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Hydrogeochemical Evaluation and Groundwater Quality Assessment in Madurai South Taluk, Tamil Nadu, India

***Ravi, M.[1], Dinesh Kumar, M.[2], Tholkapiyan, M.[3], Venkatraman, V.[4]**

[*1and 2] Department of Civil Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Thandalam, Chennai, Tamil Nadu, India, Pin code. 602105

[3] Department of Civil Engineering, Chennai Institute of Technology, Chennai, Tamil Nadu, India.

[4] Head, Department of Civil Engineering, Solamalai College of Engineering, Madurai, Tamil Nadu, India

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Abstract: This study presents a hydrogeochemical evaluation and groundwater quality assessment of Madurai South Taluk, Tamil Nadu, India. An agriculturally intensive region where groundwater is the primary source for irrigation and drinking. Groundwater samples collected from 2008 to 2022, during both pre- and post-monsoon seasons, were analyzed for key physicochemical parameters. These were compared against BIS:10500 (2012) and WHO (2011) guidelines for drinking water, and BIS:11624 (1986) standards for irrigation suitability. Parameters such as pH, EC, TDS, Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^-, SO_4^{2-}, CO_3^{2-}, NO_3^-, F^-, SAR, RSC, and Na% were assessed. Box and Whisker plots for 2022 indicated that most samples fell within acceptable limits for both drinking and irrigation. However, a few samples exhibited elevated salinity or poor sodium and potassium levels, limiting their suitability. Piper Trilinear Diagrams revealed NaCl and mixed $CaNaHCO_3$ types predominating during the pre-monsoon, shifting to $CaHCO_3$ and mixed CaMgCl types post-monsoon attributed to ion exchange and surface contamination. The Gibbs Diagram suggested that most samples were influenced by evaporation processes and anthropogenic activities such as irrigation return flow, while a few indicated rock-water interactions involving silicate and carbonate dissolution. The USSL Diagram for 2022 showed that 7 out of 9 pre-monsoon and 8 out of 12 post-monsoon samples were suitable for irrigation, reflecting variable salinity and sodium hazards. Overall, the findings emphasize the need for continuous monitoring and integrated water management in the region.

Keywords: Physicochemical parameters, Piper Trilinear Diagram, Gibbs Diagram, USSL Diagram, Irrigation suitability.

1.Introduction

Water is one of the most vital natural resources for life on Earth, significantly influencing socioeconomic development. In regions with limited surface water, groundwater becomes the primary source for human consumption, industrial processes, and agricultural activities (Delgado *et al.*, 2010). The demand for groundwater is rapidly increasing due to insufficient surface water availability and the growing need for potable and agricultural water (Nagarajan *et al.*, 2010). Alarmingly, water pollution is linked to nearly 80% of infections and fatalities in underdeveloped countries (UNESCO, 2007). Numerous naturally occurring major, minor, and trace elements in drinking water, when consumed in excess or insufficient amounts, can adversely impact human health (Frengstad *et al.*, 2001). Geochemical methods and interactions with dissolved minerals greatly impact water quality. Recently, Madurai South Taluk has faced important challenges in providing clean drinking water due to declining groundwater quality. The Madurai Corporation is responsible for supplying potable water

* Corresponding author E-mail: ravim9040.sse@saveetha.com

to the area. The intensive agricultural activities in Madurai South Taluk have increased the demand for groundwater resources. Given the non-perennial nature of the Vaigai River and frequent monsoon failures, evaluating groundwater quality in this region is critical for sustainable groundwater management.

Groundwater quality is influenced by both natural causes, such as geology and geochemical processes, and human activities. Geogenic sources contribute to the variation in groundwater's chemical composition over time and distance (Brindha and Elango, 2012; Gunduz *et al*., 2009; Kraiem *et al*., 2013; Mamatha and Rao, 2009; Vikas *et al*., 2009). Factors such as lithology, groundwater movement, geochemical reactions, residence time, salt solubility, and human activities control the dissolved ion levels in groundwater (Nisi *et al*., 2008). Key processes influencing groundwater chemistry include rock-water interaction, recharge and discharge, residence time, ion exchange, atmospheric inputs, chemical inputs from human activities, geological structures, and aquifer mineralogy (Jeong, 2001). Groundwater undergoes chemical evolution due to interactions with aquifer minerals or mixing between different groundwater reservoirs along subsurface flow pathways (Adimalla, 2020; Adimalla and Venkatayogi, 2018; Gabr, 2020; Kalaivanan *et al*., 2017; Saba and Umar, 2016; Tiwari *et al*., 2017). Surface runoff from agricultural areas is a primary source of salts and nutrients in groundwater. Exceeding permissible levels of nitrate and nitrite in groundwater makes it unsuitable for drinking (Lee *et al*., 2003; Rajmohan and Elango, 2005). High nitrate levels, primarily from surface pollution, can cause methemoglobinemia, or "blue baby syndrome," in humans and nitrate toxicity in livestock. Nitrate contamination is strongly related to land-use pattern and reported in several studies throughout the world (Elhatip *et al*., 2003; Rajmohan *et al*., 2009). Low pH levels in groundwater can lead to gastrointestinal disorders (Laluraj & Girish Gopinath, 2006). Total Dissolved Solids (TDS) levels are crucial in determining water use suitability; high TDS levels render groundwater unsuitable for both irrigation and drinking (Fetter, 1990).

Numerous studies have focused on monitoring and assessing groundwater quality for residential and agricultural use (Al-Bassam & Al-Rumikhani, 2003; Elampooranan *et al*., 1999; Elango *et al*., 2003; Jeevanandam *et al*., 2006; Pritchard *et al*., 2008; Subramani *et al*., 2005; Sujatha & Rajeshwara Reddy, 2003). Several methods, including Entropy-weighted Water Quality Index (EWQI) modeling (Kumar *et al*., 2020; Kumar and Augustine, 2021; Wagh *et al*., 2017) and geostatistical assessment of groundwater pollution (Sylus & Ramesh, 2018; Ukah *et al*., 2020), have been used. GIS-based groundwater quality evaluation (Shinde *et al*., 2021), groundwater quality assessment for drinking purpose (Khan *et al*., 2020), multivariate statistical techniques (Deepa & Venkateswaran, 2018), “groundwater quality assessment for irrigation using geostatistical analysis combined with a linear regression method” (Yazdanpanah, 2016), and groundwater quality assessment through spatial interpolation technique (Khorsandi *et al*., 2017) have been used worldwide. Groundwater quality assessment for irrigation often employs criteria such as USSL classification, SAR, RSC, and Na percent (Al-Bassam & Al-Rumikhani, 2003; Elampooranan *et al*., 1999; Elango *et al*., 2003; Jeevanandam *et al*., 2006; Subramani *et al*., 2005; Sujatha & Rajeshwara Reddy, 2003).

Hydrogeochemical investigations can help protect aquifers from pollution caused by human or natural events. Groundwater salinization due to physical and chemical processes in arid regions reduces usable groundwater quantity and degrades water quality (Ahamed *et al*., 2015; Egbueri, 2018; Ezenwaji and Ezenweani, 2018; Gabr *et al*., 2021; Krishan *et al*., 2021; Han *et al*., 2015; Mgbenu and Egbueri, 2019; Prasanna *et al*., 2017; Wang *et al*., 2008). Despite the growing dependence on groundwater in Madurai South Taluk, a comprehensive understanding of its chemical quality, seasonal variation, and hydrogeochemical evolution is lacking. The problem is further compounded by increasing anthropogenic pressures and uncertain monsoon patterns. The objective of this research is to systematically assess the hydrogeochemical characteristics and water quality of groundwater across pre- and post-monsoon seasons from 2008 to 2022, with reference to its suitability for drinking and irrigation. By applying tools such as Piper, Gibbs, and USSL diagrams alongside standard water quality indices and guidelines (BIS, WHO), the study seeks to identify dominant geochemical processes, contamination sources, and seasonal trends. The proposed solution involves establishing a scientific basis for sustainable groundwater use through spatial and temporal quality monitoring, with recommendations to guide water management policies and agricultural practices in the region.

2.Materials and methods

2.1 Study area

The Madurai district in Tamil Nadu, India, where the current study of Madurai South Taluk, is situated on the banks of the Vaigai River at a latitude of 9°52’41” N and a longitude of 78°02’20” E, with an average elevation of 138m. In the research region, the northeast monsoon brings in the most precipitation, and consequently, the groundwater recharge and runoff will be more. Whereas the summer and southwest monsoons bring in very little and extremely, very low rainfall and leads to low discharge. The south taluk of Madurai receives 72.87 cm of rain on average per year. Summertime temperatures typically reach 42˚C at their highest point and 26.3˚C at their lowest. Clay loam is the most common soil type in the Madurai South Taluk, with red loam and black cotton kinds being more common in the outlying reaches. The Madurai South Taluk is home to a large number of lakes, ponds, and other water bodies. The river Vaigai flows across the taluk, passing through the rich and level plain that is home to Madurai South Taluk. The primary use of the land in the Madurai South Taluk is agriculture, which is encouraged by the Periyar Dam. In this Madurai south taluk, the main crops grown are rice, pulses, millet, oil seed, cotton, and sugarcane. Thiruparankundram's stone quarries, rocky outcrops, boulders, and hills cover the east and west portions of the study area.

2.2 Materials

Topographic sheets from the Survey of India were used to create the base map of the research region (Madurai South Taluk), which was then digitalized using ArcGIS 10.2 software (Figure1). Between 2008 & 2022, fourteen groundwater samples (bore and open wells) were taken from the research region before and after the monsoon season. The Water Resources Department (WRD) noted each sample station's position coordinates using a handheld GPS. For the research period of 2008 to 2022, the Chief Engineer, WRD, State Ground and Surface Water Resources Data Centre, Taramani, Chennai, provided the test findings for the samples.

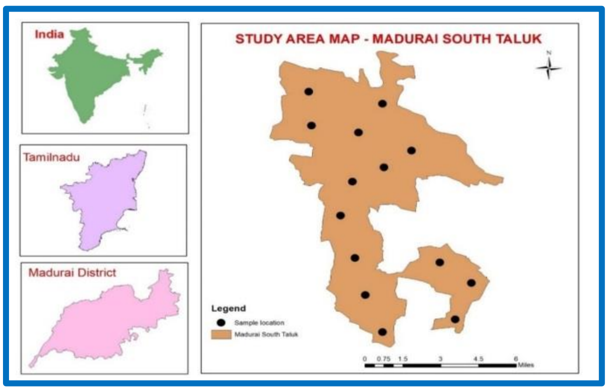

Figure (1): Location of Madurai South Taluk, Madurai District, Tamil Nadu, India

2.3 Methodology

The physical parameters, pH, EC, and TDS, as well as the chemical parameters, Total Nitrogen (NO_2 + NO_3), Ca, Mg, Na, K, Cl, SO_4, CO_3, HCO_3, F, and Total Hardness, were determined by following the guidelines set out by APHA (1995). The physio-chemical parameters for drinking water were compared using the Bureau of Indian Standards DRINKING WATER – SPECIFICATION (BIS 10500: 2012) recommendations. Sodium Absorption Ratio (SAR), Residual Sodium Carbonate (RSC), and Sodium Percentage (Na %) values were compared with the Bureau of Indian Standards Guidelines for the Quality of Irrigation Water (BIS: 11624 – 1986) in order to determine the irrigation suitability of the samples that were collected. Every parameter's average yearly value for the pre- and post-monsoon seasons were determined. To determine the most heavily polluted places, box and whisker plots were drawn for every characteristic for the most recent year, 2022, for both the pre- and post-monsoon seasons.

2.3.1. Analysis of Hydrochemical facies using Piper Trilinear Diagram

Piper (1994) created the Piper Trilinear diagram. The Piper Trilinear diagram is often used for comprehending issues related to the chemistry and geochemical evolution of groundwater. Three separate regions make up the diagram: a midriff-oriented diamond field, two trilinear triangles with a left cation and a right anion. The cation triangle represents the milliequivalent values of the cations, while the anion triangle plots the values of the anions. By plotting the corresponding points along the degree of intersection, the cations and anions in the triangles are projected into the central diamond field.

2.3.2. Analysis of mechanisms controlling groundwater Chemistry using Gibbs Diagram

The most important tool for examining the geochemical processes involved in groundwater chemistry is the Gibbs diagram. Three natural processes were noted by Gibbs as a means of verifying the chemical science of groundwater. The evaporation-crystallization process, rock weathering, and precipitation are the processes. Plotting the weight ratio $Na^+/(Na+Ca^{2+})$ on the X-axis against the TDS value on the Y-axis yields the Gibbs diagram, a boomerang-shaped envelope for cations. Anions with Cl^- / (Cl^- + HCO_3^-) Versus TDS yields the similar results. When rock weathering is the main process, the sample data plot is in the middle of the Gibbs diagram, TDS levels are modest, and the principal ions produced by the waters are Ca^{2+} and HCO_3^-. The atmospheric precipitation processes are the cause of saline fluids of the sodium chloride type, and the sample data plot is located in the bottom right corner of the Gibbs diagram. The evaporation-crystallization process is the third mechanism holding the water chemistry, and the sample data plot is located in the top right corner of the Gibbs diagram.

2.3.3. Suitability analysis for irrigation using USSL Diagram

A technique for classifying groundwater for irrigation needs is the salinity diagram, developed by the United States Salinity Laboratory (1954). There is no better way to determine the salinity of groundwater. A high salt concentration in irrigation water causes the osmotic pressure to drop and the salt solution to rise. The main supply of groundwater in this basin is necessary for agricultural production. Thus, the groundwater quality analysis based on agriculture is required. Sodium Adsorption Ratio (SAR) and Electrical Conductivity (EC) measurements are plotted in USSL Diagram using Golden Geo Grapher software to determine the appropriateness of water for agricultural usage for both pre and post monsoon seasons.

3.Results and discussion

3.1.Piper's Trilinear Diagram

3.1.1 Piper's Trilinear Diagram – Pre monsoon season (Year - 2022)

Groundwater samples were plotted using Golden Geographer software to gain a clearer understanding of their chemical characteristics within the study area. Piper's Trilinear Diagram, based on the ionic concentrations of the collected samples, helps classify the various water types present in the region. This diagram highlights the dominant cations and anions in the groundwater and serves as a valuable tool for identifying chemical relationships among the samples. The Piper Trilinear Diagram enables the categorization of groundwater into distinct chemical classes.

As seen in Figure 2, the premonsoon season (Year - 2022) dominant water types are as follows: NaCl > Mixed $CaNaHCO_3$ > $CaHCO_3$ > Mixed CaMgCl. The majority of the samples, however, are grouped in NaCl and Mixed $CaNaHCO_3$. The NaCl water type suggests that the mixing of high salinity water is caused by surface contamination sources, namely, domestic wastewater activities, such as septic tank leaks, sewage water, and fertilisers, and agricultural activities, such as irrigation return flows, fertilisers, and farm manure. It also suggests that rainfall and rock-water interactions leach minerals containing chlorine from acidic igneous rocks. Fresh water recharging and mineral dissolution are shown by mixed $CaNaHCO_3$ and $CaHCO_3$ water types.

The Piper Trilinear Diagram for the pre-monsoon season in Madurai South Taluk reveals that the dominant groundwater types are NaCl and Mixed $CaNaHCO_3$, followed by $CaHCO_3$ and Mixed CaMgCl. The prevalence of alkalies (Na^+ and K^+) over alkaline earth metals (Ca^{2+} and Mg^{2+}) suggests active ion exchange processes and significant influence from anthropogenic sources. The NaCl water type is attributed to surface contamination from septic tank effluents, sewage discharge, irrigation return flows, fertilizers, and Avaniyapuram landfill leachate. Additionally, the Mixed $CaNaHCO_3$ facies indicate mineral dissolution (especially dolomite and calcite) and freshwater recharge, likely from limited rainfall and agricultural infiltration. These geochemical signatures reflect the combined impact of human activities, stagnant water bodies (Thenkal tank), and rock-water interactions, resulting in groundwater of varied chemical composition and potential salinity concerns.

3.1.2 Piper's Trilinear Diagram – Post monsoon season (Year - 2022)

The most prevalent water types in the post-monsoon season (Year -2022) are CaHCO3 > Mixed CaMgCl > CaCl , as shown in Figure 3. However, most of the samples are clustered in $CaHCO_3$ and Mixed CaMgCl. The water type $CaHCO_3$ implies that the dominating minerals in the water are Ca and Mg due to the dominance of igneous rock that has been dissolved by minerals and recharge of freshwater. When high salinity water from surface pollution sources, such as septic tank effluents, residential waste water, and irrigation return flows, is combined with existing water, mixed CaMgCl water types suggest that ion exchange activities take place (Selvam *et al*., 2013).

In the post-monsoon season, the Piper Trilinear Diagram shows a notable shift in hydrochemical facies, with $CaHCO_3$ and Mixed Ca–Mg–Cl types becoming predominant, followed by CaCl. This seasonal transition is marked by the dominance of alkaline earth metals (Ca^{2+} and Mg^{2+}) over alkalies, indicating a greater influence of natural recharge, mineral dissolution, and dilution of contaminants following monsoonal rainfall. The $CaHCO_3$ facies suggest that carbonate-rich rocks, particularly from the Thiruparankundram hills, are contributing to groundwater chemistry through weathering and leaching. Meanwhile, the Mixed Ca–Mg–Cl water types point to ongoing ion exchange and mixing of infiltrated surface pollutants with subsurface water. These changes highlight the seasonal evolution of groundwater chemistry driven by natural hydrogeological processes and the lingering effects of human-induced contamination.

3.2. Gibbs Diagram

3.2.1. Gibbs Diagram – Pre monsoon season (Year - 2022)

The Gibbs (1970) figure displays the concentration of the area's groundwater sample points. Figure 4 plots and displays the samples taken for cations and anions during the pre-monsoon season (Year -2022). To better understand the impact of hydrochemical processes on groundwater chemistry in the research area, such as evaporation, precipitation, and rock-water interaction, Gibbs plots are used. Gibbs demonstrated that the processes controlling water chemistry can be interpreted by plotting Total Dissolved Solids (TDS) on the y-axis against the ratio of $Na^+ / (Na^+ + Ca^{2+})$ on the x-axis. A small number of groundwater samples were plotted in the rock-water interaction zone and the majority of the samples were in the evaporation zone in the Gibbs diagram. When the groundwater table is more than a few metres below the surface, evaporation from the water is often insignificant (Barica, 1972). In some situations, evaporation may happen directly from groundwater, especially in areas where the water table is located, within a metre of the surface, or when groundwater discharges to the surface. Sometimes evaporation is not the cause of changes in groundwater salinity and chemistry, but rather the dissolution of evaporite materials (Sahib *et al*., 2016).

The Gibbs Diagram for the pre-monsoon season indicates that the majority of groundwater samples fall within the evaporation dominance zone, with a few in the rock-water interaction zone. This pattern reflects the influence of surface pollution sources and concentration processes such as evaporation and evapotranspiration, which are prominent during the dry pre-monsoon period. The presence of samples in the evaporation zone suggests that irrigation return flows, septic tank effluents, and domestic wastewater discharges play a key role in altering groundwater chemistry. Simultaneously, the samples that plot in the rock-water interaction zone indicate dissolution of silicate and carbonate minerals from the underlying geological formations. This highlights the dual impact of anthropogenic activity and geogenic processes on groundwater quality during the pre-monsoon period.

3.2.2.Gibbs Diagram – Post monsoon season (Year - 2022)

The cation and anion samples collected during the post-monsoon season in 2022 are graphically shown in Figure 5. The diagram mostly depicted groundwater samples in the evaporation zone, with a limited number of samples situated in the rock-water interaction zone. In the post-monsoon season, the Gibbs Diagram shows a similar trend with most groundwater samples falling in the evaporation zone, and a limited number in the rock-water interaction zone. Despite the onset of recharge from monsoonal rainfall, the persistence of evaporation-dominated conditions suggests continued influence from surface pollution and agricultural return flows. This may be due to shallow water tables, low permeability soils, or poor drainage, which allow for ongoing evaporation and concentration of solutes. The samples that plot in the rock-water interaction zone again point to mineral dissolution processes, particularly involving carbonate and silicate-bearing rocks, contributing to the groundwater's chemical composition. These observations indicate that while natural geochemical processes remain active, surface-derived contaminants continue to significantly influence post-monsoon groundwater quality in the region.

3.3. USSL Diagram

3.3.1. USSL Diagram – Pre monsoon season (Year - 2022)

The extremely low SAR values (far less than 2) denote no sodium hazard; low SAR values (2 to 10) imply little sodium crisis; medium hazard values fall between 10 and 18; high risks fall between 18 and 26; and very high danger values fall above 26. Richards (1954), outlines four discrete tiers of salinity for irrigation water: low (EC < 250 µS/ cm), medium (250 µS/ cm–750 µS/ cm), high (750 µS/ cm–2250 µS/ cm), and very high (2250 µS/ cm–5000 µS/ cm). Alkaline soil results from increased Na concentrations in water, while saline soil is caused by increased EC concentrations in water. To ascertain the irrigation appropriateness of groundwater, one use the Sodium Absorption Ratio (SAR). An increase in the salt content present in irrigation water will facilitate the exchange of sodium ions within the soil, resulting in less permeability. Additionally, the texture of the soil will prevent it from being permeable during cultivation and hinder the sprouting of seedlings (Trivedy & Goel 1984).

The USSL Diagram analysis for the pre-monsoon season shows that seven out of nine groundwater samples fall within irrigation-suitable zones (Table 1), demonstrating varying degrees of salinity and sodium hazards. Specifically, the samples are distributed across C2-S1 (Medium Salinity–Low Sodium), C3-S1 (High

Salinity–Low Sodium), C4-S2 (Very High Salinity–Medium Sodium), and C4-S3 (Very High Salinity–High Sodium) zones. The majority of samples lie within C4-S2 and C4-S3, reflecting high to very high salinity levels and medium to high sodium hazards. These elevated levels are indicative of intensive agricultural activity, low recharge, and evaporative concentration during the dry pre-monsoon period. While some samples remain suitable for irrigation, those in the C4-S3 category may pose risks such as soil permeability reduction and sodium-induced soil degradation, particularly in clayey or poorly drained soils (Saleh *et al.*,1999).

3.3.2 USSL Diagram – Post monsoon season (Year - 2022)

In the post-monsoon season, the USSL Diagram (Figure 7) shows that eight out of twelve groundwater samples are suitable for irrigation (Table 2), with samples distributed across C2-S1 (Medium Salinity–Low Sodium), C3-S1 (High Salinity–Low Sodium), C4-S2 (Very High Salinity–Medium Sodium), and C4-S3 (Very High Salinity–High Sodium) zones. The higher proportion of samples in lower salinity zones (C2-S1 and C3-S1) indicates partial dilution and recharge from monsoonal rainfall. However, the presence of samples in C4-S3 highlights that residual salts and surface contamination continue to affect some areas. Though post-monsoon recharge improves water quality to some extent, regions with poor drainage or excessive fertilizer application retain elevated sodium and salinity levels, potentially impacting crop yield and soil health. This seasonal pattern underscores the need for site-specific irrigation planning and periodic water quality monitoring.

Table (1): Classification of Groundwater Samples based on USSL in Madurai South Taluk - Pre monsoon season (Year - 2022)

Type of Water	Total No. of Samples	Percentage of Samples	Class of Water
C2-S1	1	11.111	Medium Salinity- Low Sodium
C3-S1	2	22.222	High Salinity- Low Sodium
C4-S2	4	44.444	Very High Salinity- Medium Sodium
C4-S3	2	22.222	Very High Salinity- High Sodium

Table (2): Classification of Groundwater Samples based on USSL in Madurai South Taluk - Post monsoon season (Year - 2022)

Type of Water	Total No. of Samples	Percentage of Samples	Class of Water
C2-S1	3	25	Medium Salinity- Low Sodium
C3-S1	2	16.67	High Salinity- Low Sodium
C4-S2	3	25	Very High Salinity- Medium Sodium
C4-S3	4	33.33	Very High Salinity- High Sodium

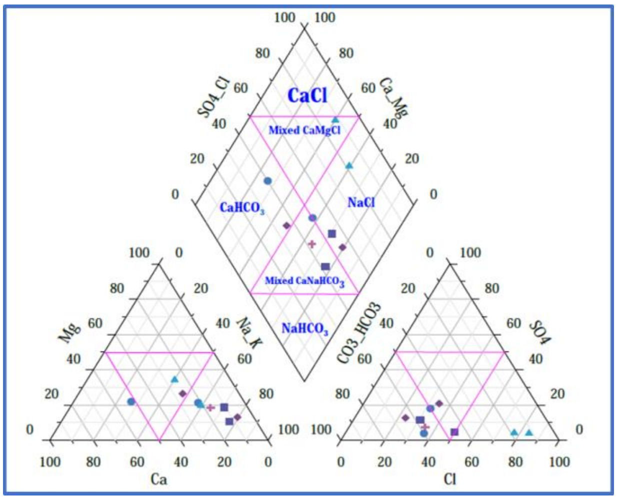

Figure (2): Pipers Trilinear Diagram – Pre monsoon season (Year - 2022)

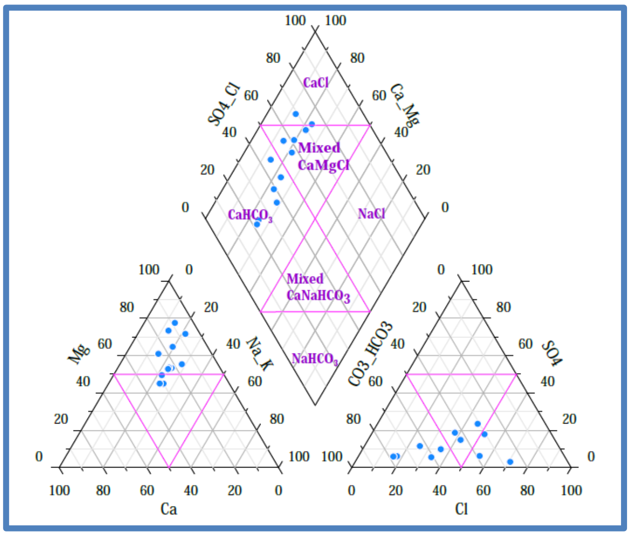

Figure (3): Pipers Trilinear Diagram – Post monsoon season (Year - 2022)

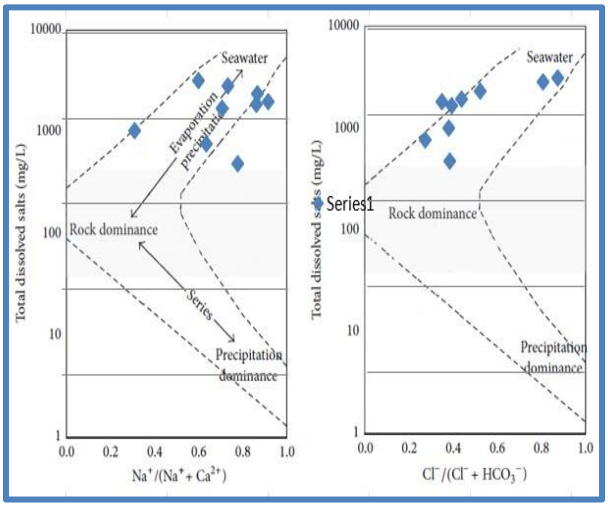

Figure (4): Gibbs Diagram – Pre monsoon season (Year - 2022)

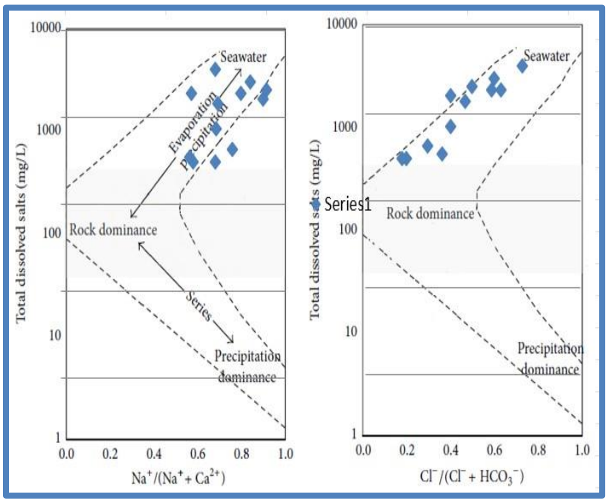

Figure (5): Gibbs Diagram – Post monsoon season (Year - 2022)

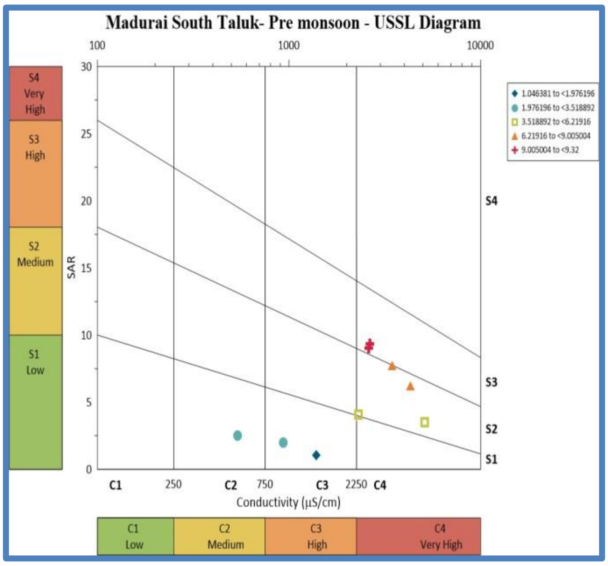

Figure (6): USSL Diagram – Pre monsoon season (Year - 2022)

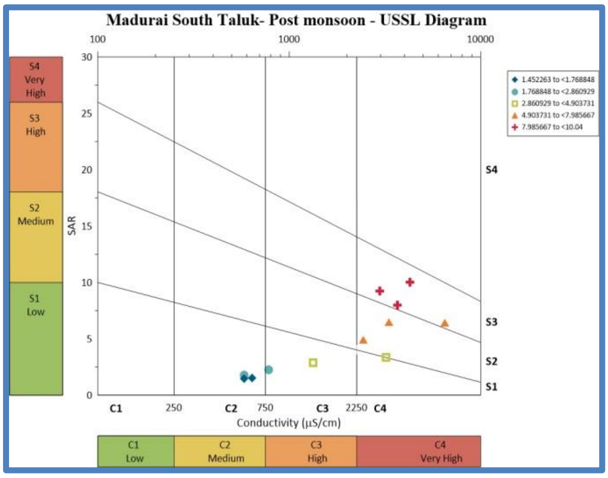

Figure (7): USSL Diagram – Post monsoon season (Year - 2022)

The statistical summary of all the groundwater quality parameters in both seasons in 2022 is given in Table (3).

3.4.Total Dissolved Solids (TDS)

Total Dissolved Solids (TDS) represent the total concentration of dissolved substances in water. TDS levels influence water's suitability for drinking and irrigation and are affected by climate, rock type, and groundwater residence time. TDS levels are often greater in arid areas (Uhl *et al*., 2008). Water that has a TDS value more than 3000 mg/L is not suitable for irrigation, according to Davis & De Weist (1966). The Bureau of Indian Standards (BIS) Drinking Water - Specification IS 10500: 2012 states that the acceptable limit of TDS in drinking water is 500 mg/L, while the Permissible limit is 2000 mg/L. (Table 4).

The average annual Total Dissolved Solids value of groundwater samples ranges from 889.8 mg/L to 1431.44 mg/L during pre-monsoon season and from 668.10 mg/L to 1536.00 mg/L during post-monsoon season in the Madurai South Taluk research region during the study years of 2008 to 2022. Most samples collected during the two monsoon seasons were found to be higher than 500 mg/L of TDS acceptable limit established by the Bureau of Indian Standards (BIS) for drinking water. This lessens the taste of the water and might lead to health problems including kidney stones and gastrointestinal distress (Colins Johnny *et al*., 2018). The high concentration value of TDS (2743 mg/L) in 2022 (Table 3) occurs in the groundwater samples in Othai Alangulam village during the pre-monsoon season shown in Box and Whisker plot (Figure 8) and 3591 mg/L at Othai Alangulam village during the post-monsoon season (Figure 8), due to the leaching of salts and household sewage. This is not suitable for irrigation and drinking as it above the BIS drinking water standards' of 2000 mg/L (Permissible limit) for TDS (Table 4) (Fetters, 1990).

Table (4): BIS and WHO Standards for Drinking Water.

Water Quality Parameter	Bureau of Indian Standard DRINKING WATER – SPECIFICATION (IS 10500 : 2012)		WHO Guidelines (2011)
	Acceptable Limit	Permissible Limit	
Total Dissolved Solids (mg/L)	500	2000	500
Total Nitrogen (NO_2+NO_3) (mg/L)	50	-	-
Calcium (mg/L)	75	200	75
Magnesium (mg/L)	30	100	50
Sodium (mg/L)	-	-	200
Potassium (mg/L)	-	-	12
Chloride (mg/L)	250	1000	250
Sulphate (mg/L)	200	400	250
Fluoride (mg/L)	1.0	1.5	1.5
pH	6.5-8.5	No relaxation	6.5-8.5
EC (micromhos/cm)	-	-	1000
Total Hardness (mg/L)	200	600	300
Carbonate (mg/L)	-	-	-
Bicarbonate (mg/L)	-	-	500

Table (3): Statistics of the groundwater quality parameters in Pre and Post-monsoon seasons in 2022.

Post-monsoon					Pre -monsoon					Water Quality Parameter
SD	Med.	Avg.	Max.	Min.	SD	Med.	Avg.	Max.	Min.	
1045.53	1533.50	1433	3591	307	837.38	1458	1431.44	2743	295	Total Dissolved Solids (mg/L)
19.26	12.50	19.17	50	1	16.57	23	19.56	52	1	Total Nitrogen (NO_2+NO_3) (mg/L)
80.24	55	91	296	24	66.02	72	92.89	224	18	Calcium (mg/L)
75.18	78.98	96.69	286.74	26.73	88.37	70.47	103.41	306.18	19.44	Magnesium (mg/L)
231.38	260.00	295.83	644	46	179.97	345	284.22	474	51	Sodium (mg/L)
16.88	7	11.83	62	2	6.32	6	7	23	3	Potassium (mg/L)
490.54	457	502.50	1773	43	503.34	383	550.22	1546	82	Chlorides (mg/L)
121.08	79.50	127	408	16	76.44	72	99.78	243	17	Sulphate (mg/L)
1.28	0	0.73	3.375075	0	0.21	0	0.07	0.6329066	0	Carbonate (mg/L)
210.32	427	430.63	768.6	172.89	205.12	335.5	410.75	725.9	134.34	Bicarbonate (mg/L)
0.31	0.67	0.68	1.41	0.28	0.31	1.12	1.08	1.43	0.55	Fluoride (mg/L)
0.41	7.7	7.67	8.2	6.8	0.41	7.6	7.5	7.9	6.5	pH
1831.94	2705	2522.50	6480	580	1519.33	2600	2585.56	5100	540	Electrical Conductivity (micromhos/cm)
494.30	540	625.42	1920	170	517.20	450	657.78	1820	125	Total Hardness (mg/L)
3.10	4.13	4.85	10.03435	1.45	3.12	4.06	5.04	9.31991	1.05	Sodium Adsorption Ratio (me/l)
0.87	0	0.25	3.004718	0	1.23	0	0.49	3.705875	0	Residual Sodium Carbonate (me/l)
11.85	42.07	46.59	67.42339	32.98	17.19	48.14	47.36	70.03661	19.66	Sodium Percentage (%)

Note: Maximam (Max.), Minimum (Min.), Median (Med.), Standard Deviation (SD), Average (Avg.)

Table (5): Bureau of Indian Standard GUIDELINES FOR THE QUALITY OF IRRIGATION WATER (IS: 11624 – 1986)

Water Quality Parameter	IS : 11624 – 1986			
	Low	Medium	High	Very High
Electrical Conductivity (micromhos/cm)	< 1500	1500 – 3000	3000 – 6000	>6000
Sodium Adsorption Ratio (SAR) (me/l)	< 10	10 – 18	18 – 26	> 26
Residual Sodium Carbonate (RSC) (me/l)	< 1.5	1.5 – 3.0	3.0 – 6.0	>6.0

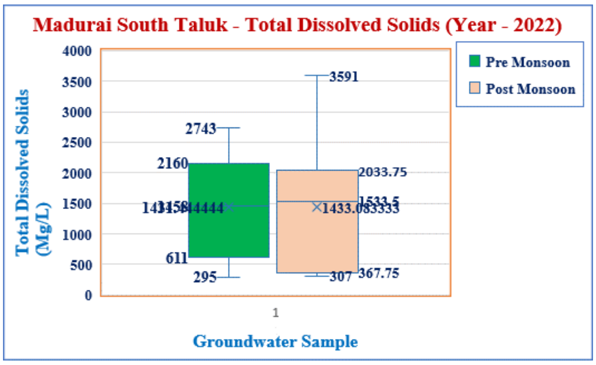

Figure (8): Madurai South Taluk – Total Dissolved Solids (Year - 2022)

3.5. Total Nitrogen ($NO_2 + NO_3$)

Nitrogen in water occurs as free ammonia, organic nitrogen, nitrites (NO_2), and nitrates (NO_3). Its presence indicates organic matter. Free ammonia signals early decomposition, while organic nitrogen exists before decomposition begins. Nitrites are harmful and should be absent in drinking water, where as nitrates, being fully oxidized, are generally safe. Different processes, including soil mineralization, organic material oxidation, irrigation practises, urban pollution, etc., are the sources of nitrate (Jeong 2001; Subba Rao 2002). Manure applied to land, agricultural fertiliser (Chettri & Smith, 1995), industrial effluent, home wastewater, septic systems, human waste lagoons, animal feedlots, native soil organic matter, and geologic sources are some potential causes of nitrate pollution (Helmut, 2000). The high levels of nitrate in drinking water are harmful and may result in diabetes, thyroid problems, stomach cancer, and blue baby illness (methemoglobinemia) in children (Krishna Kumar et al., 2011; Kumar et al., 2014). This illness may cause vomiting in children, darkening of the skin, and in severe instances, death. The acceptable limit of total nitrogen in drinking water, as per IS 10500: 2012, is 50 mg/L. (Table 4).

For the study periods of 2008 to 2022 in the study area of Madurai South Taluk, it is observed that the average annual Total Nitrogen concentration in groundwater samples ranges between 4.13 mg/L and 68.8 mg/L during pre monsoon season and it varies from 6.50 mg/L to 19.17 mg/L during post monsoon season. This confirms the Total Nitrogen concentration of the study area is good to moderate for drinking and irrigation during pre monsoon season and good for drinking and irrigation during post monsoon season in Madurai South Taluk. The primary sources of nitrate in groundwater in the research region include agricultural manure, fertiliser (mostly urea), irrigation return flow, septic tank effluents, and penetration of household waste water (Nagarajan *et al.*, 2010). The leaching of salts and household sewage is responsible for the high concentration of total nitrogen (52 mg/L) in the groundwater samples at Nedunkulam during the pre-monsoon season (Box and Whisker plot, Figure 9) and 50 mg/L in Nilaiyur village during the post-monsoon season (Figure 9), for the year 2022.

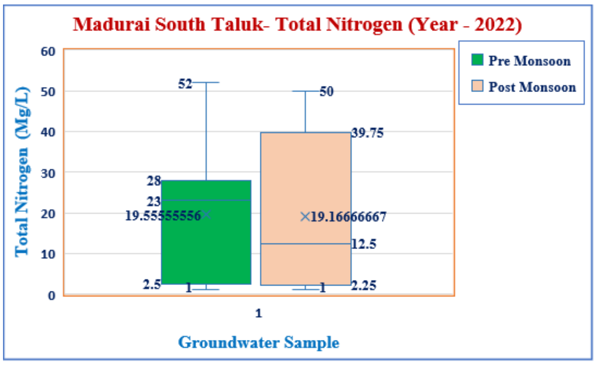

Figure (9): Madurai South Taluk – Total Nitrogen (Year - 2022).

3.6. Calcium (Ca)

When the body is exposed to acidic food, soft drinks, or sugar, it seeks to restore its pH, which results in calcium leaching from the bones. Because it promotes encrustation and scaling, the increased concentration of calcium ions is unsuitable for domestic usage and might induce stomach issues (Kumar *et al.*, 2014). The lower calcium content results in tooth decay, brittle and weak nails, and osteoporosis in human bone (Colins Johnny *et al.*, 2018). According to IS 10500: 2012, the permissible limit of calcium in drinking water is 200 mg/L, whereas the acceptable limit is 75 mg/L. (Table. 4).

For the study periods of 2008 to 2022 in the study area of Madurai South Taluk, it is observed that the average annual Calcium value of groundwater samples varies from 33.20 mg/L to 94.00 mg/L and from 54.80 mg/L to 95.20 mg/L for pre and post monsoon seasons, respectively. This indicates that the calcium content in groundwater samples is good for drinking and irrigation during both pre and post monsoon seasons. Due to the leaching of carbonate minerals including dolomite and calcite, Othai Alankulam village has high concentration values of Ca (224 mg/L) during the pre-monsoon season (Box and Whisker plot, Figure 10) and 296 mg/L during the post-monsoon season (Figure 10) in 2022 (Table 3) (Magesh *et al*., 2012).

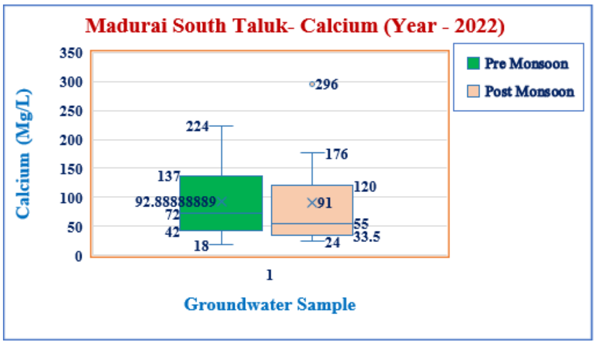

Figure (10): Madurai South Taluk - Calcium (Year - 2022)

3.7. Magnesium (Mg)

The eighth most common element in nature is magnesium. It is often found in minerals including magnesite, dolomite, olivine, serpentine, talc, and asbestos. It comprises 2.5 percent of the earth's crust. It is a primary cause of water hardness and may be found in all natural waters. Dolomite and silicate mineral dissolution may be the source of magnesium in groundwater (Hem, 1985). Increased magnesium levels in drinking water leads to sulphate laxative side effects, diarrhea, poor lathering, and deterioration of clothing. Due to a buildup, the higher magnesium content in drinking water may quickly damage household equipment (scaling). According to IS 10500: 2012, the permissible limit for magnesium in drinking water is 100 mg/L, and the acceptable limit is 30 mg/L. (Table. 4).

For the study periods of 2008 to 2022 in the Madurai South Taluk study area, it is observed that the average annual magnesium content of groundwater samples varies between 40.40 mg/L and 103.41 mg/L and from 38.76 mg/L to 107.00 mg/L for pre and post monsoon seasons, respectively. It attests to the good to moderate analytical findings of the research area's samples, making them appropriate for irrigation and drinking in both the pre- and post-monsoon seasons. The dissolution of magnesium-bearing minerals is the cause of the higher concentration of magnesium (306.18 mg/L) at Othai Alankulam village during the recent year (2022) shown in Box and Whisker plot (Figure. 11) for pre monsoon season and 286.74 mg/L at Othai Alankulam village during post monsoon season shown in Figure. 11 (Table. 3) (Colins Johnny *et al*., 2018).

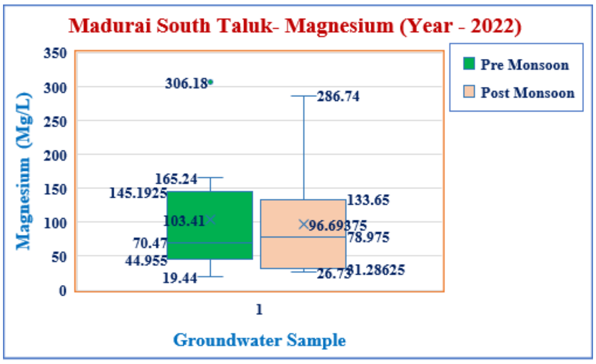

Figure (11): Madurai South Taluk - Magnesium (Year - 2022)

3.8. Sodium (Na)

Sodium is the important element for plants and animals though it is required to maintain the metabolic activities. Sodium is abundance among the elements present in most natural waters. High sodium introduces sodicity and makes the soil unproductivity. Groundwater with high Na content is not suitable for agricultural purpose and also causes increased blood pressure in humans (Sarath Prasanth *et al*., 2012). Sodium concentration of more than 50 mg/L, make the water unsuitable for domestic use (Nagarajan *et al*., 2010). A low concentration of sodium can lead to symptoms such as fatigue, muscle cramps, vomiting, headaches, and other related issues. The permissible value of Sodium in drinking water as per WHO standards is 200 mg/L (Table. 4).

It is observed that the average annual Sodium value of groundwater samples varies from 187.80 mg/L to 312.00 mg/L and from 138.10 mg/L to 322.20 mg/L during pre and post monsoon seasons respectively for the study period of 2008 to 2022 in the study area of Madurai south Taluk. It confirms that the analytical results of all the samples of the study area varies from good to poor and unsuitable for drinking and irrigation purposes in both pre and post monsoon seasons at few places. In 2022 (Table 3), the high concentration value of Na (474 mg/L) occurs at Nedunkulam village shown in Box and Whisker plot (Figure 12) for pre monsoon season and 644 mg/L at Othai Alankulam and Melakuilkudi villages during post monsoon season shown in Figure 12, is due to overuse of fertilisers in the agricultural land (Venkatramanan *et al*. 2016).

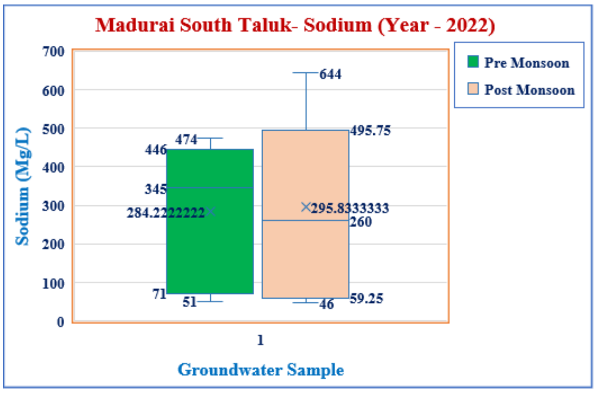

Figure (12): Madurai South Taluk – Sodium (Year - 2022)

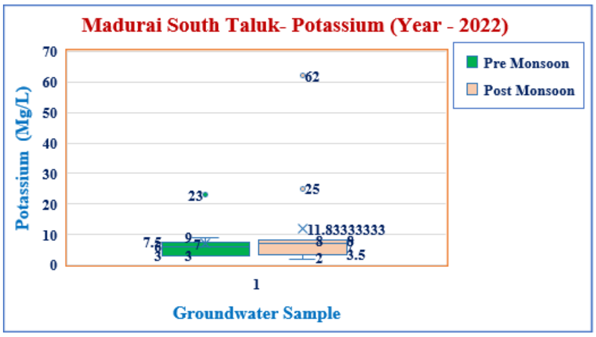

Figure (13): Madurai South Taluk - Potassium (Year - 2022)

3.9.Potassium (K)

Potassium is another less abundant cation in natural waters due to rocks containing potassium ions being relatively resistant to weathering (Hem, 1985). Potassium in groundwater reduces the geochemical mobility of other elements (Srinivasamoorthy *et al.*, 2011). Where potassium-containing rock is present, such as in certain granites and standstones, the concentration of potassium in the groundwater will be greater. Higher concentrations of potassium are found in groundwater as a result of domestic waste discharge and fertiliser application in agricultural areas (Saha *et al.*, 2019). Very low concentrations are caused by potassium that is retained with aquifer material, particularly in clay formation (Sarin *et al.*, 1989). Elevated potassium levels in drinking water can contribute to health issues such as renal failure, heart disease, coronary artery disease, hypertension, diabetes, adrenal insufficiency, and existing hyperkalemia. According to the World Health Organization (WHO) guidelines, the permissible limit for potassium in drinking water is 12 mg/L (Table 4).

For the study period of 2008 to 2022 in the study region of Madurai south Taluk, it is found that the average annual Potassium value of groundwater samples fluctuates from 4.00 mg/L to 21.13 mg/L and from 5.00 mg/L to 16.20 mg/L for pre and post monsoon seasons, respectively. It validates that, in certain locations, the analytical findings of all the samples in the research region range from good to poor and are unfit for drinking and irrigation purposes during the pre- and post-monsoon seasons at few places. Due to excessive fertiliser use on agricultural land, in 2022 (Table 3), the high concentration value of potassium (23 mg/L) in the groundwater sample occurs at Melamathur village during the pre-monsoon season, shown in the Box and Whisker plot (Figure 13), and at Nilaiyur village during the post-monsoon season, shown in Figure 13 (Venkatramanan *et al*. 2016).

3.10.Chloride (Cl)

Chloride in water, mainly from sodium chloride (common salt), can result from marine deposits, seawater intrusion, brine, or domestic and industrial waste. Levels above 250 mg/L give water a salty taste and may indicate septic system contamination. Groundwater has significant concentrations of chlorides due to agricultural and domestic wastewater (Selvam *et al*., 2013). The majority of the groundwater samples had higher chloride content values, which suggests that the research region had significant salinity (Saha *et al*., 2019). Excess chloride increases the risk of high blood pressure, diarrhoea, asthma, diabetic coma, and other conditions. The acceptable limit of chlorides in drinking water is 250 mg/L, and the permissible limit is 1000 mg/L, according to IS 10500: 2012. (Table 4).

For the study years of 2008 to 2022 in the Madurai South Taluk study region, it is noticed that the average annual Chloride value of groundwater samples fluctuates from 256.80 mg/L to 550.22 mg/L and from 159.90 mg/L to 525.00 mg/L for pre and post monsoon seasons, respectively. Higher concentrations of chloride (1546 mg/L) in the groundwater sample were found at Othai Alankulam village in the recent year 2022 (Table 3), as shown in Box and Whisker plot (Figure 14) for the pre-monsoon season and 1773 mg/L at Othai Alankulam village during the post-monsoon season (Figure 14). These concentrations are caused by surface contamination sources, which include domestic wastewater activities like septic tank leakage (Bhatia, 2003) and rainfall, as well as agricultural activities like fertilisers and farm manure and irrigation return flow (Arefegn Arota *et al*., 2022).

3.11.Sulphate (SO_4)

Sulphate in water, typically from natural deposits, waste, or sewage, can cause laxative effects, corrosion, and a medicinal taste when exceeding 250 mg/L. High levels may also lead to odor and scaling issues. Exceeding the sulphate limit might irritate the gastrointestinal tract and have a greater degree of laxative action (WHO, 1993). The permissible limit of sulphates in drinking water is 400 mg/L, whereas the acceptable limit is 200 mg/L, according to IS 10500: 2012. (Table 4).

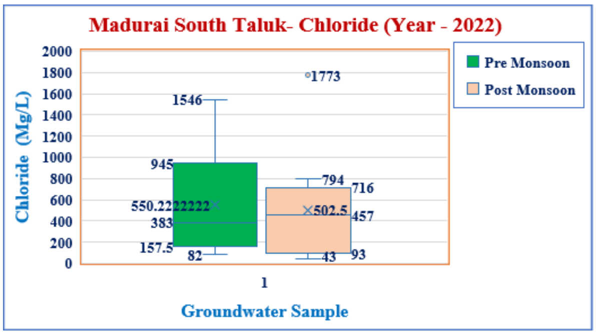

Figure (14): Madurai South Taluk - Chloride (Year - 2022)

For the study years of 2008 to 2022 in the study region of Madurai South Taluk, it is noticed that the average annual Sulphate value of groundwater samples changes from 45.20 mg/L to 137.00 mg/L and from 40.40 mg/L to 216.00 mg/L for pre and post monsoon seasons, respectively. It validates that all of the research area's sample analytical findings are satisfactory and suitable for irrigation and drinking throughout the pre and post-monsoon seasons. The precipitate that was produced as a consequence of the sulphate reaction is the cause of the low sulphate content. In 2022 (Table 3), applying gypsum (fertilisers) in the irrigation field causes sulphate content in groundwater through irrigation return flow and certain igneous rock minerals of the feldspathoid group and sulphide mineral bearing rocks. This results in a high concentration of sulphate (243 mg/L) in the groundwater sample at Melakuilkudi village during pre monsoon season, as shown in Box and Whisker plot (Figure 15), and 408 mg/L at Melakuilkudi village during post monsoon season (Figure 15) (Arefegn Arota *et al*., 2022).

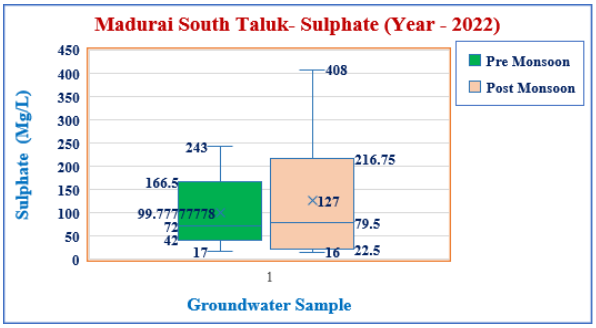

Figure (15): Madurai South Taluk – Sulphate (Year - 2022)

3.12.Carbonates (CO_3)

Water hardness is caused by calcium and magnesium salts, which reduce soap lathering. Temporary (carbonate) hardness arises from their bicarbonates and can be removed by boiling or adding lime, which precipitates calcium carbonate and releases CO_2 Less than 120 mg/L of bicarbonate and less than 15 mg/L of carbonate may react with the calcium and magnesium in soil components to generate insoluble lime like $MgCO_3$ and $CaCO_3$ (Kuttymani *et al*. 2017).

For the study years of 2008 to 2022 in the Madurai South Taluk study region, it is noticed that the average annual Carbonate value of groundwater samples fluctuates from 0.00 mg/L to 9.60 mg/L and from 0.00 mg/L to 4.09 mg/L for pre and post monsoon seasons, respectively. It validates that all of the research area's sample analytical findings are good and suitable for irrigation and drinking throughout the pre and post-monsoon seasons. The groundwater sample in Vilachery village during the pre-monsoon season (Box and Whisker plot, Figure 16) and Kochadai village during the post-monsoon season (Figure 16) in 2022 (Table 3) has a higher concentration of carbonate values of 0.6329066 mg/L and 3.375075 mg/L respectively. The variation in carbonate minerals can be explained by three factors: 1) differences in the occurrence of carbonate minerals, 2) external sources of calcium, magnesium, and alkalinity that enter the groundwater system during recharge, and 3) the infiltration of wastewater from surface contamination sources (Nagarajan *et al*., 2010).

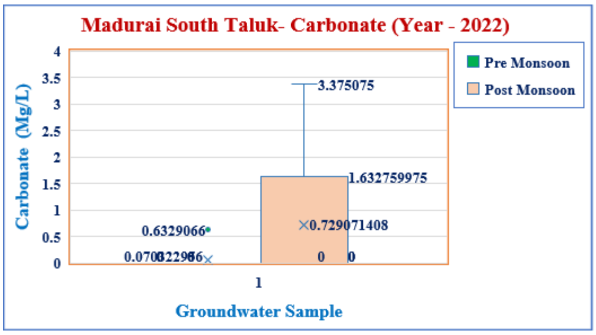

Figure (16): Madurai South Taluk - Carbonate (Year - 2022)

3.13.Bicarbonates (HCO_3)

Bicarbonate is essential in the human body and may help prevent dental plaque and cavities. High levels are common in water with pH ≥ 7.5 and often result from oxidation of organic matter, which produces CO_2 and dissolves minerals in groundwater. Bicarbonate, along with cations such as Ca^{2+} and Mg^{2+}, can also originate from the weathering of silicate minerals (Gastmans *et al*., 2010). According to the WHO guidelines (2011), the permissible limit of bicarbonate in drinking water is 500 mg/L (Table 4).

For the study years of 2008 to 2022 in the Madurai South Taluk study region, it is noted that the average annual bicarbonate values vary from 330.13 mg/L to 577.54 mg/L and from 319.87 mg/L to 538.02 mg/L for pre and post monsoon seasons, respectively. It validates the analytical findings of almost all average annual bicarbonate levels of the research area's samples, which are acceptable and suitable for irrigation and drinking throughout the pre- and post-monsoon seasons. The high concentration of bicarbonate (725.9 mg/L) in the groundwater sample in 2022 (Table 3) at Thiruparankundram (Latitude: 9°52'54") village during the pre-monsoon season (Box and Whisker plot, Figure 17) and 768.60 mg/L at Thiruparankundram (Latitude: 9°52'54") village during the post-monsoon season (Figure 17) is due to the biodegradation of organic matter and wastewater from septic tanks, landfills, and domestic and industrial sewage.

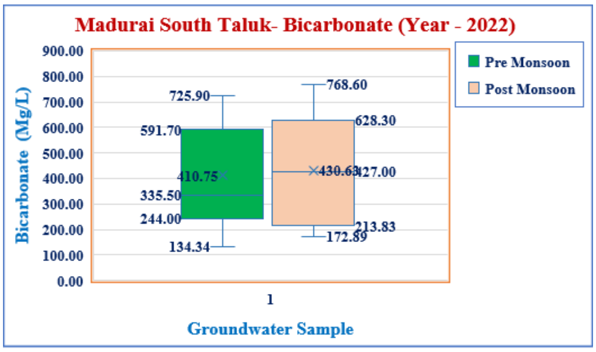

Figure (17): Madurai South Taluk - Bicarbonate (Year - 2022)

3.14 Fluoride (F)

Fluoride in water comes from the natural breakdown of rocks and minerals. Low levels help prevent tooth decay, but levels above 1.5 ppm can cause dental fluorosis (tooth staining) and, with prolonged exposure, skeletal fluorosis (bone deformities). The source of the groundwater enrichment in the studied region is the breakdown of granite rocks containing fluoride (Kalpana *et al*. 2019). The permissible level of fluorides in drinking water is 1.5 mg/L, whereas the acceptable limit is 1.0 mg/L, according to IS 10500: 2012. (Table 4).

The average annual fluoride value of groundwater samples in Madurai South Taluk from 2008 to 2022 ranged from 0.37 mg/L to 1.16 mg/L and 0.53 mg/L to 1.12 mg/L for pre and post monsoon seasons, respectively. It verifies the excellent analytical findings for the fluoride concentration found in all of the study area's samples, indicating that the water is safe to drink and use for irrigation both before and after the monsoon season since it is not in touch with fluoride-containing minerals (Krishnakumar *et al.*, 2011). Figure 18 shows a Box and Whisker plot. It shows that the high level of fluoride (1.43 mg/L) in the groundwater sample taken in 2022 at Thiruparankundram village (Latitude: 9°52'54") before the monsoon season is because granite rocks in the study area are breaking down and releasing fluoride (Table 3). This level also hit 1.41 mg/L at Thiruparankundram village (Latitude: 9°52'54") after the monsoon season (Figure 18).

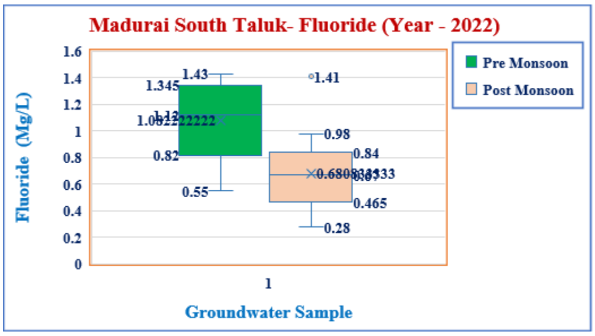

Figure (18): Madurai South Taluk - Fluoride (Year - 2022)

3.15.pH

pH indicates the acidity or alkalinity of water, with 7 being neutral. pH < 7 is acidic, pH > 7 is alkaline. Water with pH < 4 tastes sour and may cause corrosion and health issues; pH > 8.5 tastes bitter and can lead to deposits and irritation. Alkalinity arises from bicarbonates, carbonates, or hydroxides of calcium, magnesium, sodium, and potassium. According to IS 10500:2012, the acceptable pH range for drinking water is 6.5 to 8.5. (Table 4).

The average annual pH value of groundwater samples in the Madurai South Taluk study area from 2008 to 2022 is observed to vary between 7.50 and 8.18 and 7.60 and 8.23 for pre- and post-monsoon seasons, respectively. This indicates that the groundwater in the study area is alkaline in nature, indicating some degree of water-rock interaction within the aquifer materials (Magdy & Abdullah, 2021). Table 3 for 2022 shows that the high pH (7.9) concentration in the groundwater sample occurs at Eliyarpatti village during the pre-monsoon season (Box and Whisker plot, Figure 19) and 8.2 at Vilachery and Kochadai villages during the post-monsoon season (Figure 19). This indicates that the water's composition may result from the dissolution of carbonates, primarily in the form of HCO_3 (Adams *et al*., 2001).

3.16 Electrical Conductivity (EC)

Electrical Conductivity (EC) measures water's ability to conduct electricity and reflects the total concentration of dissolved salts. It is influenced by temperature, ionic concentration, and types of ions present. Ballukraya & Ravi (1999) speculate that the area's preexisting lithology and long residence times might be the cause of the higher EC values. Saline soil is created when water has a high EC (Nagarajan *et al.*, 2010). The Bureau of Indian Standard Guidelines for the Quality of Irrigation Water (IS:11624 – 1986) divides irrigation water's electrical conductivity into four groups: Low: < 1500 micromhos/cm, Medium: 1500–3000, High: 3000–6000 and Very High: > 6000. (Table. 5). Agriculture will be impacted by higher electrical conductivity values.

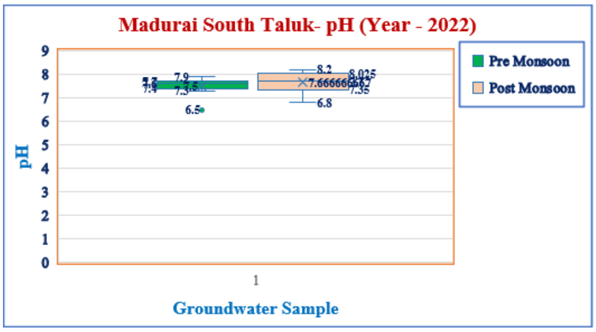

Figure (19): Madurai South Taluk- pH (Year -2022)

The study area in Madurai South Taluk was looked at from 2008 to 2022. The average annual Electrical conductivity of groundwater samples ranged from 1570.00 micromhos/cm to 2585.56 micromhos/cm and from 294.09 micromhos/cm to 2610.00 micromhos/cm before and after the monsoon season. This shows that the study area has low to medium electrical conductivity and is good for drinking and farming. A wide range of EC values suggests that the hydrochemistry of the groundwater in the studied area is caused by many different hydrochemical processes, such as water-rock interaction, cyclic salting, and agricultural activities (Magdy El Maghraby; Abdullah O. Bamousa, 2021). In 2022, Table 3 shows that the high concentration of EC (5100 micromhos/cm) in groundwater at Othai Alankulam village during the pre-monsoon season (Figure 20) and the high concentration of EC (6480 micromhos/cm) during the post-monsoon season (Figure 20) happened due to dissolution of salts.

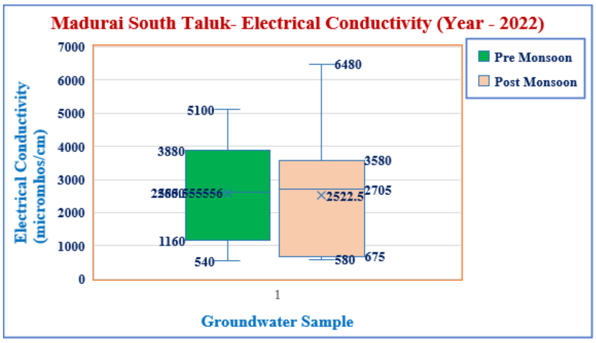

Figure (20): Madurai South Taluk - Electrical Conductivity (Year - 2022)

3.17.Total Hardness

The total hardness is determined by adding the amounts of calcium and magnesium, which are both measured in milli grams per litre of calcium carbonate (Garima Patel *et al.*, 2020). A key factor in assessing whether water is suitable for drinking, domestic, and many industrial applications is its hardness. Four categories were established by Sawyer & McCarty (1967) to categorise groundwater total hardness: soft (TH < 75 mg/L), moderately hard (75-150 mg/L), hard (150-300 mg/L), and very hard (>300 mg/L). The permissible limit for total hardness in drinking water is 600 mg/L, whereas the acceptable limit is 200 mg/L, according to IS 10500: 2012. (Table. 4).

It is observed that the average annual Total Hardness value of groundwater samples varies from 315.00 mg/L to 657.78 mg/L and from 297.00 mg/L to 660.00 mg/L for pre and post monsoon seasons respectively for the study periods of 2008 to 2022 in the study area of Madurai South Taluk. The analytical results indicate that the water in the study area is good to poor and unsuitable for drinking and irrigation purposes during pre and post monsoon seasons at few places and this total hardness of groundwater samples is due to the presence of alkaline earths such as calcium and magnesium (Sarath Prasanth *et al.*, 2012). In 2022 (Table. 3), the high concentration of total hardness (1820 mg/L) in the groundwater sample occurs at Othai Alankulam village during pre monsoon season shown in Box and Whisker plot (Figure 21) and 1920 mg/L at Othai Alankulam village during post monsoon season shown in Figure 21 is due to the presence of alkaline earths such as calcium and magnesium salts.

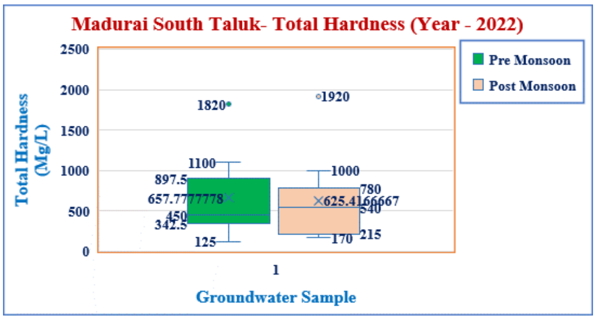

Figure (21): Madurai South Taluk - Total Hardness (Year - 2022)

3.18.Sodium Adsorption Ratio (SAR)

Alkaline soil is caused by water with a high salt concentration. High salt irrigation water will enhance the soil's exchange of sodium, affecting the permeability and creating a texture that is difficult to plough and unsuited for seedling emergence (Trivedy

& Goel, 1984). Table 5 displays the four categories in which the Sodium Adsorption Ratio of a water sample is classified: Low (SAR < 10 me/l), Medium (10-18 me/l), High (18 – 26 me/l), and Very High (above 26 me/l) in accordance with IS: 11624 – 1986 (Indian Standard Guidelines for the Quality of Irrigation Water). Clayey soils may shrink and swell as a result of irrigation water causing permeability issues if the Sodium Adsorption Ratio value is higher than 10 to 18. (Saleh *et al.*, 1999).

For the study periods of 2008 to 2022 in the Madurai South Taluk study area, it is observed that the average annual Sodium Adsorption Ratio value of groundwater samples varies from 0.00 me/l to 7.49 me/l and from 0.91 me/l to 6.59 me/l for pre and post monsoon seasons, respectively. Both seasons' SAR values fell into the low category (<10 me/l), making them suitable for irrigation. In 2022 (Table. 3), the groundwater sample from Melakuilkudi village during the pre-monsoon season shows a high concentration of SAR (9.319910 me/l), as shown in the Box and Whisker plot (Figure 22). During the post-monsoon season, Melakuilkudi village shows a concentration of 10.03435 me/l, which falls into the good category due to its low sodium content, making it suitable for irrigation water usage (Figure 22) (Deshpande & Aher, 2012).

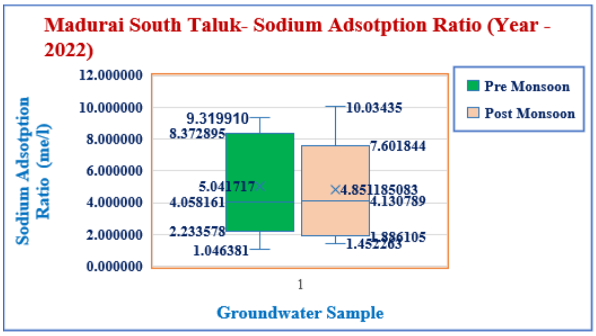

Figure (22): Madurai South Taluk - Sodium Adsorption Ratio (Year - 2022)

3.19.Residual Sodium Carbonate (RSC)

Residual Sodium Carbonate (RSC) assesses the impact of carbonate and bicarbonate on irrigation water quality. When CO_3^{2-} and HCO_3^- exceed Ca^{2+} and Mg^{2+}, it can cause soil compaction, reduced permeability, and crop damage. RSC helps determine water's alkalinity hazard and suitability for irrigation (Eaton, 1950). Based on IS: 11624 – 1986, there are four classifications for the residual sodium carbonate of water sample: low (RSC < 1.5 me/l), medium (1.5 – 3.0 me/l), high (3.0 – 6.0 me/l), and very high (above 6.0 me/l). These classifications are shown in Table 5.

For the study periods of 2008 to 2022 in the study area of Madurai South Taluk, it is observed that the average annual Residual Sodium Carbonate value of groundwater samples varies from 0.00 me/l to 2.68 me/l and from 0.00 me/l to 1.82 me/l for pre and post monsoon seasons, respectively. This indicates the safety of water for irrigation (Eaton, 1950). Both seasons' residual sodium carbonate levels fell between low and medium, making them suitable for irrigation (Lloyd & Heathcote, 1985). The results show that RSC values vary, rising during the pre-monsoon period due to drying effects, and falling during the post-monsoon period due to recharge from rainfall. In 2022 (Table 3), the high concentration of RSC (3.705875 me/l) in the groundwater sample occurs at Thiruparankundram (Latitude: 9°52'54") village during pre-monsoon season shown in Box and Whisker plot (Figure 23) and 3.004718 me/l at Thiruparankundram (Latitude: 9°52'54") village during post-monsoon season shown in Figure 23.

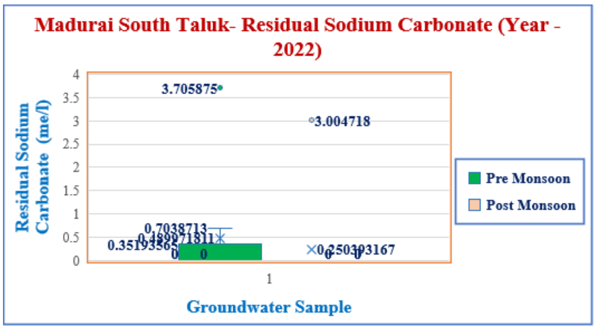

Figure (23): Madurai South Taluk - Residual Sodium Carbonate (Year - 2022)

3.20.Sodium Percentage (Na %)

The percentage of Na content is a widely used metric to evaluate groundwater's appropriateness for agricultural use (Wilcox, 1948). Alkaline soils are produced when Na and CO_3 are combined, while saline soils are created when Na and Cl are combined. Neither of the soils is good for growing plants (Nagarajan *et al.*, 2010). For agricultural purposes, groundwater may contain up to 60% Na (Ramakrishna, 1998). Three categories are used to categorise the sodium percentage of water samples: good (Na percent < 60 percent), moderate (60-75 percent), and very poor (greater than 75 percent).

For the study periods of 2008 to 2022 in the study area of Madurai South Taluk, it is observed that the average annual Sodium Percentage value of groundwater samples varies from 40.66 percent to 61.14 percent and from 37.40 percent to 58.24 percent for pre and post monsoon seasons, respectively. It shows that the sodium percentage found in all of the study area's groundwater samples from both seasons falls into the Good (Na percent < 60%) category and is suitable for irrigation. According to Table 3 for 2022, the groundwater sample from Melakuilkudi village during the pre-monsoon season has a high concentration of Na percent (70.03661 percent), as shown in the Box and Whisker plot (Figure 24). Thiruparankundram village (Latitude: 9˚52'54") has a high concentration of Na percent (67.42339 percent), as shown in Figure 24. These concentrations are suitable for irrigation, but not for all types of soils.

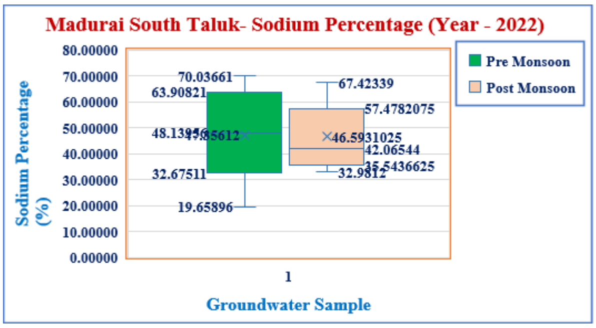

Figure (24): Madurai South Taluk – Sodium Percentage (Year - 2022)

4.Conclusion

This study provides a comprehensive hydrogeochemical evaluation and groundwater quality assessment of Madurai South Taluk, highlighting seasonal variations and the impact of both geogenic and anthropogenic factors. The analysis of key parameters such as TDS, pH, EC, major ions, and indices like SAR, RSC, and Na% revealed that while most samples fall within acceptable limits for drinking and irrigation, localized exceedances particularly in sodium, salinity, and nitrate levels pose concerns. Piper, Gibbs, and USSL diagrams further clarified the geochemical facies, dominant processes, and irrigation suitability. Seasonal trends suggest pre-monsoon water is more influenced by evaporation and anthropogenic inputs, whereas post-monsoon samples show dilution and enhanced rock-water interaction.

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