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Assessment of Industrial Impact on Groundwater Quality in Tirupur District: A Statistical Analysis

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Abstract

Groundwater acts as the main supply of drinking water, especially in developing regions. However, rapid industrialization poses significant threats to its quality. This study focuses into the condition of the groundwater in industrial zones of Tirupur District, Tamil Nadu, where accelerated industrial activities have raised serious environmental concerns. A total of 10 sampling locations were selected across key industrial areas, and water samples were analysed for physicochemical parameters during both summer and winter seasons. During the summer, the Water Quality Index (WQI) values varied from 7.14 to 224. and 76 to 210 in winter, indicating that many sites exceed acceptable limits for human consumption. Seasonal variations were assessed graphically, and a correlation matrix was used to explore inter-parameter relationships. Principal Component Analysis (PCA) further identified the dominant pollution factors, explaining 64.84% of total variance in the rainy season and 52.63% in summer. The results highlight a concerning decline in groundwater quality and emphasize the urgent need for sustainable industrial practices and appropriate water treatment interventions.

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Groundwater;
PCA;
Pollution;
Sample;
WQI.

Introduction

In the environment, groundwater is a scarce resource that supports the water needs of over two-thirds of India's population for domestic, agricultural, and industrial purposes.[1,2,5,18,30] With rapid industrial growth and increasing urban demands, the dependence on subsurface water has doubled in recent decades.[1,2] Compared to surface water, groundwater is more resilient to seasonal variability, however, once contaminated, it is extremely difficult to remediate

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due to its slow movement through subsurface formations. This makes groundwater contamination a silent and long-lasting environmental threat.[4,24]

Recent assessments by the Central Ground Water Board[5] highlight a growing concern: out of 6,584 assessment units across India, 1,034 have been classified as over-exploited, 253 as critical, and 96 as saline.[3] In states like Tamil Nadu, particularly in districts like Tirupur that host dense clusters of textile and dyeing industries, industrial effluent discharge and overuse of fertilizers have been reported as major contributors to groundwater degradation.[6,7] Elevated concentrations of chloride nitrate, sulfate, and heavy metals have been documented in aquifers near industrial zones, threatening both drinking water safety and irrigation viability.[6-9,15]

Despite growing awareness, existing literature presents several research gaps. Most previous studies have either focused on isolated physicochemical analyses or provided single-season snapshots without integrating seasonal variations. Additionally, limited studies have applied comprehensive water quality assessment tools[10,11] such as the Water Quality Index (WQI), or used Multiple-variable statistical techniques like Principal Component Analysis (PCA) to identify and interpret pollution sources.[7,9]

Furthermore, the use of Geographic Information Systems (GIS) for the spatial depiction of groundwater quality has not been widely adopted in localized studies of Tirupur district, despite its known industrial stress.[1,3,12]

To bridge these gaps, the present study provides a comprehensive, seasonally stratified assessment of groundwater quality in selected industrial regions of Tirupur District. It evaluates samples from 10 locations during both summer and winter seasons, using WQI to determine suitability for human use, correlation matrices to understand inter-parameter relationships, and PCA to identify dominant pollution sources. The study also explores spatial patterns using GIS, offering actionable insights for sustainable groundwater management and pollution mitigation in rapidly industrializing environment

Study Area
The location of the samples was selected based on the industrial areas. Tirupur is one of the cities which is situated inside the state of Southern India known as Tamil Nadu which has many industries around the Noyyal River.[10] The samples were collected in residential areas near the industrial sectors .[16,26] Ten location was selected nearby the industrial areas and the samples were collected with the help of bottles and stored in a cool storage.

Materials and Methods
Groundwater recharging is a mainly as a result of rain water, infiltration in monsoon and non-monsoon periods, rainfall, seepage from wet cultivation, infiltration from tanks, check dams, canals and reservoirs.[14,22] Since there is a scarcity of water storage especially for the following raining seasons the water available in the wells of the banks is only available during the rainy seasons. In this study 20 physicochemical characteristics include color, appearance, odor, temperature, turbidity, electrical conductivity (EC), pH, alkalinity, hardness, and total dissolved oxygen (TDS), Dissolved oxygen (DO), manganese, calcium, magnesium, sodium, potassium, chloride, fluoride, sulfate, and phosphate were assessed from 10 location, which were assessed and compared with BIS 10500: 2012 for drinking purposes tabulated in Table 1, Table 3 and Table 5. Samples were collected in dry, clean plastic bottles and are stored in refrigerator and all the samples are examined with the help of manuals and the values are noted and analysed periodically.[13] For both rainy and summer seasons the samples are collected and analysed manually using titration methods.[19,20]

Methodology
The study commenced with the selection of suitable study areas based on factors such as population density, reliance on groundwater, agricultural activity, and potential contamination sources.[21,22] Ten borewell sampling points were then identified within the study region, ensuring appropriate spatial distribution and accessibility. Groundwater samples were collected during both summer and winter to take seasonal changes in water quality into consideration. The samples were obtained following standard procedures, stored in pre-cleaned polyethylene bottles, and transported under refrigeration for laboratory analysis.[6,7,8]

Various physicochemical parameters were analysed using standard methods in the code book Indian Standards for Water Supply and Quality- IS 10500:

1991: Drinking water standards- IS 3025: Methods of sampling and testing for water and wastewater, covering parameters like pH, turbidity, and chemical contaminants.

The Water Quality Index (WQI), which assigns weights to each parameter according to their relative importance, was computed using the weighted arithmetic index approach. Statistical tools such as the Pearson correlation coefficient matrix were employed to identify relationships among water quality parameters.

Table 1: Sampling site details with latitude and longitude

S.no	Sample Location	Latitude	Longitude
1	Parapalayam	11˚07 ’42.47” N	77˚22 ’35.27” E
2	Koolipalayam	11˚08 ’36.28” N	77˚23 ’02.39” E
3	Sicar Periapalayam	11˚07 ’46.99” N	77˚24 ’14.37” E
4	Veliampalayam	11˚08 ’21.35” N	77˚24 ’57.56” E
5	SIDCO	11˚07 ’21.06” N	77˚24 ’39.52” E
6	Kulathupalayam	11˚07 ’25.10” N	77˚23 ’12.00” E
7	Valliyammai Nagar	11˚06 ’20.80” N	77˚22 ’30.54” E
8	VGV	11˚06 ’50.05” N	77˚22 ’58.72” E
9	Nallur	11˚05 ’37.69” N	77˚23 28.62” E
10	South Nallur	11˚05 ’50.26” N	77˚24 ’36.35” E

Table 2: Classification of groundwater quality based on Water Quality Index (WQI) using the weighted arithmetic method.[1,4,7]

WQI	Class of Rating
0-25	Great
26-50	Good
51-75	Poor
75-100	Extremely Poor
>100	Unsuitable

Results

Physicochemical Characteristics

The statistical analysis of groundwater samples from Tirupur District revealed substantial variation in key physicochemical parameters across sites and seasons. Total Dissolved Solids (TDS) and Electrical Conductivity (EC) recorded mean values of 2058.4 mg/L and 2940.1 µmho/cm in summer, and 1794.6 mg/L and 2563.0 µmho/cm in the rainy season, respectively, both of which exceeded BIS permissible limits. Hardness, calcium, magnesium, sodium, and chloride concentrations also surpassed acceptable levels in several locations, indicating contamination from both geogenic and anthropogenic sources.[25,26] Fluoride levels reached as high as 3.6 mg/L, exceeding the 1.5 mg/L limit, raising potential health concerns.[27-29]

Water Quality Index (WQI)

The WQI classification revealed that groundwater quality at many sites fell into “poor” or “unsuitable” categories. During summer, WQI values ranged from 7.14 (good) to 224 (unsuitable), while in the rainy season they ranged from 85 (very poor) to 481 (unsuitable). These values indicate that a considerable proportion of the study area is unsafe for direct human consumption without treatment.[27]

Seasonal Variations

Seasonal variation was evident in the results. Higher concentrations of TDS, hardness, and chloride were observed in summer, likely due to evaporation and reduced dilution. In contrast, the rainy season showed improved quality at some sites due to dilution but deterioration at others due to surface runoff carrying pollutants into aquifers. Figures 1–13 illustrate these variations in key parameters such as TDS, hardness, EC, sodium, chloride, calcium, and fluoride.[23]

Correlation Analysis

Pearson correlation analysis (Figures 14 and 15) highlighted strong positive relationships between

TDS and EC, chloride and hardness, and calcium and total hardness. Negative correlations were observed between dissolved oxygen (DO) and TDS/EC, suggesting that increased salinity reduces oxygen availability. These interrelationships provide insights into common pollution sources and chemical interactions in groundwater.[17]

Principal Component Analysis (PCA)

The PCA results (Table 7; Figures 16–17) identified major pollution sources influencing groundwater chemistry. In summer, the first two components explained 64.84% of the total variance, while in the rainy season they explained 52.63%. Industrial effluents, agricultural runoff, and natural geogenic processes were identified as dominant contributors to groundwater contamination.

Descriptive Statistical of the groundwater quality and its coherence with BIS standard (SUMMER) are mentioned in table 3

Table 3: Descriptive statistics of physicochemical parameters of groundwater samples (summer season) compared with BIS standards

Water standards		Analysis of Observed Values Using Statistics			
PARAMETER	**BIS**	**MAX**	**MIN**	**MEAN**	**SD**
TDS (mg/l)	500mg/l	3800	421	20584	1009.094
EC (µ mho/cm)	1400µ mho/cm	5428	601	29401	1441.472
pH	6.5 to 8.5	8.56	7.344	92.54	0.390504
Alkalinity (mg/l)	200mg/l	444	220	3652	78.14772
Hardness (mg/l)	300mg/l	960	213	6245	286.8665
Calcium (mg/l)	75mg/l	284	120	2035	53.62514
Magnesium (mg/l)	30mg/l	96	32	845	20.75813
Sodium (mg/l)	200mg/l	288	123	2447	42.97596
Potassium (mg/l)	30mg/l	32	8	224	8.085653
Chloride (mg/l)	250mg/l	680	166	4200	165.4228
Fluoride (mg/l)	1.5mg/l	3.6	0.1	16.82	1.096508
Sulphate (mg/l)	200mg/l	394	41	1833	104.0126
Phosphate (mg/l)	0.1mg/l	0.32	0	1.738	0.119039
Turbidity	5	21.9	10.3	156.7	3.468349
DO (mg/l)	4.0mg/l	6.24	1.3	44.69	1.513732

The statistical summary of groundwater samples from Tirupur District reveals significant variation in key physicochemical parameters, many of which exceed BIS (10500–2012) permissible limits. Total Dissolved Solids (TDS) and Electrical Conductivity (EC) showed elevated mean values of 2058.4 mg/L and 2940.1 µmho/cm, respectively, suggesting high ionic concentrations and possible contamination from industrial discharges. Hardness, calcium, magnesium, and chloride also surpassed acceptable limits, indicating both geogenic and anthropogenic influences.

Fluoride levels exceeded the BIS threshold and posed possible health hazards; they ranged up to 3.6 mg/L, with a mean value of 1.68 mg/L.

The high standard deviations in parameters such as TDS, hardness, and sulphate reflect strong spatial variability across the study sites. Parameters like phosphate, turbidity, and nitrate further point toward agricultural runoff and wastewater intrusion. While pH values were generally within the acceptable range, other indicators suggest deterioration of groundwater quality in the region. These findings emphasize the need for site-specific groundwater management strategies and regular monitoring to mitigate industrial and agricultural impacts.

Table 4: Water Quality Index (WQI) values and classification of groundwater samples (summer season) in Tirupur District.

Sample No	Sample Source	WQI Value	Class
S1	Bore Well	69.54	Poor
S2	Bore Well	224.04	Unsuitable
S3	Bore Well	79.89	Poor
S4	Bore Well	170.32	Unsuitable
S5	Bore Well	211.66	Unsuitable
S6	Bore Well	158.89	Unsuitable
S7	Bore Well	71.44	Poor
S8	Bore Well	7.14	Good
S9	Bore Well	8.12	Good
S10	Bore Well	34.01	Good

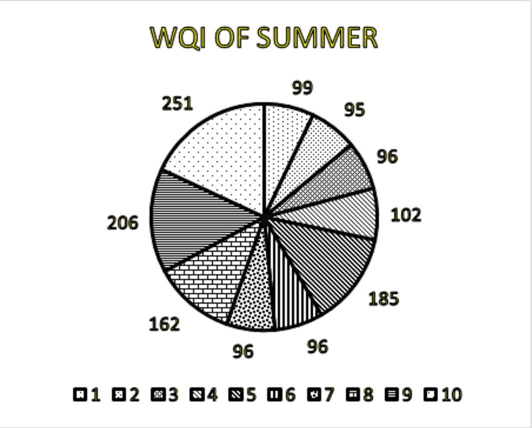
Table 5: Descriptive statistics of physicochemical parameters of groundwater samples (rainy season) compared with BIS standards.

Water standards		Analysis of observed values using statistics			
PARAMETER	**BIS**	**MAX**	**MIN**	**MEAN**	**SD**
TDS (mg/l)	500mg/l	2540	660	17946	627.7473
EC (µ mho/cm)	1400µ mho/cm	3628	942	25630	896.84
pH	6.5 to 8.5	9.4	7.4	98.88	0.717229
Alkalinity(mg/l)	200mg/l	432	226	3907	75.05916
Hardness(mg/l)	300mg/l	745	210	5370	179.7846
Calcium(mg/l)	75mg/l	256	118	1985	42.68086
Magnesium(mg/l)	30mg/l	106	35	797	23.88956
Sodium(mg/l)	200mg/l	300	84	1871	67.73486
Potassium(mg/l)	30mg/l	30	8	198	7.363574
Chloride(mg/l)	250mg/l	319	81	2233	86.77948
Fluoride(mg/l)	1.5mg/l	2.8	0.2	13	0.946338
Sulphate(mg/l)	200mg/l	388	57	2155	102.6385
Phosphate(mg/l)	0.1mg/l	0.76	0.1	3.18	0.199822
Turbidity	5	15.4	12.5	164.8	0.958529
DO (mg/l)	4.0mg/l	8.96	1.08	46.42	2.298027

Table 6: Water Quality Index (WQI) values and classification of groundwater samples (rainy season) in Tirupur District.

Sample No	Sample Source	WQI Value	Class
S1	Bore Well	89.10	Very poor
S2	Bore Well	210	Unsuitable
S3	Bore Well	76.13	Very poor
S4	Bore Well	180	Unsuitable
S5	Bore Well	481	Unsuitable

S6	Bore Well	162	Unsuitable
S7	Bore Well	94.52	Very poor
S8	Bore Well	85.05	Very poor
S9	Bore Well	136.01	Unsuitable
S10	Bore Well	85.62	Very poor



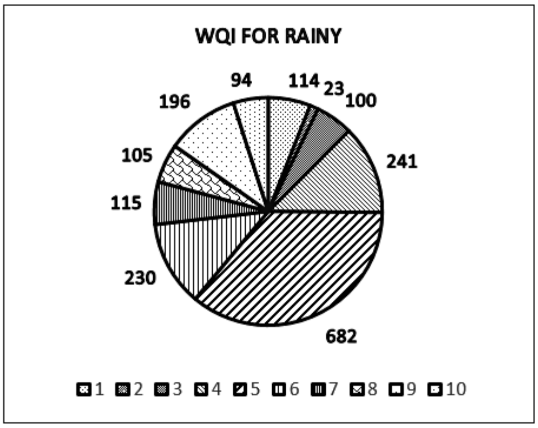


Fig. 1: Seasonal variation of Water Quality Index (WQI) values in groundwater samples across Tirupur District (summer vs rainy seasons).

The groundwater quality data from the industrial areas of Tirupur District show considerable variation in key physicochemical parameters when compared with BIS (10500:2012) standards. Total Dissolved Solids (TDS) and Electrical Conductivity (EC) recorded mean values of 1794.6 mg/L and 2563.0 µmho/cm, respectively, far exceeding their respective limits (500 mg/L and 1400 µmho/cm), indicating high salinity and ionic load likely influenced by industrial discharges. Parameters such as hardness (mean: 537.0 mg/L), calcium (198.5 mg/L), magnesium (79.7 mg/L), sodium (187.1 mg/L), and chloride (223.3 mg/L) also surpassed acceptable levels, reflecting both geogenic influence and anthropogenic contamination. Fluoride (mean: 1.3 mg/L) and sulphate (mean: 215.5 mg/L) approached or slightly exceeded safe limits, raising health concerns in some locations.[29]

High standard deviations, particularly in TDS, hardness, and sulphate, suggest significant spatial variability across the sampling sites. The pH values ranged from 7.4 to 9.4, with some samples exceeding the upper BIS threshold of 8.5, indicating possible alkaline conditions. Elevated turbidity, phosphate, and dissolved oxygen (DO) levels may be attributed to organic waste and agricultural runoff. These findings reflect the degraded groundwater condition in the industrial belt of Tirupur and underscore the urgent need for periodic monitoring, localized treatment interventions, and stricter regulation of industrial effluent disposal.

The Water Quality Index (WQI) analysis across 10 groundwater locations in Tirupur reveals clear seasonal variation between summer and rainy seasons. During summer, the WQI values ranged from 95 to 251, with most locations (Loc 4, 6, 7, 9, and 10) indicating moderate to high levels of contamination. This suggests reduced dilution capacity and potential concentration of pollutants during dry months due to lower recharge and higher water usage.

In contrast, rainy season WQI values ranged from 94 to a peak of 682 at Loc 6, showing a more extreme spatial variation. While some locations showed improvement due to rainwater dilution (e.g., Loc 1–4), others (notably Loc 6 and 7) exhibited worsening quality, likely from surface runoff carrying industrial and agricultural pollutants into shallow aquifers. The very high WQI in Loc 6 during the rainy season strongly suggests that surface-to-groundwater interaction and contamination are significant during monsoon months in industrial zones.

These seasonal disparities underscore the importance of dynamic water management strategies, tailored to both climatic conditions and land use patterns, especially in industrialized zones like Tirupur.

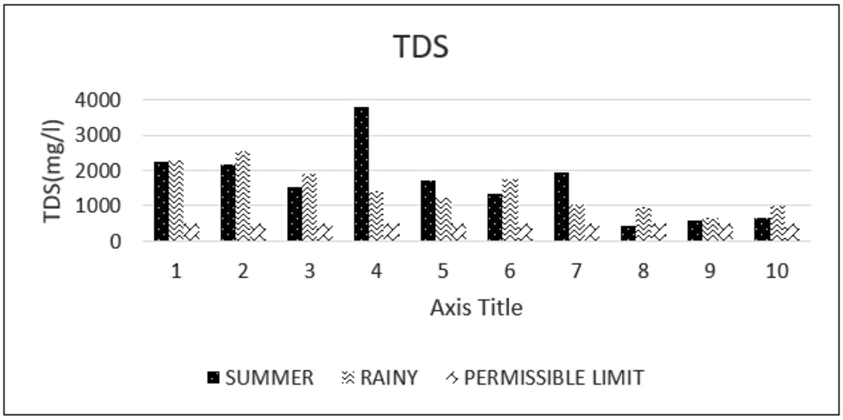


Fig. 2: Total Dissolved Solids (TDS) concentrations in groundwater samples during summer and rainy seasons compared with BIS permissible limits.

In most locations, the TDS levels during the summer season are notably higher than in the rainy season, with some values such as sample point 4 showing a drastic spike well above 3000 mg/L. This exceeds the permissible limit, indicating poor water quality, especially during drier periods. The elevated TDS levels in summer could be due to evaporation, increased mineral runoff, or reduced dilution in the water sources. In the context of current global environmental concerns, such as climate change and water scarcity, this suggests that water quality is likely to worsen in drier, hotter seasons, which are becoming more frequent and intense due to global warming.

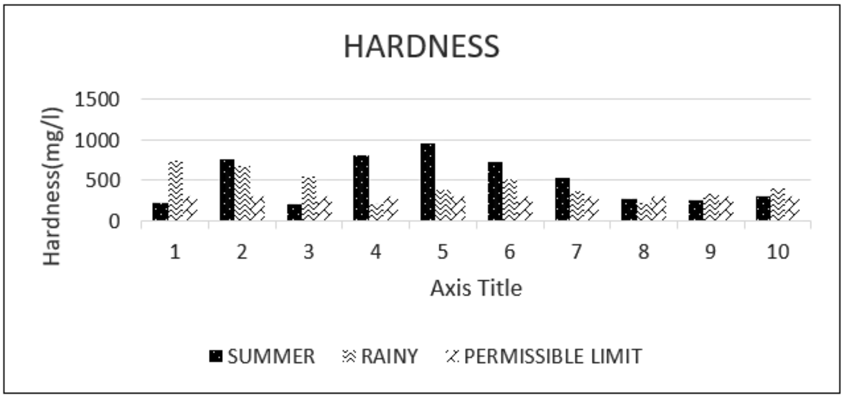


Fig. 3: Seasonal variation in groundwater hardness levels at study locations relative to BIS standards.

Sample points such as 2, 4, and 5 show hardness levels exceeding permissible limits in summer. which, because of increased rates of evaporation and mineral leaching, can be more common during the dry season. The rainy season brings down these concentrations through dilution. This trend reflects broader environmental issues such as increased mineral pollution due to urban runoff and declining groundwater quality, which are exacerbated by human activities and climate variability. The presence of high hardness levels in drinking water can pose health risks and also damage infrastructure through scaling in pipes and appliances.

These results highlight the significance of routine evaluations of water quality and incorporating all of environmental monitoring into infrastructure design and public health.

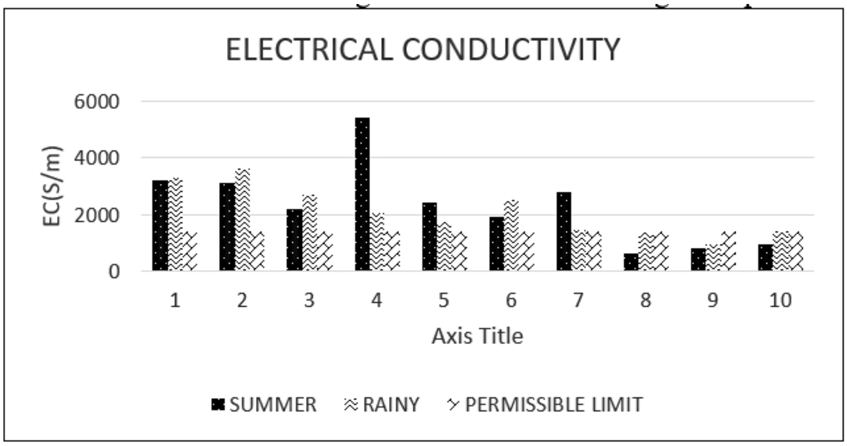


Fig. 4: Electrical conductivity (EC) of groundwater samples across summer and rainy seasons in Tirupur District industrial zones.

The spike in EC during summer suggests higher concentrations of these ions, likely due to increased evaporation, limited dilution, and possible leaching of contaminants from dry soils and industrial runoff. In contrast, the rainy season shows a noticeable reduction in EC, likely due to dilution by rainfall. In the context of global environmental challenges, especially those related to climate change and urbanization, such trends indicate rising pollution and salinization of water sources. The increased ion concentration in dry seasons could threaten both agriculture (through soil salinity) and drinking water quality, making it essential to monitor EC as a key indicator of environmental and water system health

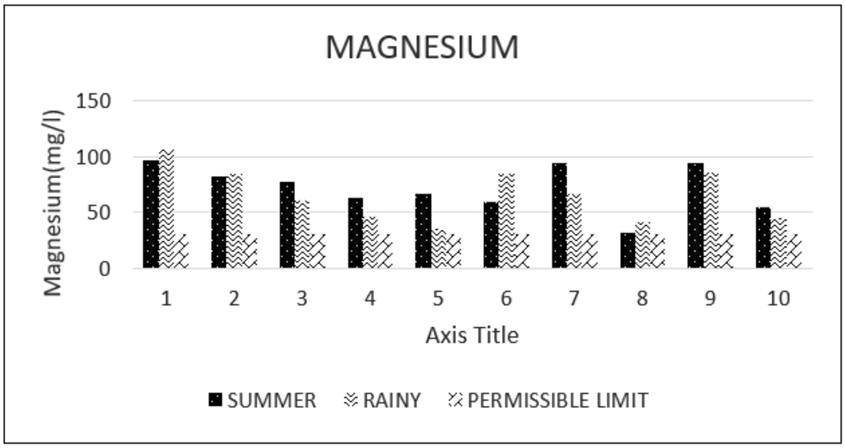


Fig. 5: Magnesium concentration in groundwater samples across summer and rainy seasons.

The magnesium concentration graph reveals elevated levels in the summer season compared to the rainy season at most sampling sites. In some locations, the values either approach or exceed the permissible limit, such as at sample point 1 and 7. Magnesium is a common mineral found in groundwater, and elevated levels often arise from weathering of rocks or anthropogenic sources such as fertilizer runoff and industrial waste. Higher levels during summer suggest intensified leaching and reduced dilution, while rainy season values are generally lower due to the dilution effect.

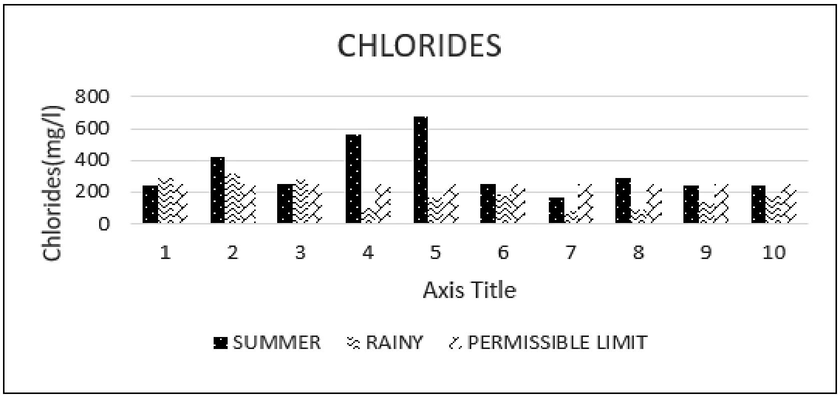


Fig. 6: Chloride levels in groundwater samples compared with BIS permissible limits during both seasons.

Particularly at locations like 4 and 5, the chloride levels exceed the permissible limit of 250 mg/L, reaching values above 600 mg/L. This seasonal spike is often attributed to factors such as increased evaporation, which concentrates salts, and possibly anthropogenic influences like sewage discharge or industrial effluents that become more prominent in the absence of rainfall dilution. The reduction in chloride levels during the rainy season is likely due to the diluting effect of rainwater. High chloride concentrations can make water unpalatable and corrosive, and pose health risks in vulnerable populations. It also contributes to the salinization of agricultural soils, which is a growing global threat to food security.

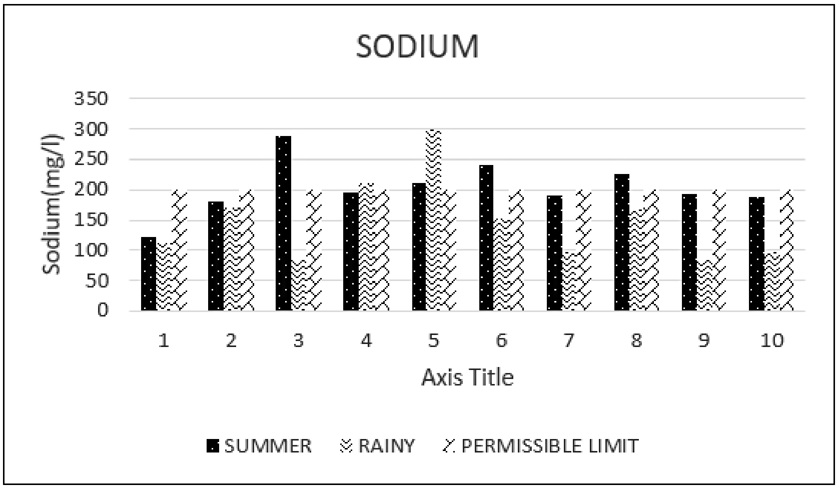


Fig. 7: Sodium concentrations in groundwater samples (summer and rainy seasons) relative to standard limits.

The sodium content chart shows that in both summer and rainy seasons, values across many sites remain close to or above the permissible limit, with minimal seasonal variation compared to other parameters. Notably, points 3 and 5 exhibit significant spikes, with summer values nearing or exceeding 300 mg/L. Sodium in drinking water is often introduced through natural mineral deposits, industrial pollution, or excessive use of road salts and fertilizers. The relatively consistent sodium levels across seasons may suggest persistent anthropogenic sources that are less affected by dilution from rainfall.

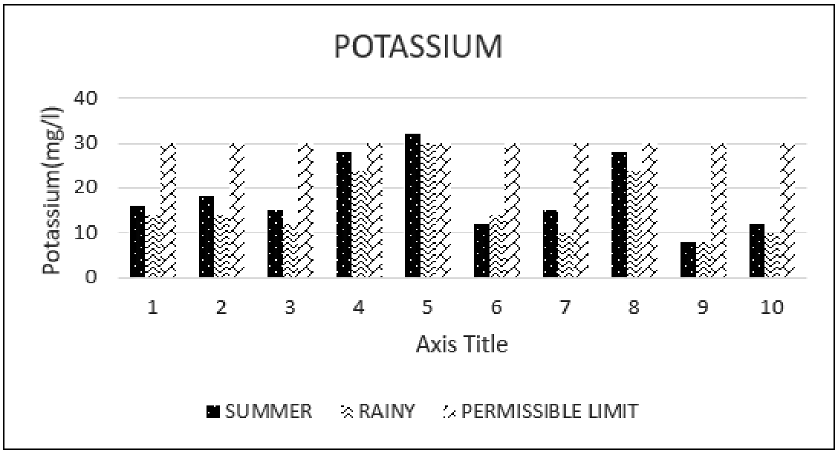


Fig. 8: Potassium concentration trends in groundwater samples during summer and rainy seasons.

The potassium concentration graph reveals moderate levels across all locations, with a clear seasonal variation where summer values are generally higher than those in the rainy season. At sites such as 4, 5, and 7, the potassium content reaches or slightly exceeds 30 mg/L, though it mostly remains within the permissible limits. Potassium, being a naturally occurring element in soils and fertilizers, often seeps into water systems due to agricultural runoff, especially during dry seasons when evapotranspiration increases the concentration of dissolved substances. In the rainy season, dilution from precipitation reduces its presence in water bodies. Globally, potassium is less frequently monitored in water quality programs, yet its increase is an indicator of agricultural intensification and unsustainable land use.

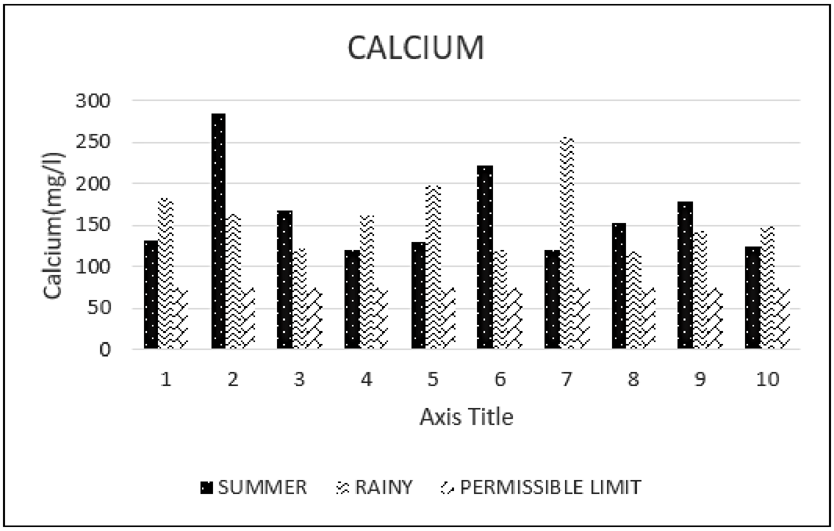


Fig. 9: Calcium levels in groundwater samples compared with permissible limits across study sites.

The calcium chart exhibits notable variability among sampling points, with summer concentrations generally higher than rainy season values, particularly at points 1, 2, 5, and 6. Elevated calcium levels can be attributed to natural rock weathering, especially in calcareous regions, as well as industrial effluents and leaching from construction materials. Seasonal concentration changes are primarily due to evaporation during the summer, which concentrates minerals in the water.

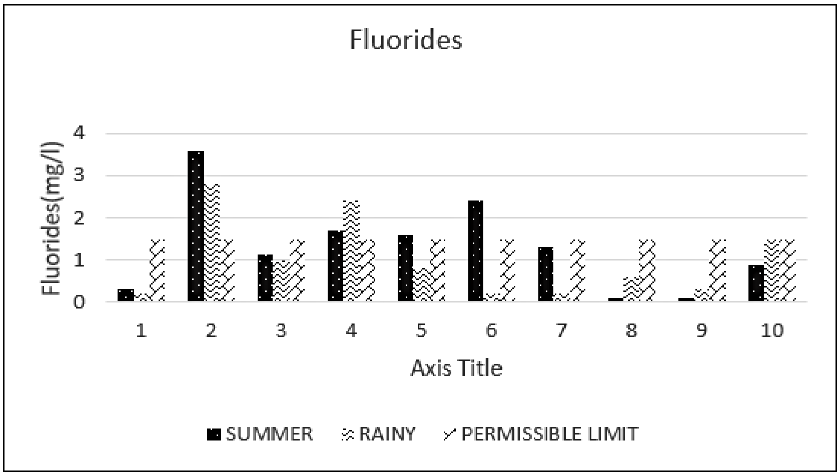


Fig. 10: Fluoride concentrations in groundwater samples (summer vs rainy seasons) with comparison to BIS standards.

The fluoride concentrations show significant fluctuations across the different locations, with several summer values—particularly at location 2 exceeding the permissible limit of 1.5 mg/L, reaching nearly 3.5 mg/L. In general, fluoride levels are higher in the summer compared to the rainy season, likely due to reduced water volume and increased leaching from fluoride-bearing minerals under high temperatures. The data suggests the need for localized water treatment strategies such as activated alumina filtration, and underscores the importance of integrating geogenic contamination monitoring into public health frameworks in an era of increasing water scarcity and climate stress.

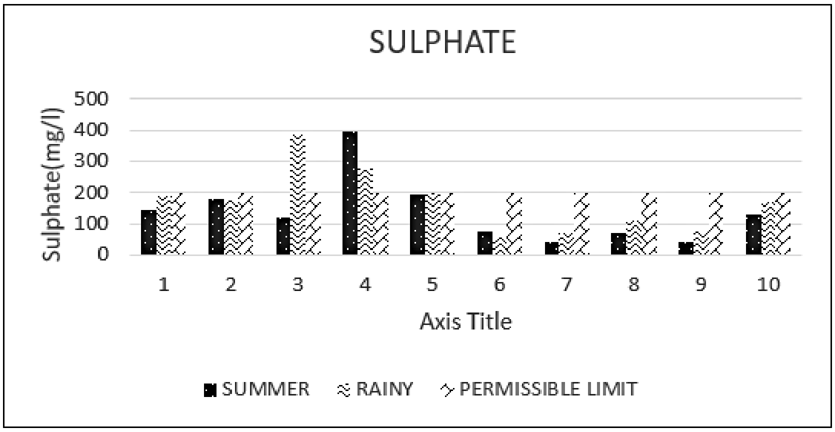


Fig. 11: Sulphate levels in groundwater samples across summer and rainy seasons compared with permissible limits.

The sulphates graph illustrates that levels across most sites remain within permissible limits, though peaks are observed at sites 3 and 4, especially during the rainy season. The increase during rainfall can be attributed to runoff from agricultural fields and industrial areas, which introduces sulphate-rich fertilizers and byproducts into water bodies. Elevated sulphate levels are not typically toxic when combined with chloride and other salts.

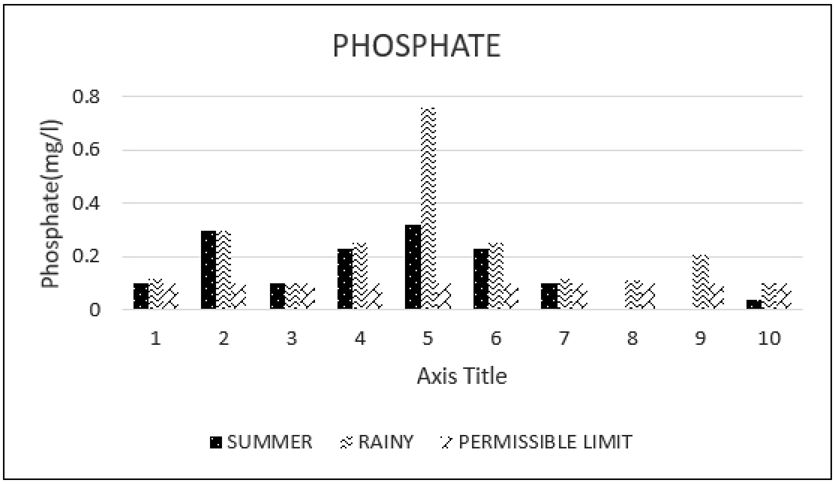


Fig. 12: Phosphate concentrations in groundwater samples during summer and rainy seasons indicating agricultural influence.

The phosphate levels in the chart remain mostly within permissible limits (typically set at 0.1 mg/L for surface water), with noticeable spikes at locations 2, 4, and especially 5 during the rainy season. This trend suggests strong influence from agricultural runoff during monsoon periods, where phosphate-rich fertilizers are washed into local water bodies. This nutrient enrichment leads to algal blooms, oxygen depletion, and the collapse of aquatic ecosystems. The significant increase in phosphate concentrations during rainy seasons across multiple sites highlights a broader issue: poor land use management and unregulated agricultural practices.

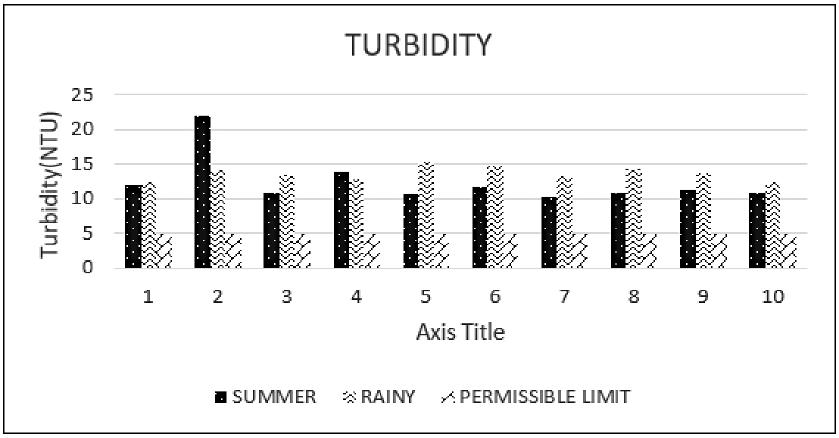


Fig. 13: Turbidity of groundwater samples compared with WHO permissible limits across summer and rainy seasons.

Turbidity levels show consistent exceedance of the permissible limit (5 NTU for drinking water by WHO standards) at most sites, especially in the summer season at location 2, which spikes above 20 NTU. This poses serious risks to water safety, especially in areas lacking advanced filtration. Turbid water not only interferes with disinfection processes but is also a visual indicator of deteriorating water quality.

Pearson Coefficent Matrix

	SAMPLE	*TDS*	*EC*	*pH*	*AL*	*TH*	*Ca*	*Mg*	*Na*	*K*	*Cl*	*F-*	*SO2-4*	*PO4*	*Turbidity*	*DO*
SAMPLE	1.0															
TDS	-0.9	1.0														
EC	-0.9	1.0	1.0													
pH	0.5	-0.3	-0.3	1.0												
AL	-0.1	-0.2	-0.2	-0.6	1.0											
TH	-0.7	0.8	0.8	0.0	-0.5	1.0										
Ca	-0.1	-0.1	-0.1	-0.1	0.2	0.0	1.0									
Mg	-0.4	0.5	0.5	0.1	-0.7	0.7	0.0	1.0								
Na	-0.2	0.0	0.0	-0.3	0.7	-0.2	0.2	-0.5	1.0							
K	-0.2	-0.1	-0.1	-0.5	0.8	-0.4	0.0	-0.6	0.9	1.0						
Cl	-0.7	0.9	0.9	-0.1	-0.4	0.9	-0.2	0.5	-0.2	-0.3	1.0					
F-	-0.3	0.4	0.4	-0.4	0.2	0.0	-0.1	-0.3	0.3	0.2	0.3	1.0				
SO2-4	-0.5	0.4	0.4	-0.4	0.3	0.1	-0.2	-0.3	0.1	0.2	0.4	0.5	1.0			
PO4	-0.2	0.0	0.0	0.0	0.3	-0.1	0.2	-0.3	0.9	0.7	0.0	0.1	0.0	1.0		
Turbidity	0.0	-0.1	-0.1	0.0	0.1	-0.1	-0.1	-0.3	0.6	0.5	-0.1	-0.1	-0.2	0.7	1.0	
DO	0.2	-0.4	-0.4	-0.1	0.3	-0.7	-0.2	-0.3	-0.1	0.1	-0.5	0.3	0.3	-0.2	-0.4	1.0

Fig. 14: Pearson correlation coefficient matrix for groundwater quality parameters (summer season).

	SAMPLE	*TDS*	*EC*	*pH*	*AL*	*TH*	*Ca*	*Mg*	*Na*	*K*	*Cl*	*F-*	*SO2-4*	*PO4*	*Turbidity*	*DO*
SAMPLE	1															
TDS	-0.7	1.0														
EC	-0.7	1.0	1.0													
pH	-0.5	0.3	0.3	1.0												
Alkalinity	0.0	0.5	0.5	0.0	1.0											
Hardness	-0.2	0.5	0.5	0.6	0.6	1.0										
Calcium	-0.3	-0.1	-0.1	0.7	-0.3	0.2	1.0									
Magnesium	-0.4	0.3	0.3	0.1	-0.4	-0.1	0.1	1.0								
Sodium	0.2	-0.3	-0.3	-0.2	0.0	0.0	0.2	-0.4	1.0							
Potassium	-0.2	0.4	0.4	0.1	0.9	0.5	-0.3	-0.5	0.0	1.0						
Chloride	-0.3	0.5	0.5	0.4	0.9	0.8	0.0	-0.2	0.0	0.8	1.0					
Fluoride	-0.4	0.4	0.4	0.9	0.2	0.7	0.7	0.0	0.1	0.1	0.4	1.0				
Sulphate	-0.4	0.8	0.8	0.2	0.8	0.5	-0.2	-0.1	-0.2	0.6	0.7	0.3	1.0			
Phosphate	-0.6	0.6	0.6	0.8	0.5	0.9	0.4	0.0	0.0	0.4	0.7	0.8	0.6	1.0		
Turbidity	-0.5	0.4	0.4	0.8	0.1	0.4	0.8	0.2	-0.2	0.0	0.3	0.7	0.4	0.5	1.0	
DO	-0.3	0.6	0.6	0.5	0.5	0.7	-0.2	0.3	-0.6	0.3	0.6	0.3	0.5	0.7	0.2	1.0

Fig. 15: Pearson correlation coefficient matrix for groundwater quality parameters (rainy season).

Hence, the influence derived from the parameters of water quality correlation studies is critical in the study of groundwater.

In Figure 14 calcium and pH(0.70), Alkalinity and potassium, chloride and alkalinity (0.9), chloride and Total Hardness (0.8), Fluoride and pH(0.9), Phosphate and pH(0.9), Phosphate and Total Hardness (0.9), Calcium and Turbidity (0.8) shows strong positive relationship towards the samples

In Figure 15 Total Hardness and TDS (0.80), Total Hardness and EC (0.80), Magnesium and Alkalinity (0.7), Magnesium and Total Hardness (0.7), Potassium and Alkalinity (0.8), Phosphate and Sodium (0.9) shows strong positive relationship towards the samples.

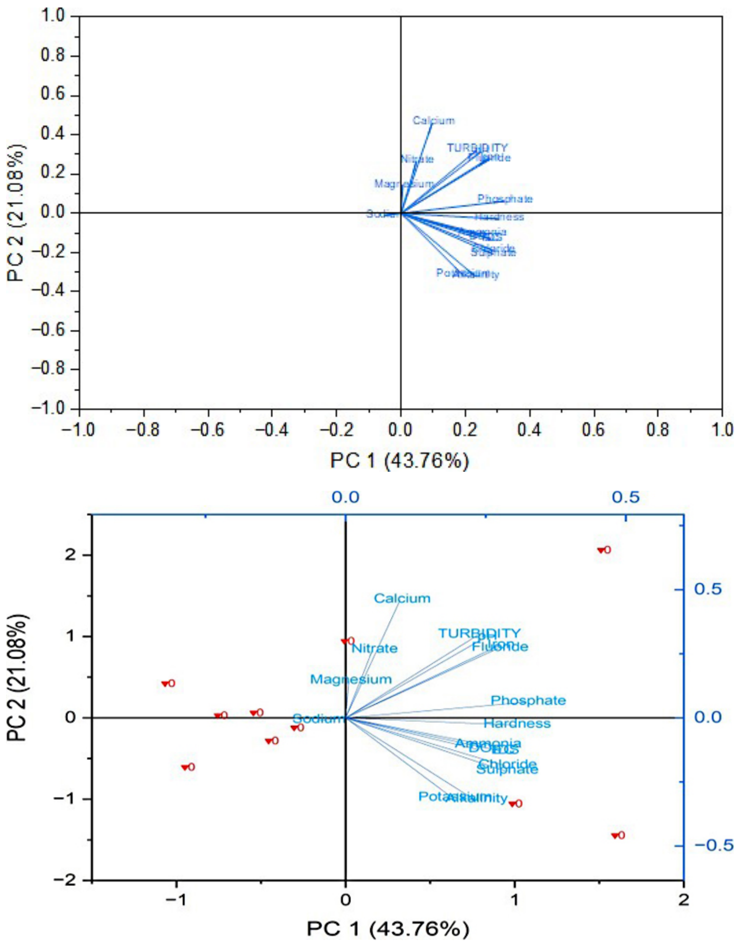


Fig. 16: Principal Component Analysis (PCA) of groundwater parameters for the summer season.

The Pearson correlation matrix of rainy groundwater samples reveals significant relationships among various physicochemical parameters. Electrical Conductivity (EC) shows a very strong positive correlation with Total Dissolved Solids (TDS) (r = 1.0), Chloride (Cl^-) (r = 0.9), and Calcium (Ca^{2+}) (r = 0.8), suggesting that EC is primarily influenced by the presence of dissolved salts. Similarly, Total Hardness (TH) is positively correlated with Calcium (r = 1.0) and Magnesium (Mg^{2+}) (r = 0.5), indicating that hardness is largely controlled by these cations.

pH exhibits a moderate negative correlation with parameters like Aluminium (Al) (r = –0.6) and Turbidity (r = –0.1), suggesting that acidic conditions may increase metal solubility. Notably, Sodium (Na^+) and Potassium (K^+) show moderate correlations with each other and with Chloride and EC, pointing to possible anthropogenic or industrial influences. Dissolved Oxygen (DO) is negatively correlated with TDS, EC, and Cl^-, which may imply that higher salinity reduces oxygen availability.

These correlations are critical for identifying pollution sources and understanding chemical interactions within groundwater systems in industrial areas during the rainy season.

Notably, the strong positive correlation between TDS and EC indicates that TDS is a major contributor to electrical conductivity. The relationships between pH and parameters like Fluoride and Phosphate suggest potential influences of agricultural or industrial activities on water quality. Furthermore, the correlations between hardness and ions like Chloride and Phosphate highlight the importance of considering multiple parameters in water quality management. These findings have implications for developing effective water treatment strategies and managing water resources sustainably during the rainy season.

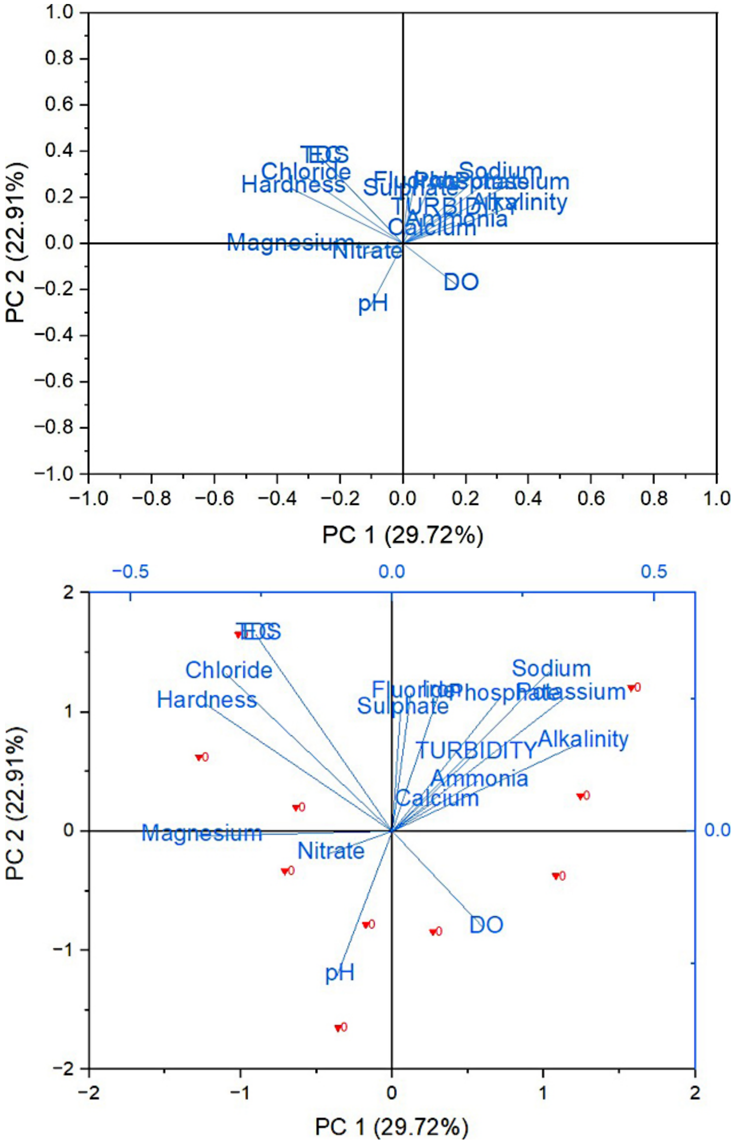


Fig. 17: Principal Component Analysis (PCA) of groundwater parameters for the Rainy season.

Table 7: Rotated component matrix from Principal Component Analysis (PCA) of groundwater chemical parameters for summer and rainy seasons.

PARAMETERS	PRINCIPAL COMPONENT			
	SUMMER		Rainy	
	PC-I	PC-II	PC-I	PC-II
TDS	0.2782	-0.1302	-0.2603	0.3702
EC	0.2782	-0.1301	-0.2603	0.3702
pH	0.2488	0.3142	-0.1055	-0.2728
Alkalinity	0.2296	-0.3193	0.3603	0.1669
Hardness	0.3021	-0.0287	-0.3588	0.2413
Calcium	0.0971	0.459	0.0804	0.0558
Magnesium	0.0057	0.1429	-0.3693	-0.0091
Sodium	-0.0516	-0.0105	0.2986	0.2997
Potassium	0.1914	-0.3138	0.336	0.2566
Chloride	0.285	-0.1876	-0.3173	0.2967
Fluoride	0.2717	0.2709	0.0355	0.2603
Sulphate	0.2847	-0.2074	0.016	0.2292
Phosphate	0.3223	0.061	0.209	0.2553
TURBIDITY	0.2353	0.3219	0.1566	0.1447
DO	0.2359	-0.1241	0.1747	-0.1825
Eigen values	3.7857	0.5584	0.126	2.7949
%variance	43.76%	21.08%	29.72%	22.91%
Cumulative %	43.76%	64.84%	29.72%	52.63%

Discussion

The study's findings highlight the critical need for dynamic water management strategies in Tirupur district, where seasonal variations significantly impact groundwater quality. The elevated Water Quality Index (WQI) values during both summer and rainy seasons indicate contamination from various sources, including industrial effluents and agricultural runoff. By addressing these research directions and implementing effective water management strategies, the study can contribute to improving water quality, protecting public health, and promoting sustainable development in Tirupur district. In this present study the majority of groundwater is unsafe for drinking, according to the results of all indexing techniques, and those locations that are unsafe for drinking require treatment before consumption.

The comparison of correlation matrices between summer and rainy seasons can provide valuable insights into seasonal variations in water quality dynamics. By analyzing these correlations, policymakers and water managers can identify key parameters to monitor and create focused interventions to safeguard public health and enhance water quality. Ultimately, this knowledge can contribute to more effective and sustainable water resource management practices. From the analysed values according to BIS 10500: 2019 standards, physicochemical parameters such as pH, alkalinity, magnesium, fluoride are within the permissible limits. The majority of groundwater is unsafe for drinking, according to the results of all indexing techniques, and those locations that are unsafe for drinking require treatment before consumption.

Due to the rapid increase in population and industrial activities major problems occurs hardly following to that the industries can take reducing measures by use of water purifiers, distillation, flocculation, neutralize process, softening, reverse osmosis process, filtration, cation exchange, boiling process can be done. Principal's component-I has explained 43.76 and 64.84 percentage of variance in pre and post monsoon season whereas principal component-II has explained 29.72 and 52.63 percentage of variance respectively. The loading relationship between the variables was displayed graphically in principle components I and II.

Conclusion

The present study demonstrated that Principal Component Analysis (PCA) effectively identified the major hydrogeochemical processes influencing groundwater quality. Two principal components were extracted, explaining the variance in pre- and post-monsoon seasons, with significant loadings observed for parameters such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}, and F^{-}. Seasonal variations revealed higher ionic concentrations during the summer due to reduced dilution and increased evaporation. Elevated levels of TDS, hardness, fluoride, chloride, and turbidity indicate risks to water safety and infrastructure, largely driven by agricultural runoff and industrial effluents. These findings emphasize the need for regular groundwater monitoring, effective treatment technologies, stricter regulation of effluent discharge, and sustainable land-use practices to safeguard water resources and ensure long-term public health protection.

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The authors do not have any conflict of interest.

Data Availability Statement

The manuscript incorporates all datasets produced or examined throughout this research study.

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Permission to reproduce material from other Sources

Not Applicable

Author Contributions

- **Kavinaya Ravi:** Data Collection, Analysis, Writing – Review & Editing.
- **Ravathi Mohanadhas Chandrika:** Visualization, Supervision, Project Administration.

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