mean value of 407.72 (mg/L). Post-monsoon EC values range from 140 to 2800 with a mean value of 446.6 (mg/L) respectively Pre-monsoon TDS levels in the study region vary from 103 to 350 with an average value of 215.4(mg/L), whereas post-monsoon TDS values range from 80 to 352 with an average value of 192.92(mg/L). The observed increase in Electrical Conductivity (EC) from pre- to post-monsoon seasons, alongside a marginal decrease in Total Dissolved Solids (TDS), indicates that while the monsoon rains may contribute to the dilution of certain dissolved solids, they can also mobilize and transport various ions from the surface and subsurface into the groundwater system,

4.3. CARBONATE AND BI-CARBONATE

In this study, pre-monsoon total carbonate of groundwater ranges from to 18 mg/L to 50 mg/L with a mean value of 30.18 mg/L, and post-monsoon Carbonate of groundwater ranges from 14 mg/L to 67 mg/L with a mean value of 32 mg/l, respectively. The concentration of HCO_3^- in the pre monsoon varies from 162 to 548 mg/L, with an average value of 337.44 mg/L, and in the post-monsoon HCO_3^-ranges from 238 mg/l to 569 mg/l, with a mean value of 373.44 mg/L respectively. Anthropogenic activities contributing more bicarbonate to groundwater are likely possible in areas with to negligible levels of total Carbonates are shown in the spatial distribution Figures (3.g, h, i & j).

4.4. TOTAL HARDNESS (TH)

In the pre-monsoon, the total hardness of the groundwater in this area ranged from 307 mg/L to 962 mg/L, with a mean value of 515.56 mg/L, whereas during post-monsoon TH varies between 200 mg/L and 1567 mg/L with a mean value of 491.56 mg/L. Due to high quantities of calcium and magnesium, the groundwater seems to be hard hardness level trends shown in the spatial distribution Figure (3. j & k)

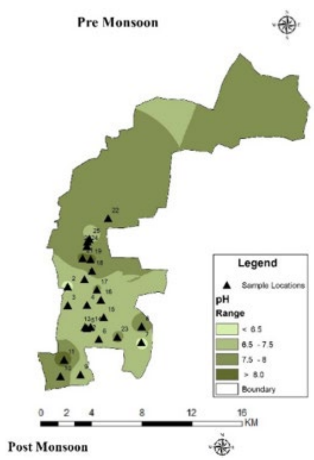


Figure 3.a

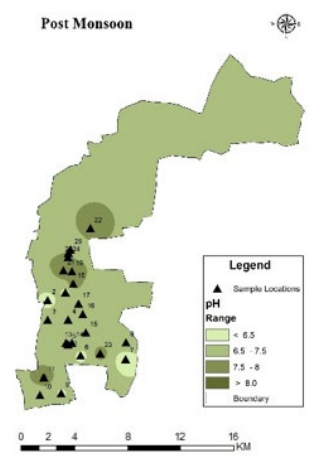


Figure 3.b

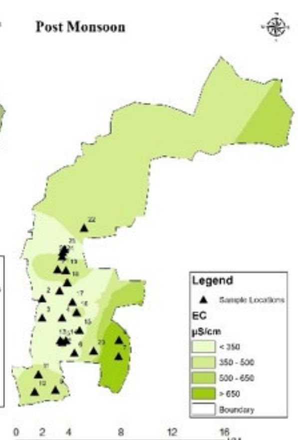


Figure 3.c

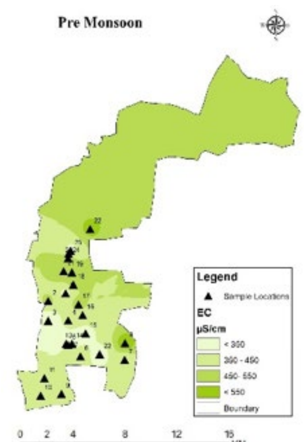


Figure 3.d

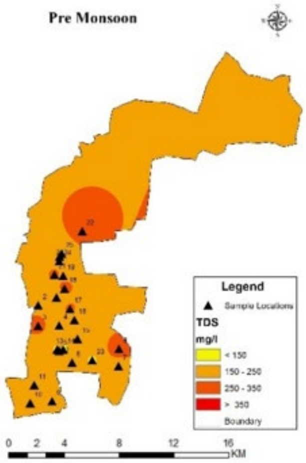


Figure 3.e

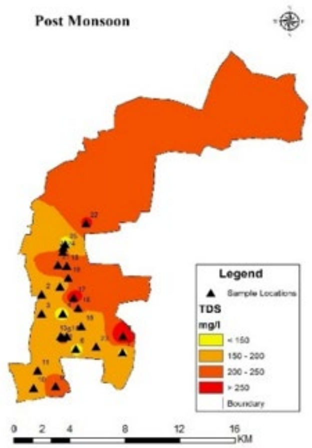


Figure 3.f

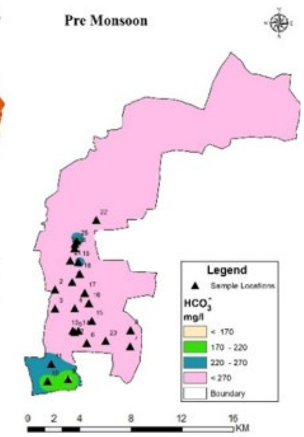


Figure 3.g

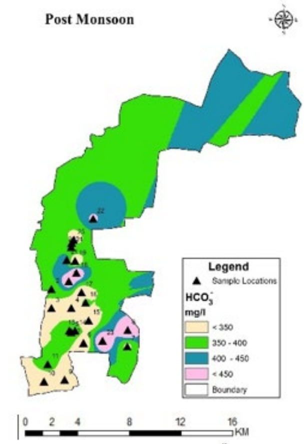


Figure 3.h

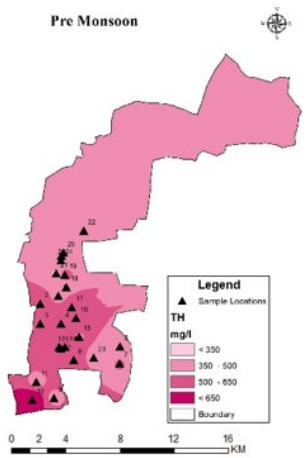


Figure 3.i

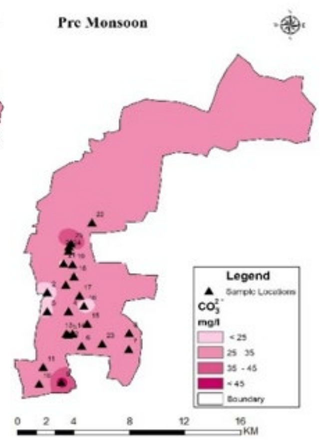


Figure 3.j

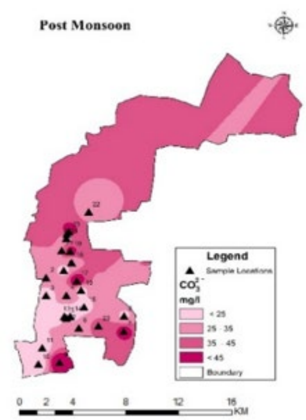


Figure 3.k

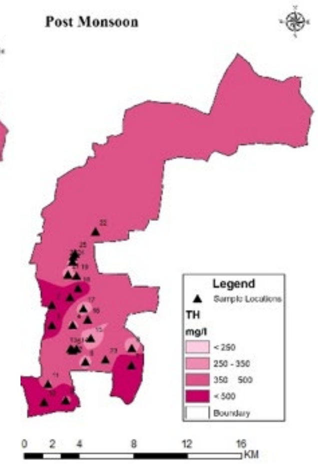


Figure 3.l

4.5. MAJOR ION CHEMISTRY

In the study area, the concentrations of Ca^{2+} in groundwater for pre-monsoon are found in the range of 53 mg/L to 177 mg/L with a mean value of 97.28 (Figure 3.m), Whereas, in the post-monsoon concentrations of Ca^{2+} in groundwater range between 26 mg/L to 287 mg/l with an average value of 82.96 mg/L, respectively, in which the majority of the wells (12 %) fell permissible and the remaining (88 %) exceeded the WHO standards. The elevated calcium concentrations in groundwater are primarily attributed to the weathering of calcium-bearing minerals within the Archaean crystalline rocks. Mg^{2+} ion concentrations in pre-monsoon varies from 36 mg/L to 160 mg/L the average concentrations of Mg^{2+} recorded as 67.92 mg/l, whereas for post-monsoon in groundwater the Mg^{2+} concentrations varied from 31 mg/L to 207 mg/l Figure (3.p), and the mean value of 69.32 mg/L, respectively. In the spatial distribution diagram, the higher Mg^{2+} is with excess values found in both pre and post-monsoon.

Na^{+} and K^{+} in the ranges in the Pre-monsoon concentrations are as follows: Na^{+} ranges between 72 mg/l to 213 mg/l with an average of 128.28mg/L, whereas, for post-monsoon samples, the concentrations of Na^{+} range between 124 mg/L to 354 mg/L, with an average of 189.16 mg/L. In pre-monsoon, concentrations of K^{+} varies between 9 mg/l to 70 mg/l with an average of 19.2 mg/L, whereas in the post-monsoon, the ionic concentrations of K^{+} ranges between 10 mg/l to 89 mg/l with a mean of 35.52 mg/L, respectively 88 % of samples exceed WHO limits Table (3). Sodium concentrations in the study area increase notably from pre- to post-monsoon, indicating both natural and human influences such as mineral weathering, ion exchange in clay-rich soils, and agricultural runoff widely employed.

Table 3 WHO limits and Physico chemical parameters for Drinking and Irrigation

	Pre monsoon			**post monsoon**			**WHO Limits**	**sample exceeding WHO permissible limits**	
	Min	Max	Avg	Min	Max	Avg		**Pre Monsoon**	**Post Monsoon**
pH	6.2	8.4	7.368	5.7	8.1	7.112	7 - 8	5	1
EC (µS/cm)	210	650	407.72	140	2800	446.6	1400	0	3
TDS (mg/l)	103	350	215.4	80	352	192.92	500	0	0
T.H	307	962	515.56	200	1567	491.56	200	25	24
NO3 (mg/l)	0.09	92	22.1648	0.05	91.3	18.4712	45	6	5
Ca	53	177	97.28	26	287	82.96	75	22	11
Mg	36	160	67.92	31	207	69.32	30	25	25
Na	72	213	128.28	124	354	189.16	20 - 200	1	7
K	9	70	19.2	10	89	32.52	12	21	23
CO3	18	50	30.08	14	67	32	150	0	0
HCO3	162	548	337.44	238	569	373.44	150	25	25
Cl	122	541	253.2	134	659	335.4	200	16	21
SO4	39	167	95.88	45	242	107.8	200	0	1
F	0.15	1.7	0.8276	0.16	1.61	0.6932	1	10	6
%Na	10	52	36.44	27	68	49.72	...	..	..
RSC	-15.08	1.705	-4.14516	-25.944	4.916	-2.899	..	..	..
Kelless Ratio	0.09	1.06	0.5476	0.31	2.05	0.9796	1	..	..
SAR	0.58	4.43	2.414	2.26	7.54	3.9156	10	..	..

Anthropogenic sources such as domestic and industrial waste and wastewater are also rich in Na+ and if percolated into groundwater can significantly contribute to raising the concentration of Na+ in groundwater. Groundwater can get enriched with K^+ as a result of agricultural operations if potassium fertilizers are widely employed. When organic matter decomposes and leaches from the soil, the K+ absorbed by plants can also serve as a source of K^+ in groundwater. (Golla et al. 2019).

Pre-monsoon chloride (Cl^-) concentrations in the groundwater in this study locality range from 122 mg/L to 541 mg/L with an average value of 253.2 mg/L, whereas post-monsoon samples have chloride concentrations that range from 134 mg/L to 659 mg/L with an average value of 335.4 mg/L. For pre-monsoon samples, the concentration of SO_4^{2-} in the groundwater in the following research ranges from 39 mg/L to 167 mg/L, with a mean of 95.88 mg/L. The concentration of SO_4^{2-} in post-monsoon samples Figure (3.v), however, varies from 45 mg/L to 242 mg/L with an average value of 107.8 mg/L.

Groundwater in the field of study may contain SO_4^{2-} due to atmospheric precipitation, agricultural activity such as the use of fertilizer and pesticides, and other factors. In the spatial distribution diagram, the 74 % Cl^- values are exceeded and 26 % are within the permissible limit. The nitrate values for the Pre-monsoon area range from 0.09 mg/L to 92 mg/L with an average of 22.16 mg/L whereas for post-monsoon samples the nitrate values are ranges from 0.05 mg/L to 91.3 mg/L with a mean value of 18.47 mg/L in pre-monsoon. The pre-monsoon values of Fluoride in the groundwater of this study region ranging from 0.15 to 1.7 mg/L with a mean of 0.82 mg/L, while post-monsoon concentrations ranging from 0.16 to 1.61 mg/L with an average of 0.69 mg/L.

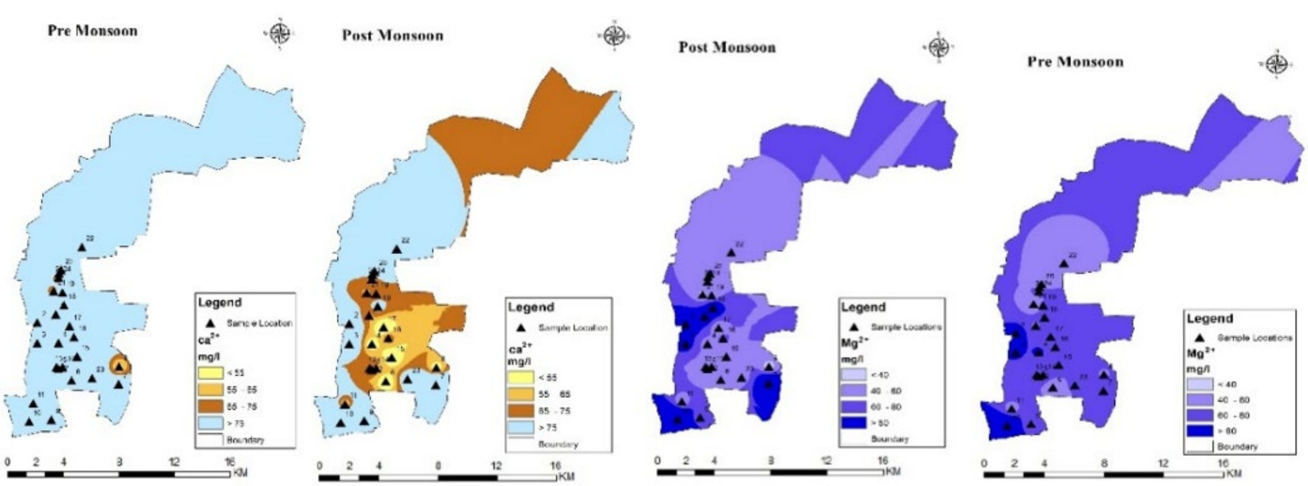
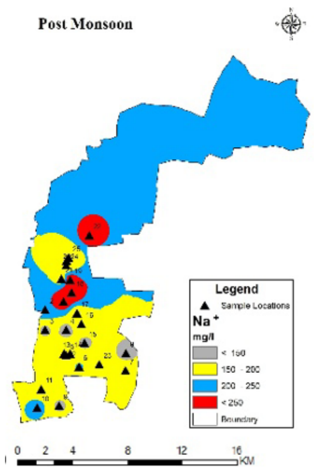
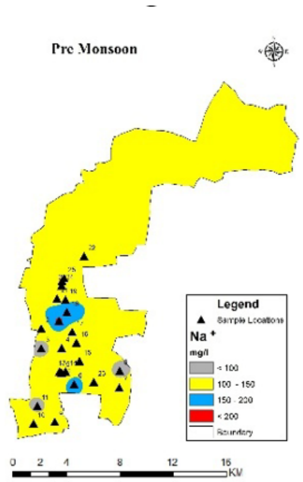
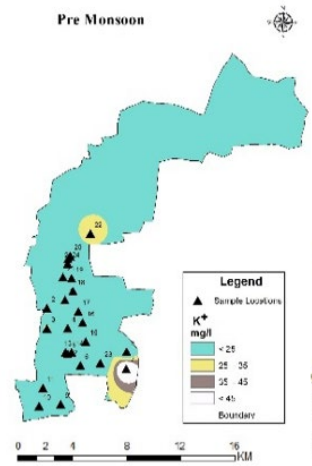


Figure 3.m **Figure 3.n** **Figure 3.o** **Figure 3.p**







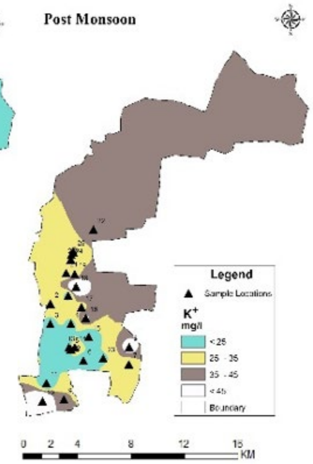
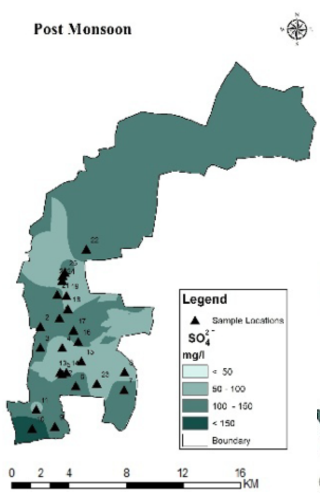
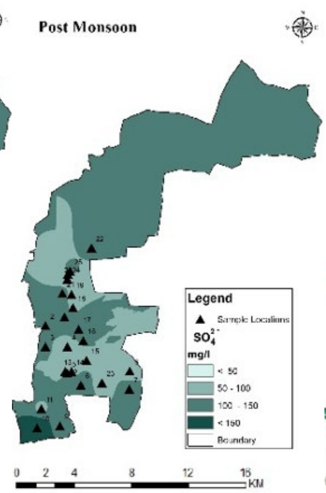
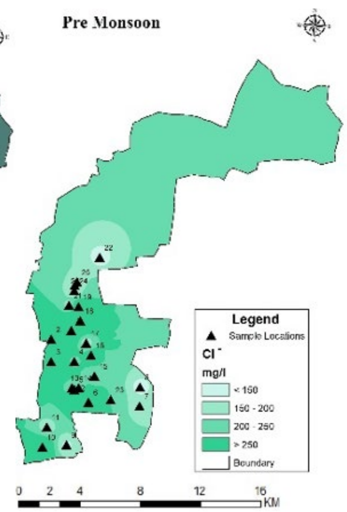


Figure 3.q **Figure 3.r** **Figure 3.s** **Figure 3.t**







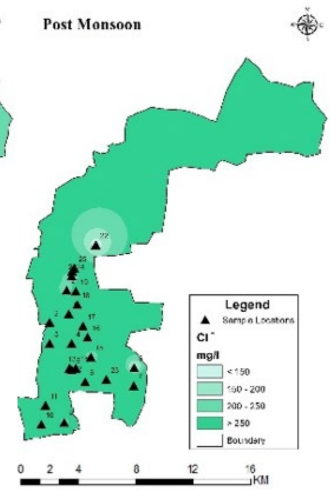


Figure 3.u **Figure 3.v** **Figure 3.w** **Figure 3.x**

4.6. IRRIGATION WATER QUALITY CLASSIFICATION

4.6.1. USSL CLASSIFICATION

In the post-monsoon diagram, most samples fall within C1S1, C2S1, and C2S2 zones, indicating low to medium salinity and low sodium hazard, making the water excellent to good for irrigation. A few samples, such as Sample No. 7, fall in higher salinity zones like C3S2 and C4S1, likely due to localized contamination or geological influences. The low SAR values (<10) across most samples suggest minimal sodicity issues, and the dilution effect from monsoonal recharge appears to improve overall water quality. In the premonsoon plot, samples are also concentrated in C1S1 and C2S1 zones, confirming the dominance of low sodium and moderate salinity waters; however, there is a slight shift toward higher EC values, indicating salt accumulation due to limited recharge and higher evaporation. Notably, no premonsoon samples fall into the C3 or C4 salinity zones, and sodicity remains low, highlighting continued suitability for irrigation. Comparing both seasons, groundwater quality is generally acceptable year-round, though post monsoon water is slightly better, with a higher proportion of samples in safer zones and reduced salinity hazards.

Figure 4

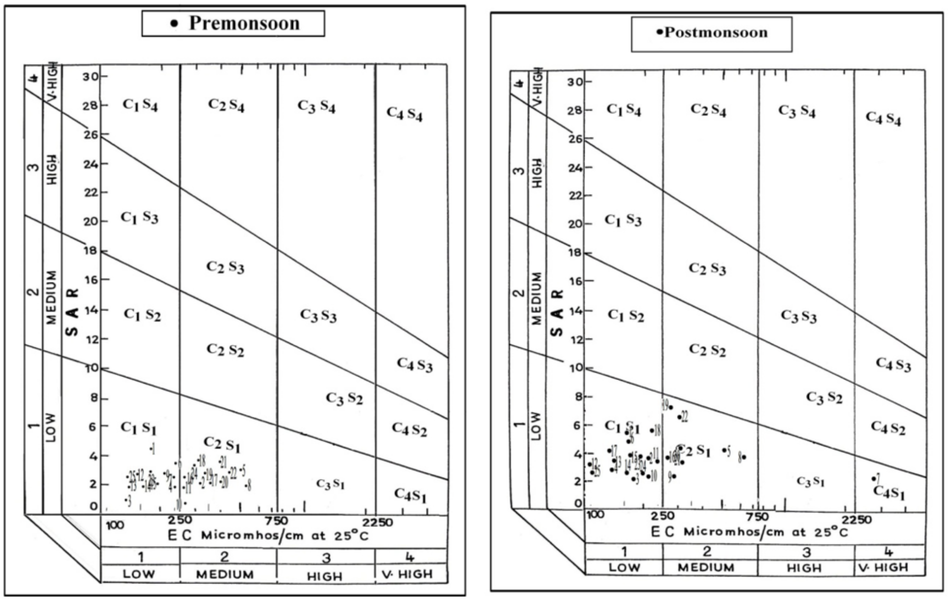


Figure 4 USSL diagram

4.6.2. WILCOX DIAGRAM

The Wilcox diagrams for Na% versus Electrical Conductivity (EC) effectively illustrate the irrigation suitability of groundwater during pre-monsoon and post-monsoon seasons in the study area Figure (5). In the post-monsoon plot, most samples fall within the "Excellent to Good" category, characterized by lower EC values (<750 µS/cm) and moderate Na% (40–60%), indicating that monsoonal recharge has significantly improved water quality by diluting dissolved salts. However, a few samples, such as Sample No. 7, extend into the "Good to Permissible" and "Doubtful to Unsuitable" zones, suggesting localized contamination due to anthropogenic or geogenic factors. In contrast, the premonsoon plot also shows a majority of samples in the "Excellent to Good" class, but with slightly higher EC values at similar Na% levels, likely due to salt accumulation from evaporation and limited recharge. Although a few samples edge toward the "Permissible to Doubtful" zone, the overall quality remains relatively favourable. Comparative analysis of both seasons reveals a modest improvement in groundwater quality post-monsoon, primarily attributed to dilution from rainfall, while pre-monsoon data reflect the impact of dry-season concentration of ions. These findings underscore the seasonal variability of groundwater chemistry and highlight the necessity for continuous monitoring to prevent long-term degradation and ensure sustainable use for irrigation.

Figure 5

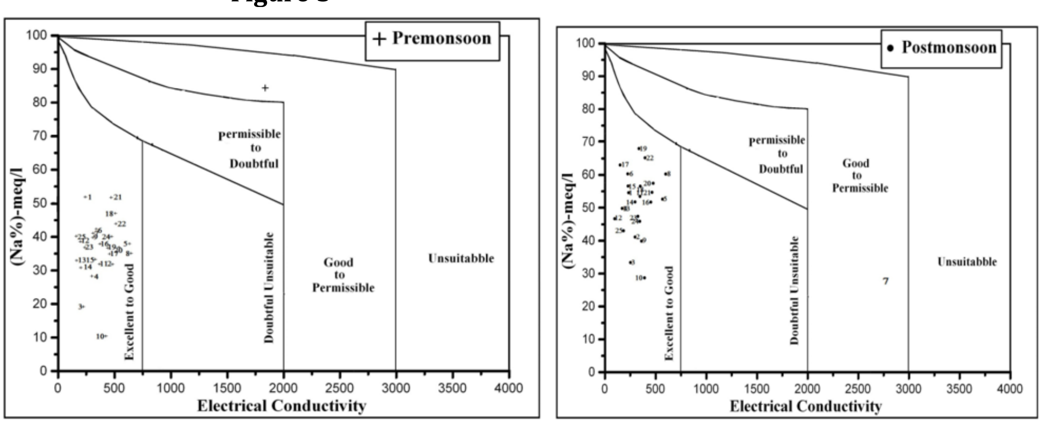


Figure 5 Wilcox diagram

4.6.3. PIPER DIAGRAM

Piper diagrams for premonsoon and postmonsoon seasons provide insight into the hydrochemical facies and geochemical evolution of groundwater in the study area Figure (6). During the premonsoon period, most samples plot toward the $Na^+ + K^+$ and Cl^- apices in the cation and anion triangles, respectively, indicating a dominance of sodium and chloride ions and suggesting a Na–Cl facies, commonly associated with prolonged water–rock interaction, ion exchange, or anthropogenic inputs such as domestic effluents and fertilizers. Many samples fall within field 9 of the central diamond, representing mixed water types, with some trending toward field 5, further confirming the influence of salinity and ion exchange processes under dry-season conditions. In contrast, the postmonsoon diagram shows a shift of several samples toward Ca^{2+} and Mg^{2+} in the cation field and increased $HCO_3^- + CO_3^{2-}$ in the anion field, indicating the emergence of Ca–Mg–HCO_3-type waters likely due to monsoonal recharge and carbonate weathering. Although mixed facies remain dominant in both seasons, the postmonsoon samples reflect dilution of ions and fresher water inputs, suggesting temporary chemical rejuvenation of the aquifer. Overall, the seasonal comparison underscores the dynamic nature of groundwater chemistry, shaped by a combination of geogenic processes, recharge variability, and anthropogenic activities.

Figure 6

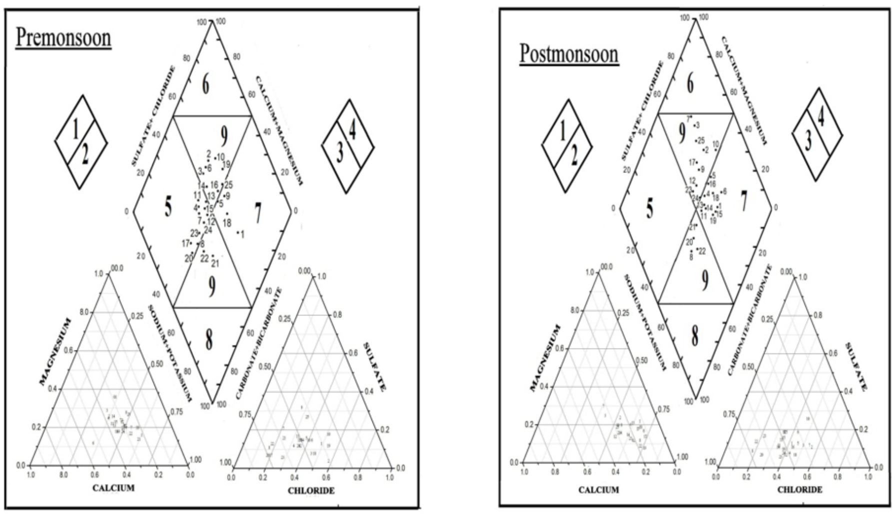


Figure 6 Piper diagram

5. CONCLUSIONS

The hydrogeochemical evaluation of groundwater in Hindupur Mandal reveals that water quality is influenced by both natural and anthropogenic processes, including mineral weathering, ion exchange, agricultural activities, and seasonal recharge patterns. The majority of groundwater samples fall within permissible limits for drinking and irrigation as per WHO and BIS standards, although elevated levels of sodium, potassium, and chloride in some samples raise concerns about potential long-term impacts on soil health and crop productivity. Piper diagram interpretation shows a dominant Na–Cl facies during the pre-monsoon season, transitioning to a more diluted Ca–Mg–HCO_3 facies post-monsoon, indicating aquifer rejuvenation through rainfall recharge. USSL classification further confirms that groundwater is suitable for irrigation, with low to moderate salinity and sodicity hazards in both seasons. Seasonal comparisons highlight the dynamic nature of groundwater chemistry in semi-arid regions, underscoring the need for continuous monitoring, improved land-use practices, and integrated water resource management to safeguard this vital resource for future generations.

CONFLICT OF INTERESTS

None.

ACKNOWLEDGMENTS

None.

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