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Groundwater Quality Assessment in Madurai North Taluk: Seasonal Variations and Impacts on Drinking and Irrigation Water

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Abstract: Groundwater has been the primary source for drinking and irrigation in Madurai North Taluk for several decades. This study evaluates its quality over a 15-year period (2008–2022) to determine its suitability for these purposes. Groundwater samples were collected from 22 locations during both pre-monsoon and post-monsoon seasons. The Water Quality Index (WQI) analysis indicates that groundwater quality ranges from poor to unsuitable for drinking, with significant seasonal variations. Elevated levels of Electrical Conductivity (EC), chloride, sodium, and calcium in both seasons suggest progressive water quality deterioration, primarily due to rock-water interactions involving gypsum and salt-bearing formations. For irrigation suitability, key parameters such as Kelly's Ratio (KR), Magnesium Hazard (MH), Potential Salinity (PS), Permeability Index (PI), and Corrosivity Ratio (CR) were assessed. The findings indicate that most groundwater samples are unsuitable for irrigation due to high salinity, increased magnesium content, and low permeability. Post-monsoon samples generally exhibited improved quality for both drinking and irrigation compared to pre-monsoon samples. Hydrochemical analysis, including the Durov diagram, identified ion exchange and mineral dissolution as dominant processes affecting groundwater composition. Statistical correlation analysis over the study period revealed strong positive relationships among salinity indicators such as chloride, sodium, sulphate, and EC, indicating a common source of contamination.

Keywords: Water Quality Index, Magnesium Hazard, Kelly's Ratio, Potential Salinity, Permeability Index, Corrosivity Ratio, Hydrochemical Analysis.

1.Introduction

Water is one of the most vital and valuable natural resources on Earth, serving as a fundamental necessity for life and a key determinant of community well-being. Groundwater, in particular, plays a crucial role in fulfilling water demands both in India and globally. It is a primary source of drinking water for nearly one-third of the world's population (Nickson *et al.,* 2005). In India, approximately 85% of the rural population depends on groundwater, and nearly 65% of irrigated agricultural land relies on it (Raju, 1998). Beyond domestic and drinking purposes, groundwater is essential for sustaining agricultural productivity and driving industrial development (Ehab *et al.,* 2019).

Climate change has profoundly affected groundwater resources by altering rainfall patterns, temperature fluctuations, and soil moisture levels (Raju *et al.,* 2011; Raju *et al.,* 2014; Toumi *et al.,* 2015). These disruptions have intensified water shortages and accelerated the depletion and degradation of groundwater sources

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worldwide. The intricate relationship between groundwater quality and environmental factors is evident in how solutes, soil gases, and geological interactions shape its chemical composition. Groundwater chemistry is primarily influenced by the mineral content of aquifers and the hydrogeochemical processes occurring as water moves through subsurface environments (Hwang *et al*., 2017). In India, rapid urbanization and industrial expansion have placed immense pressure on groundwater availability and quality (Singh, 2002). Despite being widely perceived as a pollution-free resource, groundwater is increasingly threatened by contamination from human activities (Iqbal & Gupta, 2009). Agricultural runoff, industrial effluents, and inadequate waste disposal have severely compromised groundwater quality, making it unfit for consumption in many areas. Studies indicate that water pollution accounts for 80% of human diseases and 30% of infant mortality in India (Singh & Parwana, 1992).

Groundwater quality is shaped by both natural processes and human activities. Natural influences include atmospheric precipitation, rock-water interactions, and geological formations, while human-induced factors stem from industrial waste, agricultural runoff, and urban effluents (Arnade, 1999; Hem, 1991). Contaminants such as nitrates from fertilizers, heavy metals, and pesticides have become prevalent due to intensive farming practices and inadequate waste management (Hubbard & Sheridan, 1994; Postma *et al*., 1991). Additionally, the dissolution of minerals from rocks can introduce undesirable elements into groundwater, impacting its suitability for various uses (Johnson, 1979; Sastri, 1994).

In India, groundwater quality is classified based on electrical conductivity (EC), with categories including saline (EC > 6.0 µmho/cm), marginal (EC 2.0–6.0 µmho/cm), and fresh (EC ≤ 2.0 µmho/cm) (Walton, 1970). Monitoring these parameters provides valuable insights into the geochemical history of rocks, groundwater recharge, and flow dynamics. Research has emphasized the significance of hydrogeochemical assessments in understanding regional water quality variations (Madhav *et al*., 2018; Nagaraju *et al*., 2016). As groundwater is extensively used for irrigation, it remains the primary water source for agriculture in India, supporting nearly 65% of cultivated land (Foster & Garduño, 2013; Raju, 1998). However, poor groundwater quality can negatively impact both crop productivity and human health (US Salinity Laboratory Staff, 1954). Therefore, evaluating physicochemical parameters is crucial in determining water quality and its suitability for drinking and agricultural applications (Aher & Deshpande, 2014; Purushotham *et al*., 2011).

Numerous studies have examined groundwater quality concerning drinking and irrigation standards in different parts of India (Agarwal & Jagetia, 1997; Dasgupta & Purohit, 2001; Durvey *et al*., 1997; Khurshid *et al*., 2002; Majumdar & Gupta, 2000; Niranjan Babu *et al*., 1997; Subba Rao *et al*., 1999). These studies have employed various hydrochemical indices, such as Kelly's Ratio (KR), Magnesium Hazard (MH), Permeability Index (PI), and Sodium Adsorption Ratio (SAR), to assess water suitability for agricultural and domestic uses (Bauder *et al*., 2011; Wagh *et al*., 2018). With rising concerns over groundwater contamination, regular monitoring and maintenance of groundwater quality are essential for sustainable resource management and public health protection. Studies have shown that both geogenic and anthropogenic factors play a significant role in determining groundwater quality, highlighting the need for continuous assessment (Aher & Dhumal, 2017; Srinivasmoorthy *et al*., 2011). Identifying key ionic contributors and analyzing ion interactions can aid in developing effective groundwater management strategies.

This study aims to evaluate groundwater quality concerning its suitability for drinking and agricultural use. Hydrogeochemical models and indices, including Na%, RSC, PI, MH, and PS, have been applied to assess water quality. Furthermore, the research explores the impact of natural and human-induced factors on groundwater chemistry, providing valuable insights for sustainable resource development and management in the study area.

2.Materials and methods

2.1.Materials

The study area, Madurai North Taluk, was delineated using topographic sheets from the Survey of India and digitally processed with ArcGIS 10.2 software (Figure 1). Groundwater samples were collected from 22 locations, including bore and open wells, during both the pre-monsoon (first week of July) and post-monsoon (first week of January) seasons from 2008 to 2022. The exact coordinates of each sampling station were recorded by the Water Resources Department (WRD) using a handheld GPS device. The test results for the collected samples, covering the study period from 2008 to 2022, were obtained from the Chief Engineer, WRD, State Ground and Surface Water Resources Data Centre, Taramani, Chennai.

2.2. Methodology

The physical parameters (pH, EC, and TDS) and chemical parameters (NO_2 + NO_3), Na, K, Cl, SO_4, CO_3, HCO_3, F, TH, Ca, and Mg were measured according to the APHA (1995) guidelines. The methods used for groundwater analysis in Madurai north taluk is shown in Figure 2.

2.3.Groundwater Quality Analysis for Drinking

2.3.1.Water Quality Index (WQI)

The Water Quality Index (WQI) serves as an essential tool for assessing the overall condition of water resources (Ketata *et al*., 2012). By consolidating extensive data into a single value, it simplifies the interpretation and communication of water quality information. WQI is widely applied to evaluate the suitability of groundwater for drinking purposes (Gibrilla *et al*., 2011). In this study, the Weighted Arithmetic Water Quality Index (WAWQI) method, introduced by Horton (1965), was employed to compute the WQI using the following equations:

The Water Quality Index (WQI) is a crucial tool for assessing groundwater suitability for drinking, consolidating complex physicochemical data into a single value for easier interpretation (Ketata *et al*., 2012; Gibrilla *et al*., 2011). In this study, the Weighted Arithmetic Water Quality Index (WAWQI) method (Horton, 1965) was employed, considering key parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), nitrates (NO_2 + NO_3), sodium (Na), potassium (K), chloride (Cl), sulfate (SO_4), carbonate (CO_3), bicarbonate (HCO_3), fluoride (F), total hardness (TH), calcium (Ca), and magnesium (Mg). Each parameter was assigned a weight (Wi) based on its impact on health, and a quality rating (Qi) was calculated by comparing the measured concentration (Ci) with the standard permissible limit (Si). The sub-index (SIi) was determined by multiplying Qi with Wi, and the final WQI was derived as the weighted sum of all sub-indices. In this study, the Water Quality Index (WQI) was evaluated for human consumption, with a maximum permissible limit of 100 for drinking water. The rating scale ranged from 0 to 100, categorizing water quality as follows: 0–25 (Excellent), 26–50 (Good), 51–75 (Poor), 76–100 (Very Poor), and values exceeding 100 indicating water unsuitable for drinking. This analysis provides valuable insights into groundwater contamination trends, aiding in sustainable water management and policy decisions for Madurai North Taluk.

2.3.1.1.Relative Weight

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

Where, W_i is the relative weight,

w_i is the weight of each parameter $= \frac{k}{S_i}$

n is the number of parameter

k is the proportionality constant $\left(k = \frac{1}{\Sigma\left(\frac{1}{S_i}\right)}\right)$

S_i is the Standard Value for i^{th} parameter.

$\sum_{i=1}^{n} w_i$ is the summation of all parameters.

2.3.1.2.Quality Rating

The quality rating scale for each parameter is calculated by dividing its Measured value of each water sample by its respective standards (WHO, 2011) and multiplying the result by 100.

$$Qi = \left(\frac{M_i}{S_i}\right) * 100 \quad (2)$$

Where, Qi is the Quality Rating based on concentration of ith parameter.

M_i is the Measured value of each water sample.

2.3.1.3.Sub Index

$$SI_i = W_i * Q_i \quad (3)$$

Where, SI_i is the Sub index of ith parameter.

2.3.1.4.Water Quality Index

$$WQI = \sum SI_i \quad (4)$$

Where, $\sum SI_i$ is the summation of Sub Index.

2.4.Groundwater Quality Analysis for Irrigation Purposes

2.4.1 Kelly's Ratio (KR)

Kelly's Ratio is used for the classification of water for irrigation purposes (Brooks *et al*., 2005). A Kelly's Ratio greater than 1 shows an excess of sodium and Kelly's Ratio greater than 2 signifies its deficit in waters (Kelly, 1940). The waters with low Kelly Ratio (<1) are suitable for irrigation and high Kelly Ratio are not suitable for irrigation (Sundaray *et al*., 2009).

$$KR = \frac{Na}{Ca+Mg} \quad (5)$$

2.4.2.Magnesium Hazard

Magnesium hazard analysis method is used to assess the agricultural suitability of groundwater, particularly in terms of its impact on soil structure (Szabolcs, 1964). The analysis is based on the idea that as the Mg^{2+} (magnesium ion) concentration in groundwater increases relative to Ca^{2+} (calcium ion) concentration, soil quality may degrade. This happens because high levels of magnesium ions can cause the dispersion of clay particles in the soil, leading to a breakdown of the soil structure. When magnesium ions dominate over calcium ions, the soil particles are more likely to separate (scatter) rather than aggregate, which negatively affects the soil's ability to retain water and nutrients. This process reduces hydraulic conductivity, making the soil less permeable. As a result, water movement becomes hindered, leading to poor water infiltration and drainage, which can significantly affect agricultural productivity (Paliwal, 1972).

To quantify this potential impact, the MH is calculated using the following formula:

$$MH = \frac{Mg}{Ca+Mg} \times 100 \quad (6)$$

2.4.3.Potential Salinity

Potential Salinity (PS) is a key parameter used to evaluate the suitability of water for irrigation. It represents the total concentration of dissolved salts that could potentially affect plant growth and soil health over time (Doneen, 1954).

$$PS = Cl + \sqrt{SO_4^{\ 2-}} \quad (7)$$

2.4.4.Permeability Index (PI)

The Permeability Index (PI) is an essential parameter used to assess the suitability of water for irrigation (Tank & Chandel, 2010). It helps to determine the potential impact of water quality on soil permeability over time. Based on the PI value, the water is categorized into three classes:

1. **Class 1 (>75%, Suitable)**: Water with a PI value more than 75% is considered suitable for irrigation as it has minimal impact on soil permeability and long-term soil health.

2. **Class 2 (25–75%, Good)**: Water with a PI value in between 25% and 75% is categorized as good for irrigation. While it may not have as detrimental an effect as class 3, its long-term use should be monitored.

3. **Class 3 (<25%, Unsuitable)**: Water with a PI value less than 25% is considered as not suitable for irrigation. It can significantly affect soil permeability and degrade soil quality over time.

The formula for calculating the Permeability Index (PI) is as follows:

$$PI = \frac{Na+\sqrt{HCO3}}{Ca+Mg+Na} \times 100 \quad (8)$$

All ion concentrations are expressed in meq/L. This formula helps to evaluate the balance of sodium, calcium, magnesium, and bicarbonate in irrigation water, and it indicates how these factors may affect the long-term permeability and fertility of the soil.

2.4.5.Corrosivity Ratio

Ryznar (1944) proposed a ratio to assess the corrosive nature of groundwater on metals, as corrosion is an electrolytic process that can degrade metal surfaces over time. Corrosion occurs when water interacts with metals, leading to the deterioration of the metal through electrochemical reactions. The amount of corrosion depends on a variety of factors, both chemical and physical. According to Ayers & Westcot (1985), the key factors influencing corrosion include, Chemical Reactions and Physical Factors such as temperature, pressure and velocity of flow.

The Corrosivity. Ratio. (CR) = ((Cl/35.5) + (SO_4/96))/ ((2 *H CO_3)/ 100) (9)

If the CR is < 1, then the water is non–corrosive and if the CR > 1, then the water is corrosive (Regarajan et al, 1990).

2.5.Hydrochemical Analysis

2.5.1.Durov Diagram

The **Durov Diagram** is a graphical representation used in hydrogeology to analyze water chemistry, particularly the relationship between major ions in a water sample. It's an alternative to the more commonly used **Piper Diagram**, and it's particularly useful for understanding the composition of water in terms of its ionic balance. The Durov Diagram comprises two triangular plots, where data points are projected onto a square grid positioned perpendicular to the third axis of each triangle. This arrangement offers a clearer visualization of the distribution and relationships between different ions.

2.6.Statistical Analysis

2.6.1.Correlation Analysis

Correlation Analysis is a statistical tool for defining how closely two variables are associated. Pearson correlation analysis was used to discriminate the link between several water chemical parameters in this study.

2.7.Study Area

The study area, Madurai North Taluk, located in Madurai district, Tamil Nadu, India, spans an average elevation of 134 meters above mean sea level, positioned at 9°56′07″N latitude and 78°05′17″E longitude. The region, influenced by the Vaigai River, has a semi-arid climate with an annual average rainfall of 85.76 cm, predominantly during the Northeast monsoon, while the Southwest monsoon and summer bring minimal precipitation. The area's temperature ranges from 26.3°C to 42°C in summer and 18°C to 29.6°C in winter. Hydrogeologically, the region is characterized by hard rock formations such as granite, charnockite, and gneiss, with groundwater occurring in shallow weathered and deeper fractured aquifers. These aquifers are primarily recharged through rainfall, surface water interactions with the Vaigai River, and irrigation return flow. The weathered zone, at depths of 5–20 meters, supports dug wells, while the fractured zone, extending up to 150 meters, serves deeper bore wells. Groundwater movement is influenced by secondary porosity, with fractures and joints acting as conduits. Soils in the region include clay loam, red loam, and black cotton soil, affecting groundwater recharge and retention. Water bodies such as lakes and ponds also contribute to groundwater dynamics. The Periyar Dam aids irrigation in the area, supporting crops like paddy, millets, oilseeds, cotton, sugarcane, and pulses, with paddy being the dominant crop. However, over-extraction of groundwater, coupled with high salinity levels, threatens groundwater sustainability, necessitating water management strategies like artificial recharge and conservation practices.

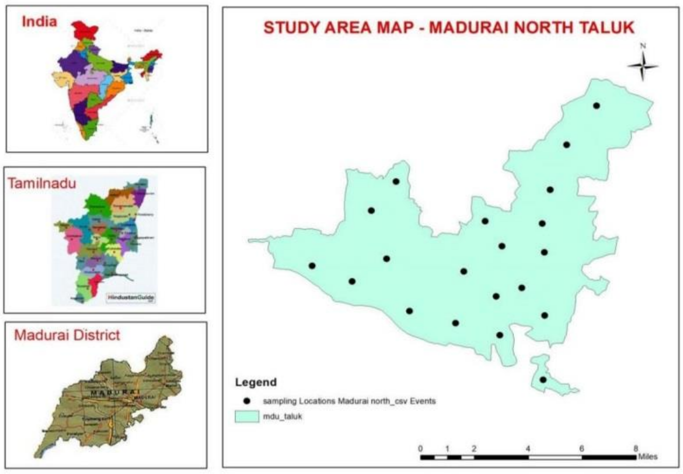

Figure 1: Study area map

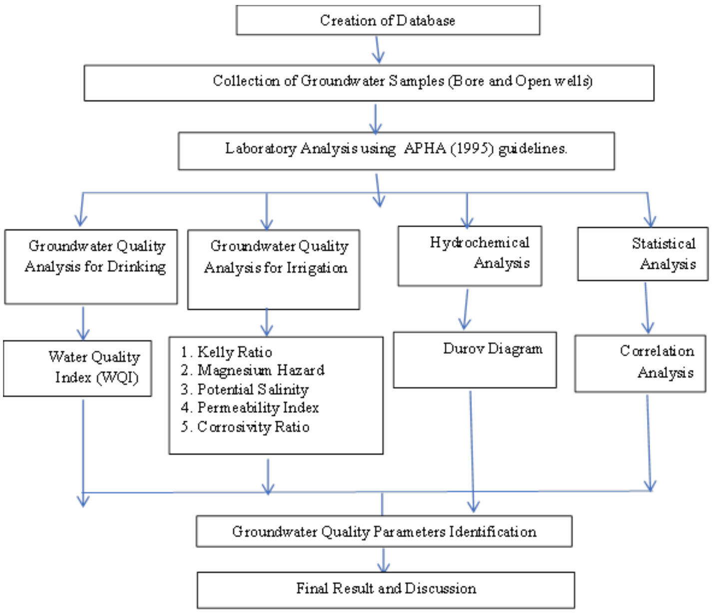

Figure 2: Methodology of this study

3.Results and discussion

3.1.Groundwater Quality Analysis for Drinking

3.1.1.Water Quality Index (WQI)

Groundwater chemistry is widely used to assess water quality for both drinking and irrigation purposes (Subba Rao, 2006; Vasanthavigar *et al*., 2010). The Water Quality Index (WQI) serves as a key indicator for evaluating overall water quality and its suitability for human consumption (Magesh *et al*., 2013; Subba Rao, 1997). This index integrates multiple physicochemical parameters into a single value, reflecting the combined impact of various contaminants on water quality (Mitra & ASABE Member, 1998). The World Health Organization (WHO, 2011) has established drinking water standards, as shown in Table 1, and the assigned weight (wi) and relative weight (Wi) of all parameters were calculated accordingly.

The calculated WQI for Madurai North Taluk ranged between 59.88 and 105.64 during the pre-monsoon season and 51.19 to 105.31 during the post-monsoon season (Tables 2 and 3). The pre-monsoon groundwater quality classification indicates that in 2008, 2009, and 2021, water quality was "poor" (WQI: 51–75), while in 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2019, and 2020, it was "very poor" (WQI: 75–100). The years 2018 and 2022 recorded WQI values exceeding 100, categorizing the water as unsuitable for drinking. The WQI analysis from 2008 to 2022 reveals notable seasonal variations, with post-monsoon samples generally exhibiting better quality than pre-monsoon samples due to rainfall-induced dilution and groundwater recharge. However, despite this improvement, certain years, such as 2014 (102.91) and 2018 (105.31), still exceeded safe limits, indicating persistent contamination concerns. The elevated levels of fluoride, nitrate, total dissolved solids (TDS), chloride, sodium, and calcium suggest that rock-water interactions, anthropogenic pollution, and agricultural runoff significantly influence groundwater deterioration.

These findings highlight the urgent need for sustainable groundwater management in the region. Strategies such as rainwater harvesting, artificial recharge structures (e.g., check dams, percolation ponds), fluoride and nitrate removal technologies, and controlled agricultural practices must be implemented to mitigate contamination. Additionally, continuous monitoring and proactive intervention are essential to safeguard groundwater quality and ensure its long-term sustainability for both drinking and irrigation in Madurai North Taluk.

Table 1: Relative Weight of Physico-chemical parameters

Chemical Parameters	Standard Value (Si)	1/Si	weight of each parameter (wi) =k/Si	Relative Weight (Wi)=wi/∑wi
TDS	500	0.002	0.0016	0.0015
NO_2+NO_3	45	0.0222	0.0172	0.0172
Ca	75	0.0133	0.0103	0.0103
Mg	30	0.0333	0.0258	0.0258
Na	200	0.005	0.0039	0.0039
K	12	0.0833	0.0646	0.0646
Cl	250	0.004	0.0031	0.0031
SO4	200	0.005	0.0039	0.0039
F	1	1	0.775	0.7747
pH	8.5	0.1176	0.0912	0.0911
Total Hardness	200	0.005	0.0039	0.0039
	∑Si=1521.5	∑(1/Si)=1.2909	∑wi=1.0004	∑Wi=1

k=1/∑(1/Si) =1/1.2909 =0.775

Table 2: Water Quality Index during pre-monsoon season

Annual Average for the Year	Sum of Measured Value (∑Mi)	Sum of Quality Rating (∑Qi)	Water Quality Index (WQI=∑WiQi)	Water Quality
2008	1851.003	1067.721	59.875	Poor
2009	2726.86	1722.78	62.333	Poor
2010	1835.383	1268.89	99.74	Very Poor
2011	2713.478	1503.99	86.79	Very Poor
2012	2642.391	1647.17	90.50	Very Poor
2013	1888.378	1122.96	92.54	Very Poor
2014	1544.8225	936.0309	80.68	Very Poor
2015	1451.628056	903.2673747	81.50	Very Poor
2016	1868.02	1107.69	94.13	Very Poor
2017	1943.95	1202.89	98.72	Very Poor
2018	2266.04	1294.62	100.49	Unsuitable for Drinking
2019	2206.23	1259.49	93.65	Very Poor
2020	2601.01	1345.79	91.13	Very Poor
2021	1809.76	1033.07	66.71	Poor
2022	1674.55	1032.27	105.64	Unsuitable for Drinking

Table 3: Water Quality Index during post monsoon season

Year	Sum of Measured Value (∑Mi)	Sum of Quality Rating (∑Qi)	Water Quality Index (WQI=∑WiQi)	Water Quality
2008	1962.893	1145.446	78.332	Very Poor
2009	1247.31	871.92	66.07	Poor
2010	1974.94	1245.13	65.95	Poor
2011	1765.084	1053.82	80.70	Very Poor
2012	2031.059	1396.71	91.77	Very Poor
2013	2313.69	1398.15	86.41	Very Poor
2014	2065.606	1362.95	102.91	Unsuitable for Drinking
2015	2049.6726	1103.7414	51.19	Poor
2016	1828.68	1051.23	93.68	Very Poor
2017	1676.01	1049.70	94.89	Very Poor
2018	2174.59	1300.52	105.31	Unsuitable for Drinking
2019	1667.51	1194.56	83.68	Very Poor
2020	1733.52	1074.19	91.08	Very Poor
2021	2003.97	1146.12	68.64	Poor
2022	1993.44	1145.31	78.68	Very Poor

3.2. Groundwater Quality Analysis for Irrigation Purposes

The assessment of groundwater quality for irrigation is essential to prevent soil degradation and ensure sustainable agricultural productivity. Excessive salt accumulation in the soil can alter its structure, reduce permeability, and limit aeration, negatively impacting plant growth (Alam, 2010, 2013; Mohan *et al*., 2000; Umar *et al*., 2001). High salinity disrupts osmotic balance, reducing water availability for plant uptake and ultimately leading to decreased crop yields (Rao *et al*., 2013). To mitigate these effects, systematic evaluation of irrigation water quality is necessary for informed resource management and long-term agricultural sustainability (Jalali, 2011; Srinivasamoorthy *et al*., 2014). Several hydrogeochemical indices and parameters are used to determine the suitability of groundwater for irrigation. These include:

3.2.1 Kelly's Ratio (KR)

Kelly's Ratio is used to assess the suitability of groundwater for agricultural purposes. It is calculated by comparing sodium (Na^+) concentrations to calcium (Ca^{2+}) and magnesium (Mg^{2+}), as proposed by Kelly (1963). Groundwater with a Kelly's Ratio greater than 1 is considered unsuitable for irrigation (Patel et al., 2016; Srinivasamoorthy et al., 2014; Sundaray et al., 2009).

The Kelly's Ratio of groundwater samples from Madurai North Taluk was evaluated from 2008 to 2022 to determine irrigation suitability. During the pre-monsoon season, values ranged from 0.07 (2021) to 22.28 (2016) (Table 4), while in the post-monsoon season, they varied from 0.08 (2010) to 41.91 (2020) (Table 5). Kelly's Ratio (KR) is a key parameter for assessing groundwater suitability for irrigation, with values below 1 indicating suitability and values above 1 signifying excessive sodium levels that can degrade soil quality. The analysis of groundwater samples from Madurai North Taluk (2008–2022) revealed significant seasonal variations, with pre-monsoon KR values ranging from 0.07 (2021) to 22.28 (2016) and post-monsoon values varying between 0.08 (2010) and 41.91 (2020). During the pre-monsoon season, only 24.85% of samples (41 out of 165) were suitable for irrigation, while 75.15% (124 samples) exceeded the threshold, indicating high sodium hazards. The post-monsoon season showed slight improvement, with 36.11% of samples (65 out of 180) falling within the safe limit, while 63.89% (115 samples) remained unsuitable. The lowest irrigation suitability was recorded in 2020 (7.14% of post-monsoon samples suitable), while 2009 exhibited 100% suitability, demonstrating the beneficial impact of rainfall-induced dilution. The consistently high sodium levels suggest anthropogenic influences such as intensive agriculture, excessive fertilizer use, and rock-water interactions. To mitigate sodium hazards and enhance irrigation suitability, sustainable water management strategies, including controlled fertilizer application, improved irrigation techniques (e.g., drip irrigation), artificial groundwater recharge, and periodic soil conditioning, must be implemented. Additionally, continuous groundwater monitoring is essential to track sodium accumulation trends and develop long-term mitigation strategies to ensure irrigation sustainability in Madurai North Taluk.

3.2.2.Magnesium Hazard

Magnesium Hazard (MH) assesses the potential soil damage caused by excessive magnesium in irrigation water (Tahmasebi *et al*., 2018). High magnesium concentrations can lead to soil alkalinity by binding with clay particles, reducing permeability, andrestricting water infiltration, ultimately affecting crop growth. A Magnesium Ratio below 50 is considered suitable for irrigation, whereas values exceeding 50 indicate unsuitability. Prolonged use of water with a high Magnesium Ratio can degrade soil quality and lower agricultural productivity by increasing alkalinity (Raju *et al*., 2011; Sreedevi, 2004).

Magnesium Hazard (MH) is a key parameter in evaluating groundwater suitability for irrigation, as excessive magnesium levels increase soil alkalinity, reducing permeability and crop productivity. A Magnesium Hazard below 50% is considered suitable for irrigation, while values exceeding this threshold indicate unsuitability. The MH analysis of groundwater samples from Madurai North Taluk (2008–2022) revealed pre-monsoon values ranging from 9.19% (2011) to 91.62% (2018) and post-monsoon values from 11.89% (2020) to 93.58% (2017).

Table 4: The Statistical summary of Kelly's Ratio during Pre Monsoon Season

Year	Minimum	Maximum	Mean	Standard Deviation	Permissible Limit	Number of Samples		Percentage of Samples	
						Suitable	Unsuitable	Suitable	Unsuitable
2008	0.28	4.19	1.85	2.06	1	1	2	33.33	66.67
2009	0.99	2.52	1.47	0.71	1	1	3	25.00	75.00
2010	0.36	3.10	1.49	1.04	1	1	4	20.00	80.00
2011	0.43	2.76	2.11	0.98	1	1	4	20.00	80.00
2012	0.39	2.76	1.76	1.09	1	2	3	40.00	60.00
2013	0.52	5.18	2.61	2.02	1	2	3	40.00	60.00
2014	0.54	4.03	2.06	1.16	1	3	15	16.67	83.33
2015	0.70	8.67	2.02	1.90	1	4	14	22.22	77.78
2016	0.24	22.28	3.64	5.87	1	4	13	23.53	76.47
2017	0.27	12.69	2.57	2.92	1	5	15	25.00	75.00
2018	0.70	14.70	3.22	3.67	1	5	13	27.77	72.23
2019	0.61	18.56	4.06	6.53	1	4	8	33.33	66.67
2020	0.80	17.31	4.63	6.02	1	3	9	25.00	75.00
2021	0.07	21.98	3.40	5.70	1	2	11	15.38	84.62
2022	0.31	2.61	1.46	0.80	1	3	7	30.00	70.00
					Total	41	124		

Table 5: The Statistical summary of Kelly's Ratio during Post Monsoon Season

Year	Minimum	Maximum	Mean	Standard Deviation	Permissible Limit	Number of Samples		Percentage of Samples	
						Suitable	Unsuitable	Suitable	Unsuitable
2008	0.17	3.25	1.40	1.63	1	2	1	66.67	33.33
2009	0.43	0.43	0.43	-	1	1	0	100.00	0.00
2010	0.08	2.61	0.85	1.04	1	4	1	80.00	20.00
2011	0.61	2.83	1.81	0.80	1	1	4	20.00	80.00
2012	0.11	2.24	1.08	0.97	1	3	2	60.00	20.00
2013	0.30	3.61	1.53	1.31	1	2	3	20.00	30.00
2014	0.10	3.01	1.11	0.85	1	10	5	66.67	33.33
2015	0.38	37.56	5.69	11.12	1	6	11	35.29	64.71
2016	0.23	14.83	2.87	3.84	1	7	11	38.89	61.11
2017	0.22	21.78	3.64	4.89	1	5	15	25.00	75.00
2018	0.22	9.68	2.16	2.27	1	8	11	42.11	57.89
2019	0.26	16.77	2.92	3.95	1	8	12	40.00	60.00
2020	0.86	41.91	6.13	11.53	1	1	13	7.14	92.86
2021	0.49	13.09	2.82	3.98	1	4	9	30.77	69.23
2022	0.35	6.33	2.10	1.58	1	3	17	15.00	85.00
					Total=	65	115		

During the pre-monsoon season, only 31.52% of samples (52 out of 165) were suitable for irrigation, whereas 68.48% (113 samples) exceeded the safe limit, indicating soil degradation risks. In the post-monsoon season, 46.67% of samples (84 out of 180) fell within the suitable range, while 53.33% (96 samples) remained unsuitable, showing slight seasonal improvement due to rainfall-induced dilution. The persistently high MH values suggest intensive groundwater extraction, geogenic influences from magnesium-bearing rocks, and agricultural runoff as contributing factors. To improve irrigation suitability, sustainable practices such as gypsum application for soil conditioning, controlled fertilizer use, periodic soil testing, and artificial groundwater recharge must be adopted. Additionally, long-term groundwater monitoring and improved water management policies are essential to enhance irrigation sustainability in Madurai North Taluk. The similar results found on the previous studies (Ayers & Westcot, 1985) (Pandian & Sankar, 2007).

3.2.3 Potential Salinity

Potential Salinity (PS) is a key parameter for assessing groundwater suitability for irrigation, defined as the sum of chloride concentration and half of the sulfate concentration (Tahmasebi *et al*., 2018). Doneen (1954) emphasized that irrigation water quality is influenced not only by total soluble salts but also by their solubility. While low-solubility salts tend to precipitate and accumulate in the soil over time, highly soluble salts contribute to increased soil salinity, which can negatively impact crop growth. Groundwater with a Potential Salinity value below 3 meq/L is considered suitable for irrigation (Ememu & Nwankwoala, 2018).

A PS value below 3 meq/L is considered suitable for irrigation, while higher values indicate severe salinity hazards. The analysis of groundwater samples from Madurai North Taluk (2008–2022) revealed pre-monsoon PS values ranging from 28.0 to 1811.5 meq/L and post-monsoon values from 28.5 to 1960.5 meq/L, indicating extremely high salinity levels.

Table 6: The Statistical summary of Magnesium Ratio during Pre Monsoon Season

Year	Minimum	Maximum	Mean	Standard Deviation	Permissible Limit	Number of Samples		Percentage of Samples	
						Suitable	Unsuitable	Suitable	Unsuitable
2008	47.68	63.36	53.37	8.68	50	2	1	66.67	33.33
2009	50.94	62.37	54.52	5.32	50	0	4	0.00	100.00
2010	45.19	70.47	61.06	9.45	50	1	4	20.00	80.00
2011	9.19	71.15	44.26	23.47	50	3	2	60.00	40.00
2012	57.45	87.38	71.74	11.40	50	0	5	0.00	100.00
2013	19.55	71.84	42.57	25.48	50	3	2	60.00	40.00
2014	42.78	79.54	59.15	9.73	50	2	16	11.11	88.89
2015	44.99	90.84	59.70	12.26	50	5	13	27.78	72.22
2016	32.22	90.93	57.81	15.29	50	4	13	23.53	76.47
2017	27.00	83.37	57.98	14.10	50	6	14	30.00	70.00
2018	14.79	91.62	50.52	18.55	50	9	9	50.00	50.00
2019	31.30	74.38	53.30	15.33	50	4	8	33.33	66.67
2020	9.79	83.97	45.01	19.79	50	7	5	58.33	41.67
2021	34.44	89.91	61.68	14.69	50	2	11	15.38	84.62
2022	21.86	65.97	46.80	13.70	50	4	6	40.00	60.00
					Total=	52	113		

Table 7. The Statistical summary of Magnesium Ratio during Post Monsoon Season

Year	Minimum	Maximum	Mean	Standard Deviation	Permissible Limit	Number of Samples		Percentage of Samples	
						Suitable	Unsuitable	Suitable	Unsuitable
2008	34.49	45.39	39.23	5.59	50	3	0	100.00	0.00
2009	52.54	52.54	52.54	-	50	0	1	0.00	100.00
2010	32.41	70.85	51.25	18.43	50	3	2	60.00	40.00
2011	14.59	57.66	30.26	16.67	50	4	1	80.00	20.00
2012	30.99	69.37	49.40	15.18	50	3	2	60.00	40.00
2013	38.57	66.19	48.97	11.19	50	3	2	60.00	40.00
2014	33.02	76.97	55.17	12.02	50	5	10	33.33	66.67
2015	32.56	82.48	51.03	14.34	50	9	8	52.94	47.06
2016	20.30	85.56	48.48	17.70	50	11	7	61.11	38.89
2017	28.09	93.58	57.76	16.34	50	5	15	25.00	75.00
2018	26.42	74.26	50.30	50.30	50	9	10	47.37	52.63
2019	20.37	81.39	50.66	14.61	50	8	12	40.00	60.00
2020	11.89	85.87	55.47	19.56	50	5	9	35.71	64.29
2021	29.71	73.22	51.73	15.13	50	7	6	53.85	46.15
2022	21.47	84.24	52.55	15.30	50	9	11	45.00	55.00
					Total=	84	96		

During both pre-monsoon and post-monsoon seasons, all samples (100%) exceeded the safe limit of 3 meq/L, making the groundwater unsuitable for irrigation. The lowest PS values were recorded in 2008 (28.0 meq/L) and 2009 (28.5 meq/L), while the highest were in 2018 (1811.5 meq/L) and 2017 (1960.5 meq/L), respectively, demonstrating persistent salinity issues despite seasonal variations. The consistently high PS values suggest that geogenic influences, prolonged irrigation with saline water, and agricultural runoff are key contributors to groundwater salinity. To mitigate these risks, integrated water management strategies, including periodic salt leaching, cultivation of salt-tolerant crops, improved drainage systems, and artificial groundwater recharge, should be implemented. Additionally, reducing excessive groundwater extraction and promoting alternative water sources are essential to controlling soil salinity and ensuring sustainable agricultural practices in Madurai North Taluk.

3.2.4.Permeability Index (PI)

The Permeability Index is a crucial parameter for evaluating irrigation water quality, as it determines the impact of groundwater on soil permeability over prolonged usage. This index is influenced by the concentrations of sodium, calcium, magnesium, and bicarbonates (Sharma *et al.*, 2016). According to Doneen (1964), the Permeability Index is classified into three categories: Type I (>75% - Suitable), Type II (25-75% - Good), and Type III (<25% - Unsuitable). Water classified under Type I and Type II is considered suitable for irrigation. In this study, during the pre-monsoon season, 59 out of 165 samples (35.76%) fell under Type I (Suitable), while 105 samples (63.64%) were classified as Type II (Good). Similarly, during the post-monsoon season, 54 out of 180 samples (30%) were Type I, whereas 122 samples (67.78%) fell under Type II. However, one pre-monsoon sample (0.60%) and four post-monsoon samples (2.22%) were categorized as Type III, rendering them unsuitable for irrigation. The classification of Permeability Index for groundwater samples in Madurai North Taluk from 2008 to 2022 is presented in Tables 10 and 11.

Table 8: The Statistical summary of Potential Salinity during Pre Monsoon Season

Year	Minimum	Maximum	Mean	Standard Deviation	Permissible Limit	Number of Samples		Percentage of Samples	
						Suitable	Unsuitable	Suitable	Unsuitable
2008	91	514	317.67	213.13	3	0	3	0.00	100.00
2009	92.5	766	447.00	276.72	3	0	4	0.00	100.00
2010	98.5	505	261.40	175.79	3	0	5	0.00	100.00
2011	90.5	1023	400.80	383.31	3	0	5	0.00	100.00
2012	64.5	676.5	422.00	223.00	3	0	5	0.00	100.00
2013	88.5	422	280.90	174.94	3	0	5	0.00	100.00
2014	28	509.5	217.28	152.90	3	0	18	0.00	100.00
2015	42	405	194.86	116.31	3	0	18	0.00	100.00
2016	83.5	943	285.12	265.87	3	0	17	0.00	100.00
2017	50.5	730	292.25	205.38	3	0	20	0.00	100.00
2018	67.5	1811.5	375.22	421.47	3	0	18	0.00	100.00
2019	91.5	1296.5	353.58	389.69	3	0	12	0.00	100.00
2020	42	1421	436.58	426.98	3	0	12	0.00	100.00
2021	42.5	976.5	278.54	320.13	3	0	13	0.00	100.00
2022	77.5	527.5	238.60	142.48	3	0	10	0.00	100.00
					Total =	0	165	0.00	100.00

Table 9: The Statistical summary of Potential Salinity during Post Monsoon Season

Year	Minimum	Maximum	Mean	Standard Deviation	Permissible Limit	Number of Samples		Percentage of Samples	
						Suitable	Unsuitable	Suitable	Unsuitable
2008	89	502	295.50	206.50	3	0	3	0.00	100.00
2009	115	115	115.00	-	3	0	1	0.00	100.00
2010	81.5	518	281.30	183.79	3	0	5	0.00	100.00
2011	95	531.5	235.00	171.30	3	0	5	0.00	100.00
2012	58.5	483	256.30	185.35	3	0	5	0.00	100.00
2013	81	578	317.10	221.43	3	0	5	0.00	100.00
2014	48	1311	280.00	313.96	3	0	15	0.00	100.00
2015	54.5	1812	351.74	455.03	3	0	17	0.00	100.00
2016	35	942	280.94	268.24	3	0	18	0.00	100.00
2017	44.5	955.5	271.03	250.81	3	0	20	0.00	100.00
2018	28.5	1763	349.50	402.37	3	0	19	0.00	100.00
2019	37	1415	328.53	335.02	3	0	20	0.00	100.00
2020	40	1548	322.00	456.06	3	0	14	0.00	100.00
2021	53	820	273.42	227.90	3	0	13	0.00	100.00
2022	38	1960.5	303.58	409.74	3	0	20	0.00	100.00
					Total =	0	180	0.00	100.00

The predominance of Type II samples in both seasons suggests potential long-term impacts on soil permeability due to sodium accumulation and ion imbalances, while the increase in Type III samples post-monsoon (2.22%) compared to pre-monsoon (0.60%) highlights the influence of seasonal variations on soil-water interactions. To mitigate soil degradation and sustain irrigation suitability, periodic soil conditioning, controlled groundwater extraction, and efficient irrigation techniques such as drip irrigation and alternate wetting and drying (AWD) should be adopted. Additionally, continuous groundwater quality monitoring is essential to prevent further decline in soil permeability and ensure long-term agricultural sustainability in Madurai North Taluk.

3.2.5.Corrosivity Ratio (CR)

The Corrosivity Ratio provides insight into the suitability of water for distribution. A ratio below 1 indicates that the water is safe to transport through any type of pipe, while a ratio above 1 suggests a corrosive nature, which can cause damage to metal pipes (Khodapanah *et al*., 2009). The groundwater quality classifications based on the Corrosivity Ratio are listed in Table 12 and 13 for pre and post monsoon seasons.

The analysis of groundwater samples from Madurai North Taluk (2008–2022) revealed that pre-monsoon CR values ranged from 0.08 to 7.05, while post-monsoon values varied from 0.16 to 10.13. During the pre-monsoon season, 67.27% (111 out of 165) of samples recorded CR values below 1, indicating safe transport through any type of pipeline, while 32.73% (54 samples) had values above 1, rendering them corrosive. In the post-monsoon season, 72.22% (130 out of 180) of samples were non-corrosive, whereas 27.78% (50 samples) exceeded the limit, classifying them as corrosive. The higher proportion of corrosive samples in the pre-monsoon season suggests that reduced rainfall and groundwater

Table 10: The Statistical summary of Permeability Index during Pre Monsoon Season

Year	Minimum	Maximum	Mean	Standard Deviation	Number of Samples			Percentage of Samples		
					Suitable (>75%)	Good (25-75%)	Unsuitable (<25%)	Suitable (>75%)	Good (25-75%)	Unsuitable (<25%)
2008	33.27	84.24	58.35	25.50	1	2	0	33.33	66.67	0.00
2009	56.64	75.92	63.49	8.52	1	3	0	25.00	75.00	0.00
2010	39.48	80.00	62.25	14.84	1	4	0	20.00	80.00	0.00
2011	43.13	82.60	70.35	15.89	3	2	0	60.00	40.00	0.00
2012	32.87	78.16	63.83	19.25	3	2	0	60.00	40.00	0.00
2013	45.00	88.66	69.41	20.33	3	2	0	60.00	40.00	0.00
2014	47.67	88.10	70.90	12.40	7	11	0	38.89	61.11	0.00
2015	50.68	95.76	68.75	12.52	4	14	0	22.22	77.78	0.00
2016	31.10	101.53	67.63	19.20	5	12	0	29.41	70.59	0.00
2017	33.33	98.76	68.72	16.85	8	12	0	40.00	60.00	0.00
2018	50.02	96.79	71.62	15.92	7	11	0	38.89	61.11	0.00
2019	42.10	100.27	67.93	17.91	4	8	0	33.33	66.67	0.00
2020	55.31	100.05	73.87	15.95	4	8	0	33.33	66.67	0.00
2021	18.86	99.43	70.32	19.16	6	6	1	46.15	46.15	7.70
2022	35.64	78.88	63.12	14.40	2	8	0	20.00	80.00	0.00
Total					59	105	1			

Table 11: The Statistical summary of Permeability Index during Post Monsoon Season

Year	Minimum	Maximum	Mean	Standard Deviation	Number of Samples			Percentage of Samples		
					Suitable (>75%)	Good (25-75%)	Unsuitable (<25%)	Suitable (>75%)	Good (25-75%)	Unsuitable (<25%)
2008	26.92	80.49	52.78	26.83	1	2	0	33.33	66.67	0.00
2009	41.50	41.50	41.50	-	0	1	0	0.00	100.00	0.00
2010	17.83	76.18	43.12	24.55	1	2	2	20.00	40.00	40.00
2011	47.95	82.60	68.96	12.73	1	4	0	20.00	80.00	0.00
2012	24.63	74.59	51.65	21.16	0	4	1	0.00	80.00	20.00
2013	35.51	83.79	59.83	18.84	1	4	0	20.00	80.00	0.00
2014	21.98	83.79	55.24	15.75	2	12	1	13.33	80.00	6.67
2015	29.13	102.35	69.33	20.07	6	11	0	35.29	64.71	0.00
2016	30.59	96.82	67.26	18.36	6	12	0	33.33	66.67	0.00
2017	31.15	101.79	71.81	18.75	9	11	0	45.00	55.00	0.00
2018	34.72	93.87	64.88	18.36	7	12	0	36.84	63.16	0.00
2019	30.45	100.16	68.05	17.58	7	13	0	35.00	65.00	0.00
2020	58.28	101.04	76.68	12.75	5	9	0	35.71	64.29	0.00
2021	44.74	96.41	66.73	16.06	3	10	0	23.08	76.92	0.00
2022	39.83	92.98	69.63	13.41	5	15	0	25.00	75.00	0.00
Total					54	122	4			

recharge contribute to increased mineral concentrations, intensifying water corrosivity. The persistently high CR values indicate geogenic influences, prolonged water stagnation, and anthropogenic activities such as industrial discharge and agricultural runoff. To minimize the adverse effects of corrosive groundwater, protective measures such as corrosion-resistant pipelines, periodic monitoring, and pH stabilization techniques should be implemented. Additionally, sustainable groundwater management practices must be adopted to reduce metal leaching and enhance water quality for long-term use in Madurai North Taluk.

3.3. Hydrochemical Analysis

Numerous studies have been conducted in India and other parts of the world to examine the geochemical characteristics of groundwater (Graniel *et al*., 1999; Umar & Sami Ahmad, 2000). A clearer understanding of the geochemical evolution of groundwater can be achieved by utilizing the Durov (1948) diagram. To facilitate visual comparison, identify hydrochemical facies, and determine the mechanisms controlling the groundwater geochemistry in the study area, the hydrochemical data of the analyzed samples were plotted in Durov diagram using Grapher software. Durov diagram is a composite plot consisting of 2 ternary diagrams where the milliequivalents percentages of the cations of interest were plotted against that of anions of interest; sides form a central rectangular, binary plot of total cation vs. total anion concentrations.

3.3.1. Durov Diagram

The Durov diagram (Durov, 1948) Figure 3 (a) and (b), was plotted to determine the dominant hydrochemical processes and the type of ion exchange during Pre and postmonsoon seasons for the year 2022. Similarly, Durov diagrams were plotted for Cation Vs Anion of Pre and post monsoon seasons of the remaining years from 2008 to 2021. It is clear from the Durov diagrams that most of the water lies in the Moderate quality of water zone indicating the dissolution or mixing line, i.e., ion exchange and reverse ion exchange are both.

Table 12: The Statistical summary of Corrosivity Ratio during Pre Monsoon Season

Year	Minimum	Maximum	Mean	Standard Deviation	Permissible Limit	Number of Samples		Percentage of Samples	
						Suitable (<1)	Unsuitable (>1)	Suitable (<1)	Unsuitable (>1)
2008	0.45	3.60	1.89	1.59	1	1	2	33.33	66.67
2009	0.39	2.61	1.69	1.00	1	1	3	25.00	75.00
2010	0.38	2.17	1.15	0.91	1	3	2	50.00	50.00
2011	0.23	2.04	0.88	0.75	1	3	2	60.00	40.00
2012	0.34	2.14	1.47	0.78	1	2	3	40.00	60.00
2013	0.47	1.38	0.94	0.43	1	2	3	40.00	60.00
2014	0.08	2.89	0.86	0.65	1	14	4	77.78	22.22
2015	0.27	1.99	0.77	0.48	1	14	4	77.78	22.22
2016	0.44	4.00	0.99	0.88	1	13	4	76.47	23.53
2017	0.25	3.57	1.01	0.77	1	13	7	65.00	35.00
2018	0.31	7.05	1.19	1.54	1	13	5	72.22	27.78
2019	0.47	5.14	1.08	1.30	1	9	3	75.00	25.00
2020	0.29	4.85	1.20	1.20	1	7	5	58.33	41.67
2021	0.20	3.41	0.92	0.95	1	10	3	76.92	23.08
2022	0.34	1.44	0.89	0.38	1	6	4	60.00	40.00
					Total =	111	54		

Table 13: The Statistical summary of Corrosivity Ratio during Post Monsoon Season

Year	Minimum	Maximum	Mean	Standard Deviation	Permissible Limit	Number of Samples		Percentage of Samples	
						Suitable (<1)	Unsuitable (>1)	Suitable (<1)	Unsuitable (>1)
2008	0.28	2.50	1.20	1.16	1	2	1	66.67	33.33
2009	0.42	0.42	0.42	-	1	1	0	100.00	0.00
2010	0.34	2.95	1.14	1.09	1	3	2	60.00	40.00
2011	0.25	1.99	0.80	0.70	1	4	1	80.00	20.00
2012	0.20	1.77	0.77	0.63	1	4	1	80.00	20.00
2013	0.27	1.24	0.77	0.46	1	3	2	60.00	40.00
2014	0.21	3.79	0.82	0.87	1	13	2	86.67	13.33
2015	0.30	10.13	1.59	2.39	1	11	6	64.71	35.29
2016	0.16	3.58	0.92	0.79	1	14	4	77.78	22.22
2017	0.23	3.09	0.94	0.74	1	14	6	70.00	30.00
2018	0.20	8.82	1.40	2.03	1	14	5	73.68	26.32
2019	0.20	6.06	1.23	1.30	1	11	9	55.00	45.00
2020	0.21	3.27	0.80	0.80	1	11	3	78.57	21.43
2021	0.25	1.36	0.65	0.32	1	11	2	84.62	15.38
2022	0.19	4.18	0.91	0.87	1	14	6	70.00	30.00
					Total=	130	50		

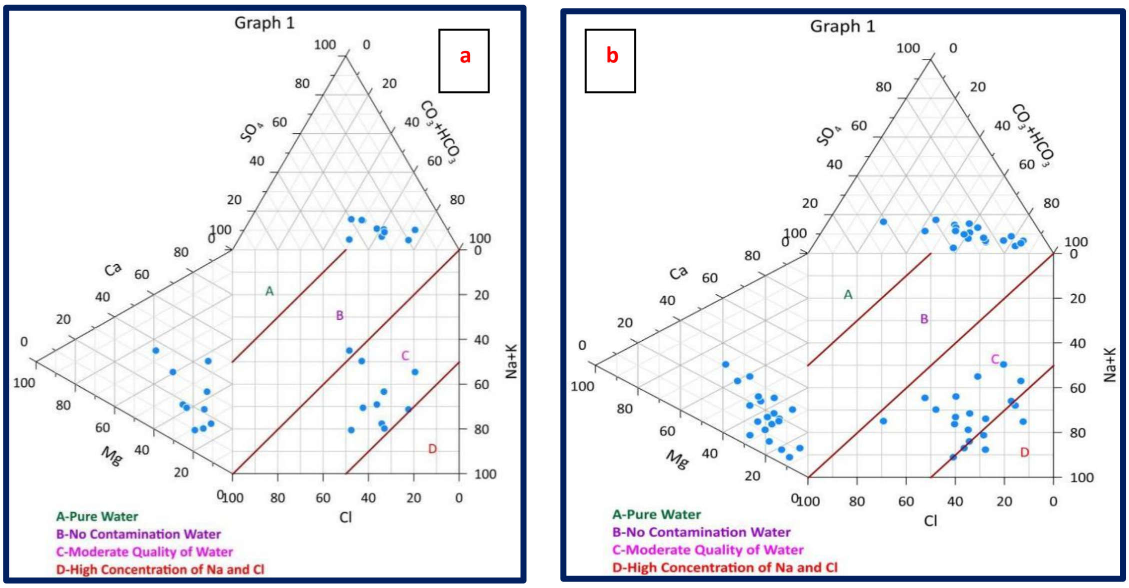

Figure 3: Durov Diagram **(a).** Pre-Monsoon (Year-2022), **(b)**. Post Monsoon (Year - 2022)

3.4.Statistical Analysis

3.4.1. Correlation Analysis

3.4.1.1.Inter-correlation among WQ Parameters for Pre and Post Monsoon seasons.

Statistical analysis was conducted on the physico-chemical parameters and major ion concentrations to identify relationships and variations among groundwater samples. The data were grouped based on geochemical parameters for discussion. The average values of variables such as TDS, NO_2 + NO_3, Ca, Mg, Na, K, Cl, SO_4, CO_3, HCO_3, F, pH, EC, TH, SAR, RSC, and Na% were calculated and organized into a 17x32 matrix covering the years 2008 to 2022. In 2022, the contents of Cl, Na, SO_4 , and EC showed strong positive correlations with salinity, with correlation coefficients of 0.969, 0.948, 0.904, and 0.999 during the pre-monsoon season (Table 14) and 0.984, 0.977, 0.970, and 1.000 during the post-monsoon season (Table 15). These values highlight the interdependence between total dissolved salts and major ions in drinking wells of Madurai North Taluk in 2022, as detailed in Tables 14 and 15.

A strong positive correlation was observed between Cl, Na, SO_4, and EC, suggesting that these parameters in most groundwater samples likely originate from a common source. Magnesium and chloride, however, showed a weaker relationship (r = 0.822), indicating that the hardness of the water is likely temporary. The potential salt combinations ($CaSO_4$, NaCl, and mixed CaNaHCO3) are probably the result of rock salt weathering, gypsum-bearing aquifers, and irrigation return flows. The presence of nitrate is likely attributed to anthropogenic activities. Effective water quality management can be achieved through proper wastewater recycling and the installation of sewage treatment plants.

4.Conclusion

The groundwater quality assessment of Madurai North Taluk over a 15-year period (2008–2022) provides crucial insights into its suitability for drinking and irrigation. The Water Quality Index (WQI) classification indicates seasonal variations in groundwater quality, with post-monsoon samples generally exhibiting better quality than pre-monsoon samples due to rainfall-induced dilution and groundwater recharge. However, elevated levels of fluoride, nitrate, chloride, sodium, calcium, and total dissolved solids (TDS) in certain years make the water unsuitable for drinking, emphasizing the need for effective groundwater management and contamination control measures.

For irrigation suitability, the study evaluated key hydrogeochemical indices such as Kelly's Ratio (KR), Magnesium Hazard (MH), Potential Salinity (PS), Permeability Index (PI), and Corrosivity Ratio (CR). The findings indicate that most groundwater samples are unsuitable for irrigation, primarily due to high salinity, excessive magnesium concentration, and poor permeability, which can lead to soil degradation and reduced agricultural productivity. The Magnesium Hazard analysis revealed that a majority of pre-monsoon and post-monsoon samples exceeded the safe threshold of 50%, indicating risks of soil alkalinity and structural deterioration. The Potential Salinity values across all samples consistentlyexceeded the permissible limit of 3 meq/L, making groundwater highly unsuitable for long-term irrigation.

Table 14: Correlation Matrix during Pre Monsoon season in 2022.

Parameters	TDS	NO2+NO3	Ca	Mg	Na	K	Cl	SO4	CO3	HCO3	F	pH	EC	TH	SAR	RSC	Na%
TDS	1																
NO2+NO3	0.777	1															
Ca	0.378	0.379	1														
Mg	0.781	0.684	-0.031	1													
Na	0.948	0.636	0.150	0.708	1												
K	0.483	0.563	0.183	0.184	0.535	1											
Cl	0.969	0.780	0.328	0.822	0.903	0.407	1										
SO4	0.904	0.776	0.404	0.869	0.759	0.207	0.923	1									
CO3	-0.655	-0.292	-0.389	-0.259	-0.675	-0.283	-0.681	-0.517	1								
HCO3	0.817	0.367	0.272	0.464	0.883	0.414	0.690	0.576	-0.635	1							
F	-0.403	-0.545	-0.473	-0.230	-0.296	-0.617	-0.321	-0.385	-0.038	-0.212	1						
pH	-0.511	-0.279	-0.400	-0.148	-0.495	0.013	-0.431	-0.407	0.652	-0.638	-0.154	1					
EC	0.999	0.766	0.354	0.781	0.957	0.504	0.961	0.892	-0.643	0.832	-0.412	-0.497	1				
TH	0.815	0.751	0.735	0.656	0.594	0.263	0.806	0.895	-0.470	0.520	-0.514	-0.403	0.798	1			
SAR	0.858	0.489	0.047	0.573	0.974	0.545	0.792	0.608	-0.681	0.905	-0.227	-0.511	0.873	0.424	1		
RSC	0.196	-0.214	-0.152	-0.116	0.412	0.124	0.088	-0.139	-0.374	0.627	0.257	-0.563	0.213	-0.193	0.567	1	
Na%	0.681	0.273	-0.028	0.360	0.842	0.442	0.591	0.442	-0.683	0.838	-0.156	-0.559	0.699	0.223	0.926	0.621	1

Table 15: Correlation Matrix during Post Monsoon season in 2022.

Parameters	TDS	NO2+NO3	Ca	Mg	Na	K	Cl	SO4	CO3	HCO3	F	pH	EC	TH	SAR	RSC	Na%
TDS	1																
NO2+NO3	0.861	1															
Ca	0.897	0.756	1														
Mg	0.889	0.946	0.777	1													
Na	0.977	0.776	0.815	0.801	1												
K	0.872	0.830	0.856	0.758	0.820	1											
Cl	0.984	0.810	0.938	0.857	0.950	0.866	1										
SO4	0.970	0.838	0.917	0.866	0.927	0.840	0.962	1									
CO3	-0.348	-0.250	-0.249	-0.248	-0.389	-0.206	-0.316	-0.320	1								
HCO3	0.640	0.586	0.296	0.567	0.726	0.461	0.512	0.534	-0.465	1							
F	-0.113	-0.210	-0.367	-0.196	0.027	-0.215	-0.175	-0.254	-0.288	0.392	1						
pH	0.056	0.177	-0.167	0.115	0.102	0.067	-0.011	-0.057	0.319	0.333	0.186	1					
EC	1.000	0.861	0.894	0.892	0.977	0.868	0.984	0.967	-0.348	0.646	-0.106	0.061	1				
TH	0.946	0.913	0.929	0.955	0.856	0.850	0.946	0.942	-0.263	0.473	-0.289	-0.011	0.946	1			
SAR	0.672	0.379	0.400	0.363	0.810	0.496	0.618	0.576	-0.472	0.789	0.412	0.197	0.672	0.402	1		
RSC	0.059	-0.191	-0.222	-0.218	0.254	-0.016	-0.013	-0.071	-0.172	0.562	0.693	0.345	0.063	-0.233	0.710	1	
Na%	0.342	0.066	0.054	0.037	0.518	0.146	0.290	0.255	-0.426	0.637	0.407	0.227	0.343	0.047	0.870	0.728	1

The Permeability Index classification suggests that most samples fall under the "Good" to "Moderate" category, with only a small percentage being completely unsuitable. Additionally, the Corrosivity Ratio (CR) analysis indicates that a significant portion of groundwater is corrosive, posing potential risks to irrigation infrastructure and groundwater storage systems.

Hydrochemical analysis using the Durov diagram identified ion exchange, mineral dissolution, and anthropogenic pollution as dominant processes affecting groundwater composition. Statistical correlation analysis confirmed strong positive relationships among chloride, sodium, sulfate, and EC, suggesting a common source of contamination, likely from rock-water interactions, industrial discharge, and excessive fertilizer application. The high sodium content in irrigation water suggests potential risks of soil sodicity, which can impact soil permeability and crop yield.

To mitigate groundwater quality issues, it is essential to implement sustainable water management strategies, including rainwater harvesting, artificial groundwater recharge (e.g., check dams, percolation ponds), fluoride and nitrate removal techniques, and controlled agricultural practices. The reduction of excessive fertilizer use, implementation of drip irrigation, and periodic soil conditioning can help minimize groundwater contamination. Regular monitoring and proactive interventions are necessary to prevent further deterioration and ensure the long-term sustainability of groundwater resources in Madurai North Taluk.

This study underscores the pressing need for integrated water resource management policies, community participation, and scientific advancements in groundwater conservation. Ensuring safe and sustainable groundwater usage will support both human consumption and agricultural productivity, thereby securing water resources for future generations.

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