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MULTIVARIATE STATISTICAL ANALYSIS FOR GROUNDWATER QUALITY DATA OF KOLAR TALUK, KOLAR DISTRICT, KARNATAKA

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Abstract

Groundwater is a vital resource for domestic, agricultural, and industrial use, and its quality is largely influenced by both natural and anthropogenic processes. The present study evaluates the hydrochemical characteristics of groundwater samples collected during pre-monsoon (PRM) and post-monsoon (PSM) seasons using physicochemical parameters and the data was applied for multivariate statistical techniques. The results indicate that groundwater is neutral to slightly alkaline, dominated by $Ca–Mg–HCO_3$ *facies, reflecting the influence of carbonate weathering and rock–water interaction. Elevated values of electrical conductivity (EC) and total dissolved solids (TDS) suggest moderate mineralization, while high total hardness is primarily controlled by calcium and magnesium ions. Pearson correlation and Principal Component Analysis (PCA) reveal that geogenic processes such as mineral dissolution and ion exchange are the major factors governing groundwater chemistry, with additional contributions from anthropogenic activities, particularly agricultural practices indicated by nitrate enrichment. Seasonal variations show that evaporation enhances salinity during the pre-monsoon period, whereas monsoonal recharge leads to dilution and redistribution of solutes in the post-monsoon season. Although most parameters fall within permissible limits, elevated levels of TDS, hardness, and nitrate in certain locations highlight potential concerns. The study emphasizes the need for continuous monitoring and sustainable management practices to ensure the long-term quality and safety of groundwater resources.*

Keywords: *Groundwater quality, Principle Component Analysis, Kolar taluk, Irrigation application*

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Introduction

Water is an essential natural resource that sustains life and supports key human activities such as agriculture and domestic use. In water resource management, quality is as important as quantity, as it determines the suitability of water for various purposes. Groundwater quality is influenced by both natural factors, including geology and climate, and anthropogenic activities such as irrigation practices and land use patterns. Its chemical composition, controlled by interactions between water and aquifer materials, plays a crucial role in determining its usability under different conditions.

The interpretation of hydrochemical data is often complex due to the involvement of multiple interacting variables. Therefore, advanced analytical approaches are required to effectively understand groundwater systems. In this context, multivariate statistical techniques such as factor analysis (FA) and cluster analysis (CA) have proven to be powerful tools for identifying relationships among variables and interpreting groundwater processes. Many studies have successfully applied these techniques to distinguish contamination sources and evaluate hydrogeochemical evolution (Olmez et al., 1994; Suk and Lee, 1999; Reghunath et al., 2002; Liu et al., 2003; Mahknecht et al., 2003; Farnham et al., 2003; Love et al., 2004; Kim et al., 2005; Yidana et al., 2010; Belkhiri et al., 2011).

In recent decades, groundwater abstraction has increased significantly due to population growth and rising water demand, particularly in regions with limited alternative water sources (Bannerman, 1994; Jorgensen and Banoeng-Yakubo, 2001; Helstrup et al., 2007). In coastal aquifers, such as the Keta basin, this has resulted in elevated electrical conductivity (EC) levels, indicating progressive salinization of groundwater systems (Helstrup et al., 2007). Salinity has become a major concern for both drinking water supply and irrigation, leading to the abandonment of several wells due to poor water quality (Gill, 1969; Bannerman, 1994).

Groundwater remains a critical resource for domestic, agricultural, and industrial uses, particularly in arid and semi-arid regions where it often serves as the primary water source (Aeschbach-Hertig and Gleeson, 2012; Shang et al., 2016). It also plays a significant role in ensuring food security and supporting sustainable development (Wada et al., 2014). However, groundwater quality is increasingly threatened by both natural processes and human activities, necessitating continuous assessment and management. Hydrochemical characteristics are influenced by water–rock interactions, recharge conditions, residence time, and processes such as seawater intrusion (Liu et al., 2003; Belkhiri and Narany, 2015). Additionally, anthropogenic inputs including agricultural practices, chemical usage, and overexploitation can introduce contaminants and accelerate groundwater degradation (Boniol, 1996; Singh, 2014). Climate variability and excessive extraction further exacerbate these impacts (MacDonald et al., 2012 ; Mani et al., 2016).

Traditional methods such as graphical plots and basic statistical analyses often provide limited insights into the complex relationships among hydrochemical parameters (Dalton and Upchurch, 1978; Einax et al., 1997). In contrast, multivariate statistical techniques offer a more robust framework for analysing large datasets, identifying controlling processes, and distinguishing between natural and anthropogenic influences (Davis, 1986; Voudouris et al., 2000; Narvaez et al., 2007). These methods have been widely applied to assess groundwater quality and trace contamination sources in various hydrogeological settings (Alberto et al., 2001; Pereira et al., 2003; Ezekwe et al., 2012; Kazakis et al., 2017).

Therefore, the present study aims to evaluate groundwater quality and identify the dominant hydrogeochemical processes using multivariate statistical techniques. By integrating physicochemical analysis data with statistical methods, provides a comprehensive understanding of groundwater system dynamics and supports effective and sustainable water resource management.

Materials and Methods

Study area

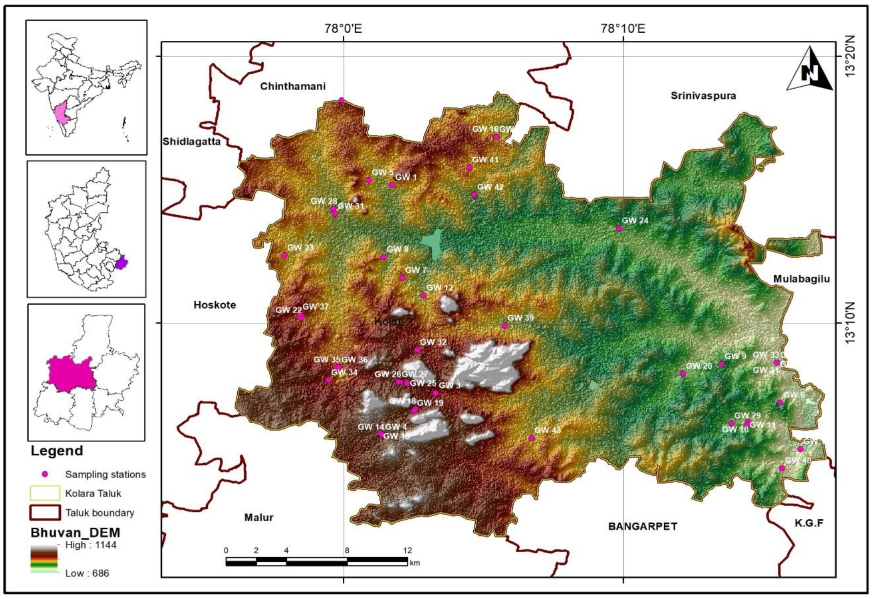


Fig 1. DEM Location map of Kolar taluk, Kolar District

Kolar district is located in the south-eastern part of the state of Karnataka and represents the easternmost district of the state. Geographically, the district is bounded by Bangalore Rural district in the west, Chikkaballapur district in the north, Chittoor district of Andhra Pradesh in the east, and Krishnagiri and Vellore districts of Tamil Nadu in the south. Administratively, Kolar district is divided into five taluks namely Kolar, Bangarpet, Srinivaspura, Malur and Mulbagal. The district is historically known as the "Golden Land of India" because of the presence of the famous Kolar Gold Fields. Kolar town serves as the administrative headquarters of the district.

Geographically, Kolar taluk lies between 13°02′03″ and 13°19′11″ north latitudes and 77°56′02″ and 78°13′02″ east longitudes, with an average elevation of about 822 m (2697 ft) above mean sea level. The taluk consists of 328 inhabited villages and 34 uninhabited villages. Kolar town is located approximately 72 km from Bengaluru and about 32 km from Kolar Gold Fields. The region forms part of the southern maidan (plains) of Karnataka, and the Kodikannur tank serves as one of the important sources of water supply in the area.

Climatically, Kolar district falls within the Eastern Dry Agro-Climatic Zone of Karnataka and experiences a semi-arid climate. The climatic conditions are characterized by typical tropical monsoon weather patterns with hot summers and relatively mild winters. The year can broadly be divided into four seasons: the dry season from January to February, the pre-monsoon season from March to May, the southwest monsoon season from June to September, and the post-monsoon or northeast monsoon season from October to December. Rainfall in the district is largely dependent on the monsoon seasons, which play a significant role in determining agricultural productivity and groundwater recharge.

The drainage system of the district is associated with several river basins including the Palar, Ponnaiar, North Pennar (North Pinakini), and South Pennar (South Pinakini). Most rivers and streams flowing through the region are seasonal in nature and carry water only during the rainy season. According to the Central Ground Water Board (CGWB, 2012) groundwater resource assessment, in Kolar taluk fall under the over-exploited category, indicating that groundwater extraction has exceeded the recharge potential. Consequently, there are limited opportunities for further groundwater development in the taluk. From a geological perspective, the taluk is predominantly underlain by granites, gneisses, schists, laterites, and alluvial deposits. In certain locations, basic dykes intrude these formations. Among these rock types, granites and gneisses occupy the largest area, forming the dominant geological formations. Schist formations are mainly observed in the vicinity of Kolar Gold Fields and in the north-western part of Gauribidanur taluk. Lateritic formations occur in limited areas of Kolar, while alluvial deposits are confined to river courses and stream channels. Structural features such as fractures and lineaments form well-defined valleys within the taluk and most of these structures trend in a north-east to south-west (NE–SW) direction. The occurrence and movement of groundwater in the region are largely controlled by weathered zones, fractures, and fissures present in the hard rock formations. These structural features play an important role in groundwater storage and movement within the crystalline rock terrain.

Although Kolar taluk possesses a large number of irrigation tanks which is the highest in Karnataka their effectiveness largely depends on the availability of rainfall. Due to the irregular nature of rainfall in the region, many tanks remain dry during years of poor monsoon. Consequently, groundwater has become the most significant source of irrigation and water supply in this drought-prone district. Groundwater resources therefore play a vital role in supporting agricultural development and sustaining livelihoods in the region.

Kolar taluk represents an important study area for evaluating water quality, groundwater resources, and hydrogeological processes in semi-arid regions. The dependence on groundwater for agricultural and domestic purposes, combined with increasing anthropogenic pressures, makes the region particularly vulnerable to water quality deterioration and groundwater depletion. The study of water quality in this region provides valuable insights into the interaction between geological formations, land use patterns, and human activities. Understanding these relationships is essential for developing sustainable water management strategies and ensuring long-term water security for the region.

Methodology

The selected ground water samples from the study area were collected and analysed by following the Standard Methods (APHA, 2017)

Multivariate Statistical Analysis

Multivariate statistical techniques were applied to analyse the hydrochemical dataset and identify the key factors controlling groundwater quality. Since groundwater chemistry is influenced by multiple natural and anthropogenic processes, individual parameter analysis is often insufficient. Therefore, methods such as Pearson correlation, Principal Component Analysis (PCA), and Hierarchical Cluster Analysis (HCA) were used to simplify the data, determine relationships among variables, and classify sampling locations. These techniques helped in identifying dominant processes such as mineral dissolution, ion exchange, and anthropogenic contamination (Helena et al., 2000; Singh et al., 2004).

Pearson Correlation Analysis

Pearson correlation analysis was used to evaluate the linear relationships between physicochemical parameters of groundwater. The correlation coefficient (r) ranges from −1 to +1, indicating the strength and direction of association between variables. Strong positive correlations suggest common sources or similar geochemical behavior, while negative correlations indicate inverse relationships. This method helps in understanding interactions among ions and identifying possible sources of contamination such as natural weathering or human activities.

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was employed to reduce the complexity of the dataset and identify the major factors influencing groundwater chemistry. PCA transforms correlated variables into a smaller number of independent components that explain most of the total variance. Components with eigenvalues greater than one were retained, and

Varimax rotation was applied for better interpretation. High factor loadings indicate significant contributions of specific parameters, which helps in identifying processes such as geogenic mineral weathering and anthropogenic pollution (Davis, 1986).

Results and Discussion

The analytical results of groundwater samples from the PRM and PSM groups reveal significant variations in physicochemical parameters, reflecting the influence of both natural hydrogeochemical processes and anthropogenic activities. The pH values in both groups range from slightly acidic to moderately alkaline, with mean values of 7.02 (PRM) and 7.11 (PSM), indicating that groundwater is generally neutral to mildly alkaline in nature. This condition is typically associated with the presence of bicarbonate and carbonate ions derived from the dissolution of carbonate minerals. The low standard deviation in pH suggests relatively stable acid–base conditions across the study area.

Electrical Conductivity (EC) and Total Dissolved Solids (TDS) exhibit considerable variation, indicating differences in ionic concentration and mineralization. The EC values range from 834 to 2291 µS/cm in PRM and 689 to 2131 µS/cm in PSM, with relatively high mean values, suggesting moderate to high salinity levels. Similarly, TDS values range from 529 to 1437.18 mg/L (PRM) and 437.45 to 1337.26 mg/L (PSM), indicating that groundwater varies from fresh to slightly brackish in nature. These elevated values may be attributed to prolonged water–rock interaction, dissolution of minerals, and possible anthropogenic inputs such as agricultural runoff.

Fluoride concentrations in both groups remain within permissible limits, ranging from 0.1 to 1.1 mg/L in PRM and 0.10 to 1.00 mg/L in PSM, suggesting minimal risk of fluorosis. Total alkalinity values are relatively high, with means of 238.53 mg/L (PRM) and 206.75 mg/L (PSM), indicating a strong buffering capacity and dominance of bicarbonate ions in groundwater. This further supports the role of carbonate weathering in controlling groundwater chemistry.

Total hardness values indicate that groundwater in the study area is predominantly hard to very hard, with mean values of 308.66 mg/L (PRM) and 277.08 mg/L (PSM). This is mainly due to the presence of calcium and magnesium ions, which are derived from the dissolution of limestone and dolomite. Calcium concentrations range from 27.77 to 141.34 mg/L in PRM and 24.19 to 104.33 mg/L in PSM, while magnesium ranges from 9.11 to 46.06 mg/L and 7.63 to 58.55 mg/L, respectively. These ions significantly contribute to water hardness and reflect geological influences.

Sodium and potassium concentrations are comparatively lower but show noticeable variation. Sodium ranges from 13.4 to 107.8 mg/L (PRM) and 11.2 to 100.5 mg/L (PSM), suggesting possible ion exchange processes and minor anthropogenic influence. Potassium levels remain low in both groups, indicating limited mobility and minimal contribution to overall water chemistry.

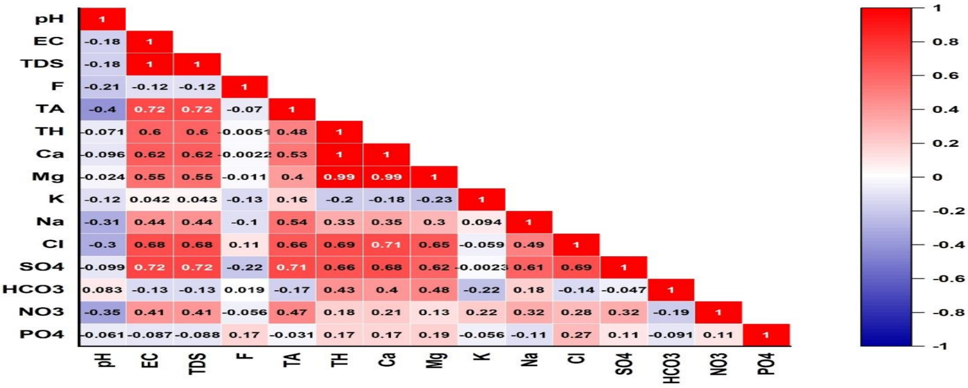
Among the anions, chloride concentrations vary between 32.13 and 184.15 mg/L in PRM and 30 to 173.70 mg/L in PSM, indicating contributions from natural sources as well as possible contamination from domestic and agricultural activities. Sulphate concentrations also show moderate variation, ranging from 45 to 229.50 mg/L (PRM) and 40.01 to 221.80 mg/L (PSM), which may originate from the dissolution of sulphate-bearing minerals such as gypsum. Bicarbonate is the dominant anion in both groups, with relatively high concentrations confirming the influence of carbonate weathering.

Nitrate concentrations range from 18.8 to 52.7 mg/L in PRM and 11.3 to 50.4 mg/L in PSM, indicating potential contamination from agricultural practices, particularly the use of nitrogen-based fertilizers. Elevated nitrate levels in certain locations highlight the impact of anthropogenic activities on groundwater quality. Phosphate concentrations are relatively low, suggesting limited contamination or rapid utilization by biological processes.

Trace elements such as bromide and silica are present in low concentrations. Bromide levels are minimal, indicating negligible industrial or saline intrusion influence, while silica concentrations reflect the weathering of silicate minerals and remain consistent across both groups.

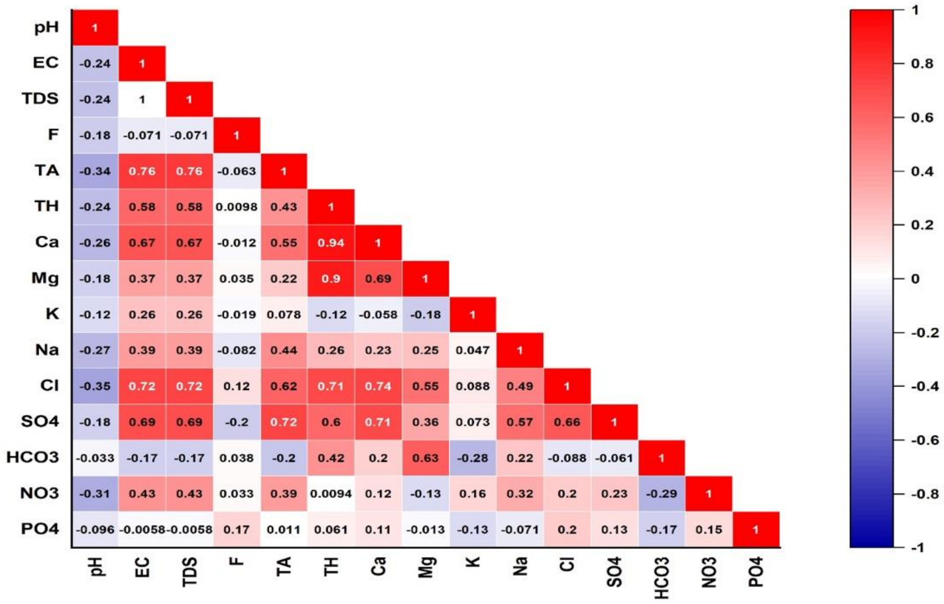
Study shows, the groundwater chemistry is primarily governed by natural processes such as rock–water interaction, mineral dissolution, and ion exchange, with localized influence from anthropogenic sources, particularly agriculture. The dominance of calcium, magnesium, and bicarbonate ions suggests that the groundwater belongs to the Ca–Mg–HCO_3 hydrochemical facies. Although most parameters fall within acceptable limits, elevated TDS, hardness, and nitrate levels in some samples indicate the need for regular monitoring and management to ensure safe and sustainable use of groundwater resources.

Correlation analysis of groundwater chemistry



	pH	EC	TDS	F	TA	TH	Ca	Mg	K	Na	Cl	SO4	HCO3	NO3	PO4
pH	1														
EC	-0.18	1													
TDS	-0.18	1	1												
F	-0.21	-0.12	-0.12	1											
TA	-0.4	0.72	0.72	-0.07	1										
TH	-0.071	0.6	0.6	-0.0051	0.48	1									
Ca	-0.096	0.62	0.62	-0.0022	0.53	1	1								
Mg	-0.024	0.55	0.55	-0.011	0.4	0.99	0.99	1							
K	-0.12	0.042	0.043	-0.13	0.16	-0.2	-0.18	-0.23	1						
Na	-0.31	0.44	0.44	-0.1	0.54	0.33	0.35	0.3	0.094	1					
Cl	-0.3	0.68	0.68	0.11	0.66	0.69	0.71	0.65	-0.059	0.49	1				
SO4	-0.099	0.72	0.72	-0.22	0.71	0.66	0.68	0.62	-0.0023	0.61	0.69	1			
HCO3	0.083	-0.13	-0.13	0.019	-0.17	0.43	0.4	0.48	-0.22	0.18	-0.14	-0.047	1		
NO3	-0.35	0.41	0.41	-0.056	0.47	0.18	0.21	0.13	0.22	0.32	0.28	0.32	-0.19	1	
PO4	-0.061	-0.087	-0.088	0.17	-0.031	0.17	0.17	0.19	-0.056	-0.11	0.27	0.11	-0.091	0.11	1

Fig 2. Correlation matrix for PRM groundwater samples



	pH	EC	TDS	F	TA	TH	Ca	Mg	K	Na	Cl	SO4	HCO3	NO3	PO4
pH	1														
EC	-0.24	1													
TDS	-0.24	1	1												
F	-0.18	-0.071	-0.071	1											
TA	-0.34	0.76	0.76	-0.063	1										
TH	-0.24	0.58	0.58	0.0098	0.43	1									
Ca	-0.26	0.67	0.67	-0.012	0.55	0.94	1								
Mg	-0.18	0.37	0.37	0.035	0.22	0.9	0.69	1							
K	-0.12	0.26	0.26	-0.019	0.078	-0.12	-0.058	-0.18	1						
Na	-0.27	0.39	0.39	-0.082	0.44	0.26	0.23	0.25	0.047	1					
Cl	-0.35	0.72	0.72	0.12	0.62	0.71	0.74	0.55	0.088	0.49	1				
SO4	-0.18	0.69	0.69	-0.2	0.72	0.6	0.71	0.36	0.073	0.57	0.66	1			
HCO3	-0.033	-0.17	-0.17	0.038	-0.2	0.42	0.2	0.63	-0.28	0.22	-0.088	-0.061	1		
NO3	-0.31	0.43	0.43	0.033	0.39	0.0094	0.12	-0.13	0.16	0.32	0.2	0.23	-0.29	1	
PO4	-0.096	-0.0058	-0.0058	0.17	0.011	0.061	0.11	-0.013	-0.13	-0.071	0.2	0.13	-0.17	0.15	1

Fig 3. Correlation matrix for POM groundwater samples

The Pearson correlation analysis indicates that groundwater chemistry in the study area is mainly influenced by dissolved ionic constituents. Electrical conductivity (EC) and total dissolved solids (TDS) show a strong positive relationship in both seasons, confirming their major role in mineralization processes. Strong correlations of EC and TDS with chloride (Cl^-), sulphate (SO_4^{2-}), and total alkalinity highlight the effect of evaporative concentration during pre-monsoon and dilution during post-monsoon periods. Water hardness is primarily controlled by calcium (Ca^{2+}) and magnesium (Mg^{2+}), reflecting carbonate mineral dissolution and recharge-related mixing. Moderate associations of bicarbonate (HCO_3^-) with alkaline earth metals indicate carbonate weathering, while sodium (Na^+) relationships suggest ion exchange and anthropogenic influences. Elevated nitrate levels, especially in the post-monsoon season, point to agricultural leaching, whereas weak fluoride and phosphate correlations indicate localized geochemical control. The findings emphasize the combined impact of geogenic processes, seasonal recharge, and human activities on groundwater quality dynamics.

Table 1. Interpretation of correlation coefficient (r) ranges and associated hydrogeochemical processes

Correlation range (r)	Strength of relationship	Indicative hydrogeochemical processes	Typical parameter examples in this study
$r \geq 0.90$	Very strong positive	Common geogenic source; direct mineral control; strong process coupling	EC–TDS; TH–Ca; TH–Mg; Ca–Mg
$0.70 \leq r < 0.90$	Strong positive	Dominant mineral dissolution; evaporative concentration; major ion control on salinity	EC/TDS–Cl; EC/TDS–SO_4; EC/TDS–TA
$0.50 \leq r < 0.70$	Moderate positive	Carbonate weathering; contribution of hardness to salinity; mixed geogenic influence	TH–EC/TDS; Ca–SO_4; Mg–Cl
$0.30 \leq r < 0.50$	Weak to moderate positive	Ion-exchange processes; secondary mineral dissolution; anthropogenic influence	Na–EC/TDS; NO_3–EC/TDS; Na–Cl
$0.10 \leq r < 0.30$	Weak positive	Localized inputs; surface-derived contamination; partial mixing effects	NO_3–Cl; PO_4–SO_4
$-0.10 < r < 0.10$	No significant correlation	Independent geochemical behavior; minimal interaction	F–major ions; PO_4–most parameters
$-0.30 \leq r \leq -0.10$	Weak negative	Dilution by recharge; replacement by dominant anions	HCO_3–EC/TDS; pH–EC
$r < -0.30$	Moderate to strong negative	Recharge-driven dilution; acidification effects; inverse geochemical control	pH–Cl; pH–NO_3

- Statistically significant at $p < 0.05$
- Correlation coefficients without an asterisk are not statistically significant ($p \geq 0.05$).
- Statistical significance was evaluated using Pearson's correlation test, assuming normality of variables.

Table 2. Season-wise comparison of statistically significant Pearson correlations ($p < 0.05$) in groundwater chemistry

Parameter	Pre-monsoon	Significanc	Post-	Significanc	Hydrogeochemical implication

pair	(r)	e	monsoon (r)	e	
EC – TDS	1.00	***	1.00	***	Salinity entirely controlled by dissolved ions in both seasons
TH – Ca^{2+}	~0.99	***	~0.94	***	Carbonate mineral control on hardness
TH – Mg^{2+}	~1.00	***	~0.90	***	Dominance of alkaline earth metals
Ca^{2+} – Mg^{2+}	~0.99	***	~0.69	***	Common geogenic source; dilution post-monsoon
EC – Cl^-	~0.68	***	~0.72	***	Salinity influenced by chloride
EC – SO_4^{2-}	~0.72	***	~0.69	***	Sulphate contribution to mineralization
EC – TA	~0.72	***	~0.76	***	Alkalinity as major salinity component
TH – EC	~0.60	***	~0.58	***	Hardness contributes to salinity
HCO_3^- – Ca^{2+}	~0.48	***	~0.40	***	Carbonate weathering
HCO_3^- – Mg^{2+}	~0.48	***	~0.63	***	Enhanced weathering after recharge
NO_3^- – EC	~0.41	***	~0.43	***	Anthropogenic inputs (agriculture/sewage)
NO_3^- – TDS	~0.41	***	~0.43	***	Surface-derived contamination
Na^+ – EC	~0.44	***	~0.39	***	Ion exchange and salinity contribution
Na^+ – Cl^-	~0.49	***	~0.49	***	Possible halite dissolution / anthropogenic source
pH – EC	~–0.32	***	~–0.35	***	Dilution and ionic-strength-related acidification
F^- – major ions	<0.20	NS	<0.20	NS	Independent geochemical control
PO_4^{3-} – major ions	<0.20	NS	<0.20	NS	Localized and adsorptive behavior

- *** $p < 0.05$ (statistically significant)
- NS: Not significant ($p \geq 0.05$)

Season-wise correlation analysis (Table Y) shows that most major ion relationships remain statistically significant ($p < 0.05$) in both pre- and post-monsoon periods, with reduced correlation strength post-monsoon indicating dilution effects associated with recharge.

Table 3. Factor Loadings and Communalities for Pre-monsoon seasons (Varimax rotation)

Variable	PC1	PC2	PC3	PC4	Communality
pH	0.063	0.337	-0.791	-0.067	0.748
EC	0.377	-0.830	-0.117	0.041	0.846
TDS	0.377	-0.830	-0.118	0.042	0.846
F	0.060	0.215	0.630	-0.377	0.588
TA	0.229	-0.833	0.181	0.094	0.788
TH	0.937	-0.322	0.015	-0.035	0.983
CaH	0.921	-0.361	0.030	-0.033	0.981
Ca	0.921	-0.361	0.030	-0.033	0.981
MgH	0.960	-0.244	-0.013	-0.038	0.982
Mg	0.960	-0.244	-0.013	-0.038	0.982
K	-0.388	-0.316	0.070	0.184	0.289
Na	0.234	-0.528	0.309	0.471	0.650
Cl	0.510	-0.665	0.175	-0.275	0.809
SO4	0.481	-0.734	-0.116	0.030	0.785
HCO3	0.646	0.474	0.159	0.473	0.891
NO3	-0.048	-0.605	0.291	0.001	0.452
PO4	0.171	0.013	0.175	-0.772	0.656
Eigen values	7.960	2.682	1.461	1.155	---
Variance	5.9077	4.6654	1.3697	1.3174	13.2601

% Var	0.348	0.274	0.081	0.077	0.780

Table 4. Factor Loadings and Communalities for Post-monsoon seasons (Varimax rotation)

Variable	PC1	PC2	PC3	PC4	Communality
pH	-0.161	0.105	-0.721	0.238	0.613
EC	0.905	0.051	0.222	0.098	0.880
TDS	0.905	0.051	0.222	0.098	0.880
F	-0.189	-0.118	0.368	-0.629	0.580
TA	0.784	0.118	0.309	0.077	0.729
TH	0.696	-0.698	0.016	-0.091	0.981
CaH	0.823	-0.464	-0.016	-0.146	0.915
Ca	0.823	-0.464	-0.016	-0.146	0.915
MgH	0.413	-0.867	0.053	-0.006	0.925
Mg	0.413	-0.867	0.053	-0.006	0.925
K	0.153	0.383	0.235	0.229	0.278
Na	0.328	-0.147	0.635	0.353	0.657
Cl	0.792	-0.219	0.269	-0.197	0.787
SO4	0.840	-0.068	0.120	0.116	0.738
HCO3	-0.223	-0.863	0.122	0.207	0.852
NO3	0.323	0.385	0.551	-0.080	0.564
PO4	0.140	0.104	-0.067	-0.767	0.623
Eigen values	7.278	2.935	1.406	1.226	----
Variance	6.1324	3.5909	1.7237	1.3942	12.8412
% Var	0.361	0.211	0.101	0.082	0.755

The Principal Component Analysis (PCA) with Varimax rotation reveals that groundwater chemistry is predominantly governed by a consistent set of hydrogeochemical processes across both pre- and post-monsoon seasons, explaining a substantial proportion of total variance (78.0 % and 75.5 %, respectively). The dominance of PC1 in both seasons, characterized by strong loadings of EC, TDS, hardness, and major ions (Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, and HCO_3^-), clearly indicates that mineral weathering and dissolution processes are the primary controls on groundwater chemistry. PC2 reflects seasonal contrasts, with pre-monsoon conditions dominated by salinity enrichment due to evaporation and anthropogenic inputs, whereas post-monsoon conditions highlight dilution and carbonate equilibrium driven by recharge. The contributions of PC3 and PC4 further emphasize the role of localized anthropogenic influences, including nutrient leaching and point-source contamination, along with ion-exchange processes. Overall, the PCA results underscore the strong influence of geogenic processes, modulated by seasonal recharge and human activities, in shaping the spatial and temporal variability of groundwater quality.

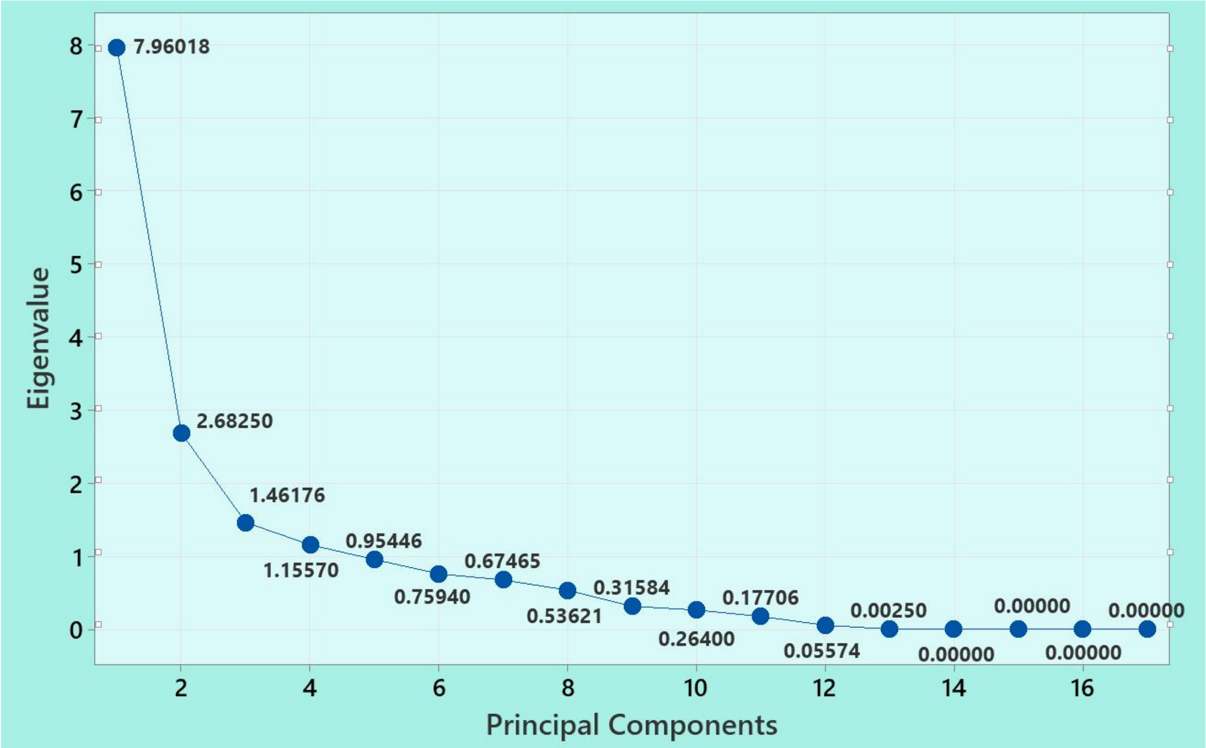


Fig 4. Scree plot for datasets of PRM groundwater water samples

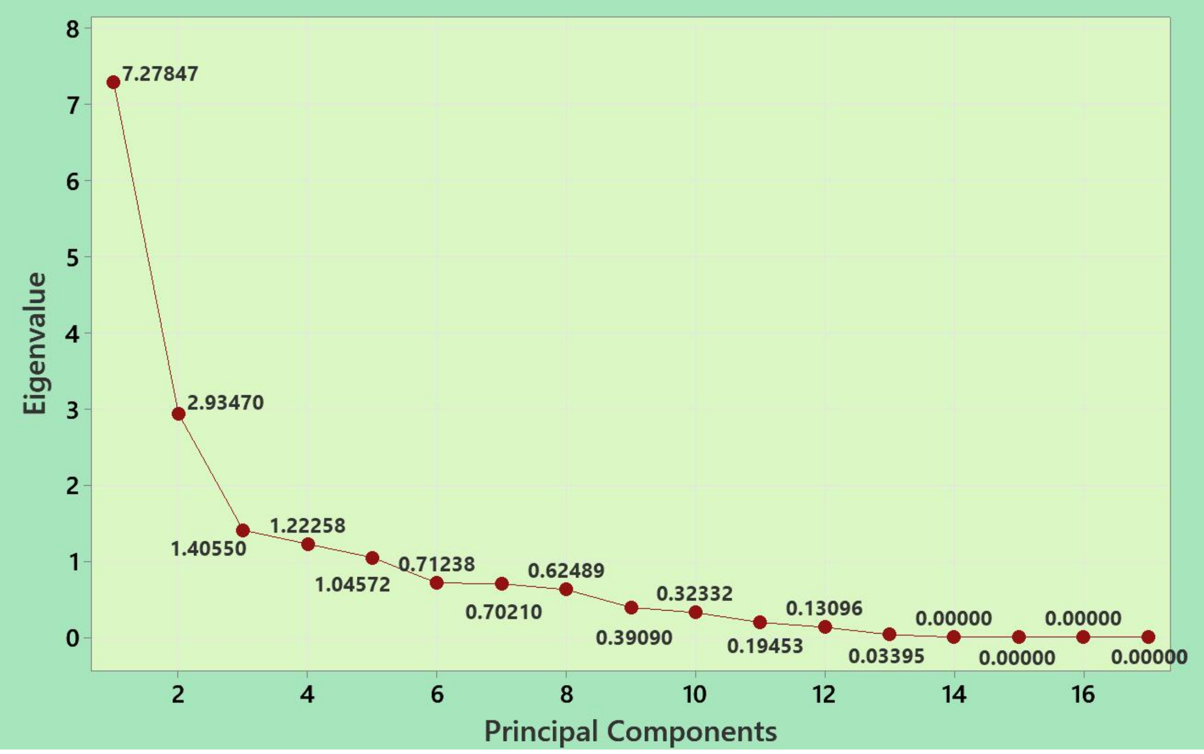


Fig 5. Scree plot for datasets of POM groundwater water samples

The Pearson correlation matrix demonstrates significant interrelationships among the physicochemical parameters, indicating that groundwater chemistry is primarily controlled by hydrogeochemical processes and seasonal variations. Strong positive correlations between EC, TDS, chloride, sulphate, and alkalinity suggest enhanced mineral dissolution, evaporative concentration, and ionic enrichment within the aquifer system. Calcium and magnesium exhibit a close association with total hardness, reflecting the dominant influence of carbonate weathering and rock–water interaction. The correlation of bicarbonate and sodium with major ions further indicates ion exchange and silicate weathering processes. Elevated nitrate concentrations imply the impact of agricultural activities and anthropogenic contamination, whereas weak fluoride and phosphate correlations suggest localized geogenic influence. The analysis highlights the combined effects of lithological characteristics, seasonal recharge, and human activities on groundwater quality evolution in the study area.

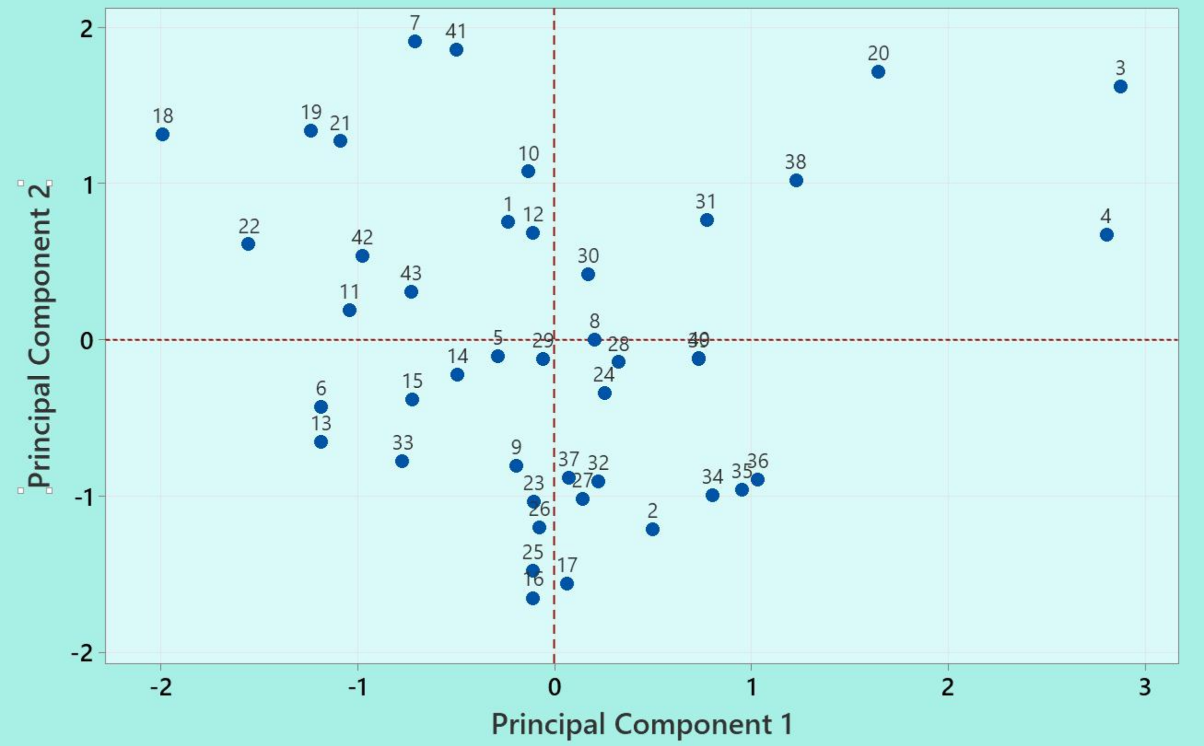


Fig 6. Score plot for PRM groundwater samples

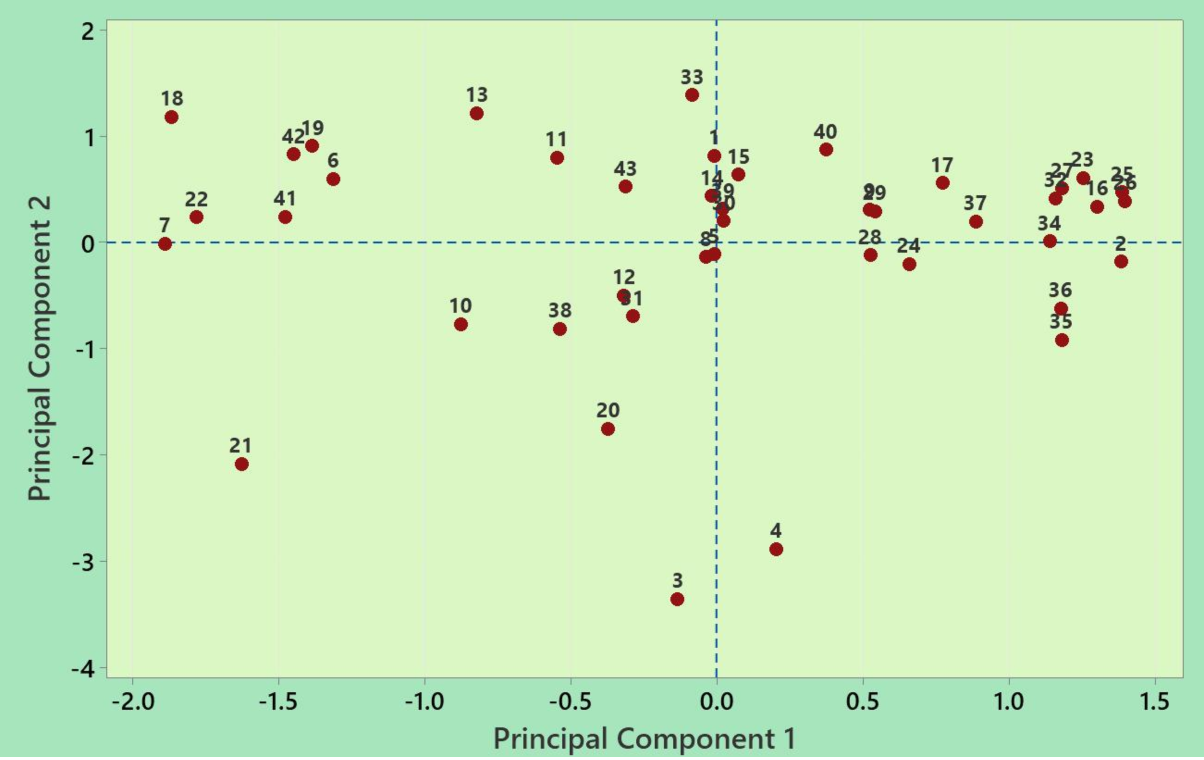


Fig 7. Score plot for POM groundwater samples

The Pearson correlation analysis reveals that groundwater hydrochemistry in the study area is predominantly governed by dissolved ionic constituents and seasonal hydrogeochemical processes. Strong positive correlations among EC, TDS, chloride, sulphate, and total alkalinity indicate the significant influence of mineralization, evaporative concentration, and dilution mechanisms during pre- and post-monsoon periods. The close association of calcium and magnesium with total hardness suggests the dominance of carbonate weathering and rock–water interaction processes. Furthermore, the relationships between bicarbonate, sodium, and other major ions reflect ion exchange, silicate weathering, and anthropogenic contributions. Elevated nitrate concentrations indicate agricultural runoff and leaching effects, whereas the weak correlations of fluoride and phosphate imply localized geogenic control. the groundwater quality is controlled by the combined influence of geogenic processes, seasonal recharge variability, and human-induced activities.

From a hydrogeochemical perspective, the score plots robustly demonstrate that while the fundamental geogenic controls remain consistent across seasons, the intensity and spatial expression of these processes are significantly modulated by monsoonal dynamics. The pre-monsoon period amplifies concentration-driven variability, whereas the post-monsoon period promotes equilibration and redistribution of solutes. This seasonal contrast underscores the dynamic nature of groundwater systems and emphasizes the critical role of recharge processes in regulating water quality and ensuring its sustainability.

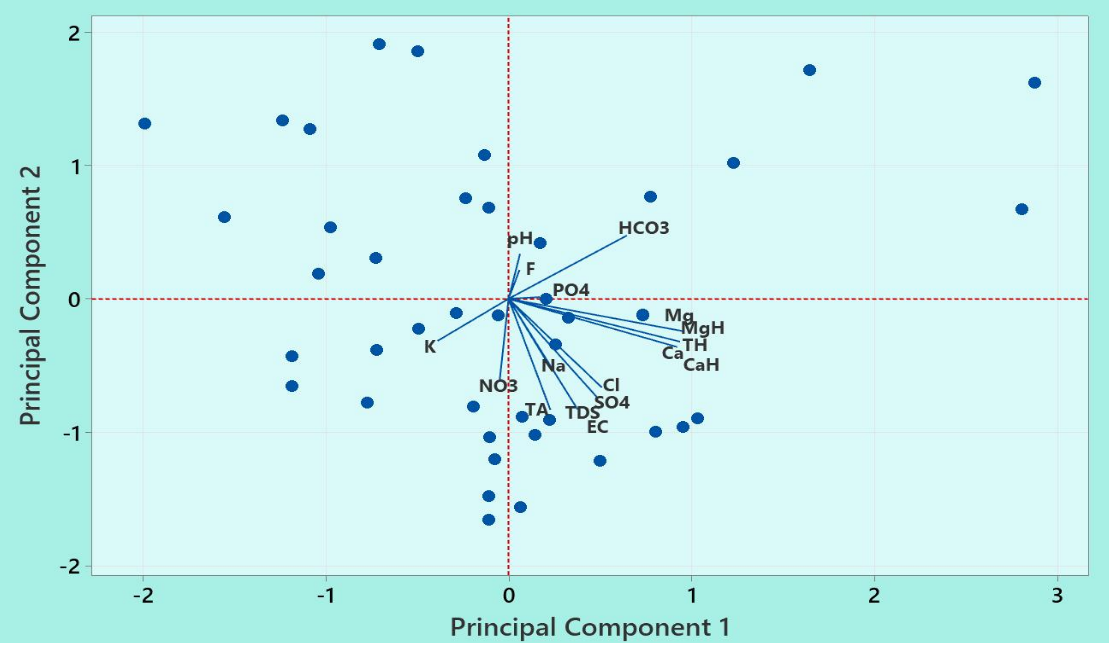


Fig 8. Biplot for PRM groundwater samples

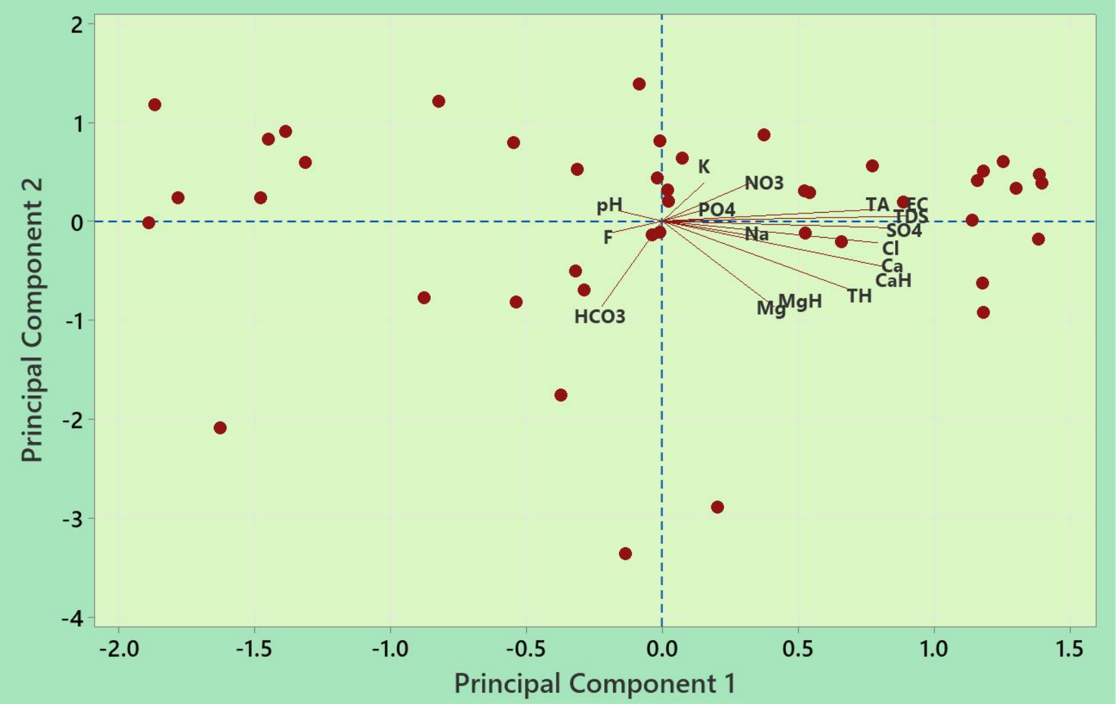


Fig 9. Biplot for POM groundwater samples

The Pearson correlation analysis reveals that groundwater quality is mainly controlled by dissolved ions and seasonal variations. Strong positive correlations among EC, TDS, chloride, sulphate, and alkalinity indicate mineralization, evaporation, and dilution effects. Calcium and magnesium significantly influence water hardness through carbonate dissolution. Relationships among bicarbonate, sodium, and other ions suggest weathering, ion exchange, and anthropogenic activities. Elevated nitrate levels indicate agricultural leaching, while weak fluoride and phosphate correlations reflect localized geochemical influence. Groundwater chemistry is governed by geogenic processes, recharge conditions, and human impacts.

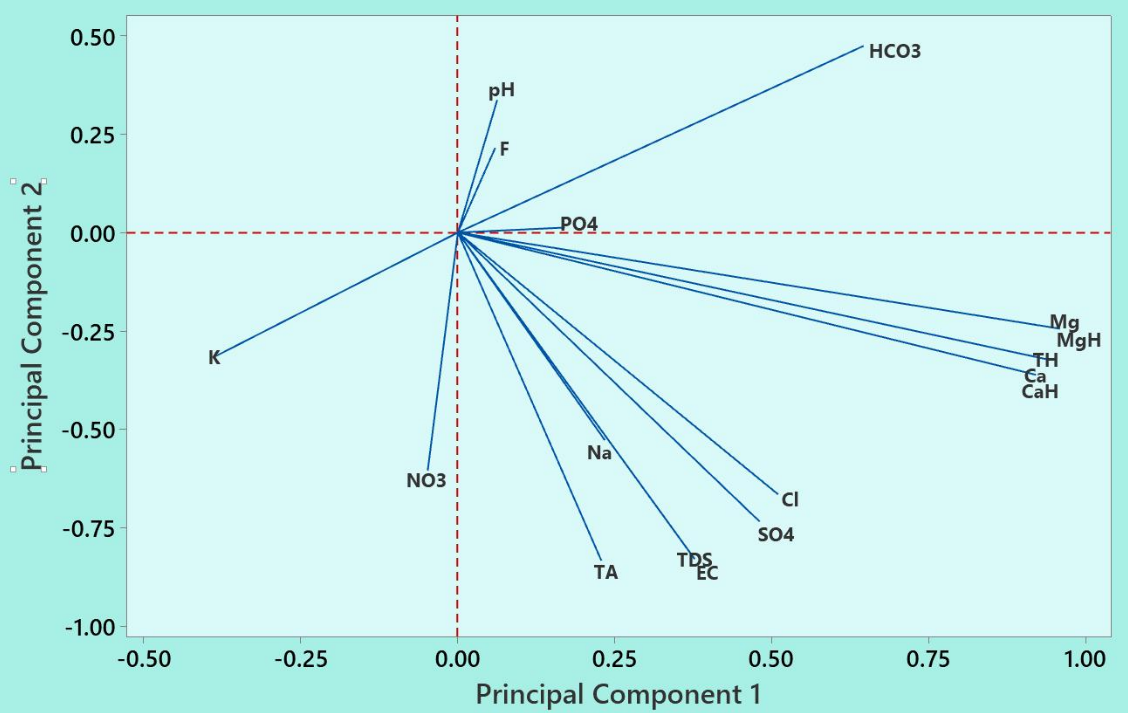


Fig 10. Loading plot for PRM groundwater samples

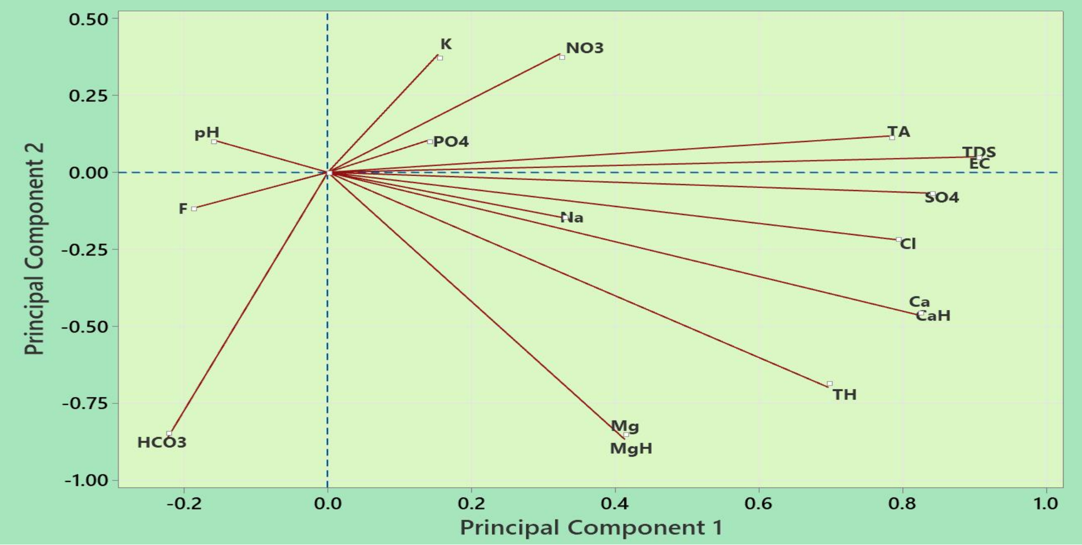


Fig 11. Loading plot for POM groundwater samples

The Pearson correlation analysis shows that groundwater chemistry is mainly controlled by dissolved ions. EC and TDS have a strong positive correlation, indicating mineralization processes. Their association with chloride, sulphate, and alkalinity reflects evaporation during pre-monsoon and dilution during post-monsoon. Water hardness is mainly influenced by calcium and magnesium through carbonate dissolution. Relationships among bicarbonate, sodium, and other ions indicate weathering, ion exchange, and anthropogenic impacts. Elevated nitrate levels suggest agricultural leaching, while weak fluoride and phosphate correlations indicate localized geochemical control. groundwater quality is influenced by geogenic processes, seasonal recharge, and human activities.

Conclusion

A comprehensive assessment of groundwater quality and hydrochemical processes in the study area through detailed physicochemical analysis and multivariate statistical approaches. The findings indicate that groundwater chemistry is predominantly controlled by geogenic factors, particularly mineral weathering, dissolution of carbonate and silicate rocks, and ion exchange processes. The dominance of Ca–Mg–HCO_3 hydrochemical facies, along with neutral to slightly alkaline pH, confirms the significant influence of natural geological formations on groundwater composition.

Elevated EC and TDS values reflect moderate mineralization, while high total hardness is attributed to the presence of calcium and magnesium ions. Seasonal variations reveal that pre-monsoon conditions are characterized by higher concentrations due to evaporation and limited recharge, whereas post-monsoon conditions show dilution effects resulting from rainfall infiltration and mixing. Multivariate statistical analyses, including Pearson correlation and PCA, further highlight the strong interrelationships among major ions and confirm the dominance of mineralization processes, while also identifying the contribution of anthropogenic activities such as agriculture, particularly through elevated nitrate levels.

Almost the groundwater quality data indicates suitable for drinking and irrigation purposes, localized exceedances of TDS, hardness, and nitrate indicate potential risks that require attention. The study underscores the importance of regular groundwater monitoring, controlled agricultural practices, and the implementation of sustainable management strategies to prevent further deterioration. The integration of hydrochemical and statistical analyses provides a robust framework for understanding groundwater systems and supports informed decision-making for the protection and sustainable utilization of groundwater resources.

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