

Factor Analysis of Seasonal Hydrochemical Data of the Varthur Catchment Area, Bangalore Urban District, Karnataka

L. Muni Krishna^{ID}, H. C. Vajrappa*

Department of Geology, Bangalore University, Bengaluru, India
Email: Krishna.geo21@gmail.com, *hcvajrappa432@gmail.com

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Abstract

Seasonal groundwater-quality variability across the Varthur Catchment, Bangalore Urban District, was assessed using R-mode factor analysis applied independently to pre- and post-monsoon 2023 hydro chemical data from 58 bore wells. The correlation matrix showed strong positive associations among EC, TDS, TH, Ca, Mg, Na, Cl and SO₄ in both seasons, indicating that mineral dissolution and rock-water interaction govern groundwater mineralization. Four and three factors were retained for the pre- and post-monsoon datasets, explaining 77.22% and 72.70% of total variance, respectively. In both seasons, Factor I loaded heavily on Ca, Mg, Cl, SO₄, EC, TH and TDS and is interpreted as a hardness-mineralization factor reflecting geogenic rock-water interaction. Factor II reflected alkali enrichment and ion exchange, dominated by K pre-monsoon and by pH post-monsoon, while a distinct carbonate/bicarbonate factor emerged in both seasons. A separate nitrate-dominated factor (loading 0.972) was retained pre-monsoon, indicating concentrated anthropogenic contamination during the dry season; post-monsoon nitrate loadings were weak and diffuse, consistent with dilution by monsoon recharge. Spatial mapping of factor scores showed that hardness-mineralization zones coincide with deeper water tables and dense urban development in the south-central and northern catchment, whereas nitrate hotspots persist near dense settlement and residual agriculture in the north. Overall, Varthur groundwater chemistry is governed by lithogenic weathering and carbonate equilibrium, with a superimposed, seasonally modulated anthropogenic nitrate signal.

Keywords

Groundwater Quality, R-Mode Factor Analysis, Principal Component Analysis, Hydrochemistry, Seasonal Variation, Anthropogenic Contamination, Varimax Rotation, Spatial Factor-Score Mapping

1. Introduction

Groundwater-quality assessment is critical for sustainable water-resource management in rapidly urbanising catchments underlain by hard-rock aquifers, where anthropogenic pressures and geogenic mineral weathering jointly shape hydrochemistry [1]. R-mode factor analysis offers a robust framework for resolving complex hydrochemical datasets into a small number of underlying processes, an approach with a long history in hydrogeochemical interpretation dating to the early work of Dalton and Upchurch [2] and Ashley and Lloyd [3], reducing dimensionality and grouping chemically similar variables by common geochemical origin [4].

In the Indian context, R-mode factor analysis has been applied extensively to characterise hard-rock aquifer systems and to separate geogenic from anthropogenic contributions to groundwater chemistry. Comparable multivariate statistical approaches to seasonal groundwater assessment have been reported for the semi-arid Godavari basin of Maharashtra [1] and, outside India, for a Nigerian hard-rock metropolis [5] and a coastal aquifer setting where factor analysis was combined with geostatistical interpolation to delineate contamination zones [6]. Within Karnataka specifically, earlier studies of the Arkavathi river basin and its Suvarnamukhi sub-basin used R-mode factor analysis to resolve TDS, carbonate and bicarbonate factors controlling groundwater chemistry in Peninsular Gneissic terrain [7], but that and subsequent regional work analysed single-season or composite datasets and did not resolve how the underlying factor structure itself reorganises between pre- and post-monsoon conditions.

This is the specific gap the present study addresses. Seasonal variability in factor structure across pre- and post-monsoon cycles, in urbanising crystalline-rock catchments of Bangalore Urban District, remains insufficiently documented: most regional studies report a single sampling round or pool seasons together, which can mask the redistribution of variance among mineralization, carbonate-equilibrium and anthropogenic axes that recharge induces. The Varthur Catchment, lying immediately east of Bangalore city and subject to intense IT-corridor urbanisation alongside residual agricultural land use, presents a setting where both geogenic mineralization and anthropogenic nitrate enrichment are plausible, and potentially seasonally decoupled, controls on groundwater quality. The novelty of this study is therefore twofold: 1) it applies R-mode factor analysis, principal-axis extraction, varimax rotation, communality evaluation and spatial factor-score mapping independently rather than jointly to matched pre- and post-monsoon datasets from the same 58 wells, enabling a direct, well-by-well seasonal comparison of the dominant hydrogeochemical controls; and 2) it documents, for the first time for this catchment, how the nitrate signal collapses from a sharply resolved, near-unit-loading factor in the dry season to a diffuse, sub-threshold signal after monsoon recharge, a seasonal contrast with direct relevance to the timing of groundwater-quality monitoring and nitrate-source management in similarly urbanising hard-rock catchments.

2. Study Area

The Varthur Catchment occupies the southern sector of Bangalore Urban District, Karnataka, lying between latitudes $12^{\circ}48'24.52''\text{N}$ and $12^{\circ}53'59.85''\text{N}$ and longitudes $77^{\circ}24'59.95''\text{E}$ and $77^{\circ}30'6.72''\text{E}$, covering approximately 284 km^2 . The catchment forms part of the Dakshina Pinakini drainage system on the Mysore Plateau and is underlain predominantly by Precambrian crystalline rocks of the Peninsular Gneissic Complex granites, gneisses and schists, with localised pegmatites and quartzites representing the principal source of dissolved Ca, Mg, Na, K and HCO_3 in groundwater through silicate and carbonate mineral weathering.

The aquifer system is of the fractured hard-rock type, with groundwater occurring chiefly in the weathered mantle and fractured zones of the crystalline basement; well yields are therefore strongly controlled by weathering depth and fracture density. Land use is predominantly urban, with residential colonies, IT-corridor commercial development and remnant agricultural pockets concentrated towards the periphery. Anthropogenic pressures include domestic sewage, septic-tank effluent, stormwater runoff and residual fertiliser application, contributing to locally elevated nitrate concentrations superimposed on the underlying geogenic mineralization signal.

3. Material and Methodology

Groundwater samples were collected from 58 bore wells distributed across the Varthur Catchment during the pre- and post-monsoon 2023 seasons, with the same wells sampled in both seasons to ensure direct comparability. Wells were selected to represent the spatial heterogeneity of land use and hydrogeological conditions, spanning agricultural, residential and commercial zones.

At each well, samples were collected after purging standing water and allowing at least 5 minutes of pumping to obtain a representative aquifer sample. Samples for cation analysis were filtered in the field through $0.45\text{ }\mu\text{m}$ cellulose-nitrate membrane filters and acidified to $\text{pH} < 2$ with ultrapure HNO_3 in acid-washed high-density polyethylene bottles; samples for anion, alkalinity and general physicochemical analysis were collected unacidified in separate pre-cleaned polyethylene bottles. All samples were stored at 4°C in insulated coolers during transport and analysed within 48 hours of collection, following standard APHA (2017) sample-preservation protocols. Field-measured parameters (pH, EC, temperature) were recorded at the time of collection using a calibrated portable multiparameter probe.

Physicochemical parameters Ca, Mg, Na, K, Cl, SO_4 , NO_3 , HCO_3 , CO_3 , pH, EC, TH and TDS were determined following standard BIS (IS 3025) and APHA (2017) protocols. Ca and Mg (and, by extension, total hardness) were determined titrimetrically by the EDTA method; HCO_3 and CO_3 by acid-base titration to the phenolphthalein and methyl-orange end points; Cl by argentometric (Mohr) titration; SO_4 by UV-visible spectrophotometry, Na and K by flame photometry, NO_3 by UV-visible spectrophotometry, and pH and EC by calibrated conductivity meter. TDS was computed from EC using a site-calibrated conversion factor. Analyses

were checked for internal consistency via the percentage error between total soluble cations and anions, with samples exceeding $\pm 5\%$ re-analysed. Raw analytical concentrations (mg/L, except pH, which is dimensionless and EC in $\mu\text{S}/\text{cm}$) were used as model input; no transformation or standardisation beyond the correlation-matrix computation itself was applied prior to factor extraction.

Thirteen variables, Ca, Mg, Na, K, Cl, SO_4 , NO_3 , HCO_3 , CO_3 , pH, EC, TH and TDS, were used for R-mode factor analysis, carried out using the FORTRAN program Factor of Davis [8]. TH and TDS were retained alongside their contributing ions (Ca, Mg, EC); their loadings were interpreted jointly with, rather than independently of, the constituent ions, to avoid circular interpretation. The program computes the Pearson product-moment correlation matrix from the raw concentration data, extracts principal-axis factors, and reports eigenvalues, percentage and cumulative percentage of trace, unrotated loadings, varimax-rotated loadings and communalities. Eigenvalues greater than unity were retained as the extraction criterion, following Kaiser [9], and varimax rotation was applied to the extracted principal axes to sharpen variable-factor associations while preserving total explained variance [9] [10]. Communality analysis evaluated the proportion of variance in each variable accounted for by the retained factors, and factor scores for each well were computed and mapped spatially using contoured surfaces.

4. Factor Analysis

Factor analysis is useful for explaining interrelationships among large numbers of variables through a small number of underlying factors. Dalton and Upchurch [2] noted that factor analysis offers advantages over classical graphical approaches in that both chemical and non-chemical data can be incorporated, and variation in minor constituents is not masked by chemically similar ions present at higher concentration. R-mode factor analysis is particularly suited to identifying variables that covary and relate to a specific hydrochemical process, with the areas influenced by each process subsequently delineated by mapping the corresponding factor scores [7]. This approach is adopted here to resolve the pre- and post-monsoon hydrochemical datasets of the Varthur Catchment.

4.1. R-Mode Factor Analysis

For the thirteen hydrochemical variables, the correlation matrix was computed independently for the pre- and post-monsoon datasets, together with the corresponding eigenvalues, percentage variance and cumulative percentage variance (Table 1(a), Table 1(b)). Values are Pearson correlation coefficients, eigenvalues are dimensionless; variance and cumulative variance are expressed as % of total trace. Underlying concentrations were measured in mg/L for all ionic species except pH and EC $\mu\text{S}/\text{cm}$.

The pre-monsoon matrix shows strong positive correlation among Ca, Mg, Cl, SO_4 , EC, TH and TDS (r up to 0.96), indicating that dry-season mineralization is governed predominantly by Ca and Mg derived from silicate and carbonate weath-

ering, concentrated through evaporative enrichment. Nitrate correlates only weakly with the major ions ($r < 0.30$), consistent with an anthropogenic source decoupled from the geogenic signal, while CO_3 shows weak negative correlation with most major ions.

Table 1. (a) Correlation matrix of chemical constituents, groundwater samples, Varthar Catchment pre-monsoon season; (b) Correlation matrix of chemical constituents, groundwater samples, Varthar Catchment post-monsoon season.

(a)													
Variable	Ca	Mg	Na	K	Cl	SO_4	NO_3	HCO_3	CO_3	pH	EC	TH	TDS
Ca	1	0.944	0.392	0.118	0.747	0.623	0.219	0.665	-0.314	0.151	0.688	0.942	0.916
Mg	0.944	1	0.482	0.127	0.727	0.675	0.138	0.562	-0.262	0.196	0.706	0.958	0.933
Na	0.392	0.482	1	0.255	0.41	0.426	0.196	0.263	0.001	0.166	0.347	0.51	0.643
K	0.118	0.127	0.255	1	0.43	0.176	-0.082	0.015	0.098	-0.143	0.056	0.085	0.269
Cl	0.747	0.727	0.41	0.43	1	0.662	0.188	0.489	-0.237	0.076	0.668	0.722	0.787
SO_4	0.623	0.675	0.426	0.176	0.662	1	0.299	0.211	-0.149	0.106	0.65	0.656	0.677
NO_3	0.219	0.138	0.196	-0.082	0.188	0.299	1	0.334	-0.165	0.097	0.08	0.165	0.145
HCO_3	0.665	0.562	0.263	0.015	0.489	0.211	0.334	1	-0.201	0.123	0.429	0.538	0.569
CO_3	-0.314	-0.262	0.001	0.098	-0.237	-0.149	-0.165	-0.201	1	0.098	-0.17	-0.305	-0.261
pH	0.151	0.196	0.166	-0.143	0.076	0.106	0.097	0.123	0.098	1	0.09	0.241	0.17
EC	0.688	0.706	0.347	0.056	0.668	0.65	0.08	0.429	-0.17	0.09	1	0.698	0.705
TH	0.942	0.958	0.51	0.085	0.722	0.656	0.165	0.538	-0.305	0.241	0.698	1	0.935
TDS	0.916	0.933	0.643	0.269	0.787	0.677	0.145	0.569	-0.261	0.17	0.705	0.935	1
Eigenvalue	6.59	1.4	1.18	1.03	0.8	0.71	0.64	0.38	0.2	0.18	0.04	0.03	0.02
Variance (%)	49.86	10.6	8.95	7.81	6.06	5.4	4.86	2.86	1.49	1.37	0.32	0.24	0.18
Cumulative %	49.86	60.46	69.41	77.22	83.28	88.68	93.54	96.4	97.89	99.26	99.58	99.82	100
(b)													
Ca	1	0.692	0.228	-0.01	0.666	0.631	0.254	0.039	-0.275	-0.152	0.54	0.825	0.88
Mg	0.692	1	0.384	0.158	0.612	0.577	-0.035	0.122	-0.356	0.121	0.573	0.849	0.795
Na	0.228	0.384	1	0.123	0.356	0.374	0.188	0.05	0.065	0.206	0.281	0.485	0.43
K	-0.01	0.158	0.123	1	0.211	0.123	-0.131	0.089	-0.084	-0.097	0.084	0.079	0.163
Cl	0.666	0.612	0.356	0.211	1	0.661	0.193	0.107	-0.32	0.11	0.529	0.668	0.682
SO_4	0.631	0.577	0.374	0.123	0.661	1	0.259	-0.18	-0.145	0.03	0.546	0.645	0.672
NO_3	0.254	-0.035	0.188	-0.131	0.193	0.259	1	0.055	-0.011	-0.015	-0.044	0.121	0.186
HCO_3	0.039	0.122	0.05	0.089	0.107	-0.18	0.055	1	-0.151	0.201	-0.135	0.078	0.128
CO_3	-0.275	-0.356	0.065	-0.084	-0.32	-0.145	-0.011	-0.151	1	-0.161	-0.19	-0.281	-0.238
pH	-0.152	0.121	0.206	-0.097	0.11	0.03	-0.015	0.201	-0.161	1	0.144	0.084	-0.16
EC	0.54	0.573	0.281	0.084	0.529	0.546	-0.044	-0.135	-0.19	0.144	1	0.642	0.54
TH	0.825	0.849	0.485	0.079	0.668	0.645	0.121	0.078	-0.281	0.084	0.642	1	0.903
TDS	0.88	0.795	0.43	0.163	0.682	0.672	0.186	0.128	-0.238	-0.16	0.54	0.903	1
Eigenvalue	6.82	1.51	1.12	0.98	0.82	0.61	0.44	0.31	0.19	0.11	0.05	0.03	0.01
Variance (%)	52.46	11.62	8.62	7.54	6.31	4.69	3.38	2.38	1.46	0.85	0.38	0.23	0.08
Cumulative %	52.46	64.08	72.7	80.24	86.55	91.24	94.62	97	98.46	99.31	99.69	99.92	100

Post-monsoon, TH and TDS show the strongest mutual correlation ($r = 0.903$), while EC shows only moderate association with TDS (0.54) and Cl (0.53), notably weaker than the equivalent pre-monsoon associations, indicating that post-monsoon recharge dilutes overall ionic strength while the Ca-Mg-TH-TDS hardness framework remains dominant.

4.2. Principal-Axis Matrix

The eigenvalues obtained from the correlation matrices are used to decide the number of factors required to explain the data variation, following the Kaiser [9] criterion (eigenvalue > 1), four principal components were retained pre-monsoon, jointly accounting for 77.22% of total variance (first eigenvalue 6.59, 49.86%), and three were retained post-monsoon, accounting for 72.70% (first eigenvalue 6.82, 52.46%). A fourth post-monsoon component approached but did not exceed unity (eigenvalue 0.98, 7.54% of variance) and was not formally retained, though it is discussed qualitatively below. Unrotated principal-axis matrices (eigenvectors scaled by the square root of the corresponding eigenvalue) are given in **Table 2(a)** and **Table 2(b)**.

Table 2. (a) Principal-axis matrix, pre-monsoon season; (b) Principal-axis matrix, post-monsoon season.

(a)				
Variables	PC-I	PC-II	PC-III	PC-IV
Ca	0.942	-0.118	-0.08	-0.11
Mg	0.946	-0.034	0.012	-0.177
Na	0.579	0.262	0.34	0.277
K	0.217	0.806	-0.118	0.297
Cl	0.845	0.235	-0.13	0.085
SO ₄	0.753	0.118	0.039	0.113
NO ₃	0.265	-0.444	0.061	0.815
HCO ₃	0.63	-0.325	-0.05	0.152
CO ₃	-0.303	0.417	0.624	0.009
pH	0.196	-0.288	0.781	-0.139
EC	0.782	0.018	-0.042	-0.221
TH	0.946	-0.083	0.036	-0.17
TDS	0.966	0.102	0.023	-0.061
Eigenvalue	6.59	1.4	1.18	1.03
% of Trace	49.86	10.6	8.95	7.81
Cumulative % of Trace	49.86	60.46	69.41	77.22

Continued

(b)			
Variables	PC-I	PC-II	PC-III
Ca	0.866	-0.205	-0.007
Mg	0.862	0.174	-0.157
Na	0.498	0.071	0.389
K	0.167	0.172	-0.515
Cl	0.816	0.085	0.017
SO ₄	0.785	-0.251	0.088
NO ₃	0.199	-0.253	0.726
HCO ₃	0.067	0.67	0.169
CO ₃	-0.346	-0.466	0.222
EC	0.704	-0.024	-0.154
pH	0.061	0.696	0.39
TH	0.938	0.022	0.007
TDS	0.925	-0.12	-0.053
Eigenvalue	6.82	1.51	1.12
% of Trace	52.46	11.62	8.62
Cumulative % of Trace	52.46	64.08	72.7

PC-I loads positively on Ca, Mg, Cl, SO₄, EC, TH and TDS (0.75 - 0.97), confirming this axis as the principal mineralization component. PC-II is dominated by K (0.806) with a moderate negative loading on NO₃, suggesting an alkali-enrichment axis distinct from the hardness component. PC-III is dominated by pH (0.781) and CO₃ (0.624), reflecting a carbonate-equilibrium axis, while PC-IV is dominated by NO₃ (0.815), isolating an independent anthropogenic nitrate axis already discernible prior to rotation.

PC-I loads positively on Ca, Mg, Cl, SO₄, EC, TH and TDS (0.70 - 0.94), confirming persistence of the hardness-mineralization axis after recharge. PC-II is jointly weighted on HCO₃ (0.670) and pH (0.696), reflecting a recharge-driven carbonate-alkalinity axis, while PC-III is dominated by NO₃ (0.726) with a secondary pH/K contribution and a comparatively diffuse anthropogenic signal that, unlike pre-monsoon, does not emerge as a single sharply defined axis before rotation.

4.3. Factor Loadings

By observation of the principal axis matrix (**Table 2(a)** and **Table 2(b)**) and the varimax-rotated factor loadings, the main factors identified for the pre-monsoon and post-monsoon datasets are summarised in **Table 3(a)** and **Table 3(b)**.

Factor I accounts for 49.86% of variance and reflects rock-water interaction and carbonate/silicate dissolution. Factor II (10.60%) reflects potassium release from feldspar weathering combined with cation exchange. Factor III (8.95%) represents pH-dependent carbonate speciation. Factor IV (7.81%), weighted almost exclusively on NO_3 , strongly supports an anthropogenic source fertiliser application, sewage infiltration or septic-tank leakage concentrated during the dry season.

Table 3. (a) Factor loadings, pre-monsoon season; (b) Factor loadings, post-monsoon season.

(a)		
Factor	Dominant Loadings	Interpretation
Factor I	EC, TDS, TH, Ca, Mg, Cl, SO_4 (0.71 - 0.97)	Hardness-mineralization factor
Factor II	K (0.883)	Alkali-enrichment factor
Factor III	pH (0.791), CO_3 (0.630)	Carbonate-equilibrium factor
Factor IV	NO_3 (0.972)	Anthropogenic (nitrate) factor
(b)		
Factor I	Ca, Mg, Cl, SO_4 , EC, TH, TDS (0.68 - 0.95)	Hardness-mineralization factor
Factor II	pH (0.845)	Alkaline/carbonate-buffering factor
Factor III	HCO_3 (0.921)	Bicarbonate factor

Factor I (52.46%) persists as the hardness-mineralization factor. Factor II (11.62%), dominated by pH, is an alkaline/carbonate-buffering factor reinforced by recharge. Factor III (8.62%), weighted almost exclusively on HCO_3 , indicates carbonate-mineral dissolution and recharge-related bicarbonate enrichment. Nitrate loads weakly on all post-monsoon factors (maximum 0.198), in marked contrast to its near-unit pre-monsoon loading, consistent with dilution of anthropogenic nitrate by monsoon recharge.

4.4. Factor Rotation

Varimax rotation was applied to the unrotated principal-axis solutions to maximise the variance of squared loadings on each factor and sharpen the variable-factor structure while preserving total explained variance [9] [10]. Communalities analysis was performed in parallel to confirm the adequacy of the retained factor model; the near-zero difference between initial and rotated communalities confirms that rotation redistributes loadings among factors without materially altering the variance accounted for in each variable. Combined communalities values and the varimax-rotated factor matrix are given in **Table 4(a)** and **Table 4(b)**.

Rotation sharpens Factor I to very high loadings on Ca, Mg, Cl, SO_4 , EC, TH and TDS. Factor II sharpens to an almost pure K loading (0.883); Factor III isolates pH (0.791) and CO_3 (0.630) as the carbonate-equilibrium pairing; and Factor IV remains dominated by NO_3 (0.972), confirming that rotation does not alter the independent, anthropogenically controlled nature of the nitrate signal.

Table 4. (a) Communalities values and varimax-rotated factor matrix, pre-monsoon season; (b) Communalities values and varimax-rotated factor matrix, post-monsoon season.

(a)							
Chemical Constituent	Communalities			Rotated Factor Matrix			
	Initial	After Rotation	Difference	Factor I	Factor II	Factor III	Factor IV
Ca	0.936	0.936	0.000	0.956	−0.037	−0.049	0.135
Mg	0.944	0.944	0.000	0.969	0.012	0.051	0.046
Na	0.606	0.606	0.000	0.483	0.426	0.35	0.263
K	0.812	0.812	0.000	0.128	0.883	−0.106	−0.059
Cl	0.806	0.806	0.000	0.808	0.354	−0.103	0.13
SO ₄	0.607	0.607	0.000	0.708	0.249	0.057	0.199
NO ₃	0.952	0.952	0.000	0.083	−0.022	0.008	0.972
HCO ₃	0.537	0.537	0.000	0.594	−0.152	−0.049	0.398
CO ₃	0.666	0.666	0.000	−0.336	0.34	0.63	−0.201
EC	0.673	0.673	0.000	0.819	0.02	−0.005	−0.051
pH	0.763	0.763	0.000	0.198	−0.299	0.791	0.09
TH	0.948	0.948	0.000	0.967	−0.03	0.073	0.074
TDS	0.965	0.965	0.000	0.958	0.187	0.059	0.092

(b)						
Chemical Constituent	Communalities			Rotated Factor Matrix		
	Initial	After Rotation	Difference	Factor I	Factor II	Factor III
Ca	0.904	0.904	0.000	0.925	−0.131	0.006
Mg	0.807	0.807	0.000	0.841	0.19	0.079
Na	0.78	0.78	0.000	0.4	0.509	0.055
K	0.902	0.902	0.000	0.097	−0.048	0.074
Cl	0.688	0.688	0.000	0.798	0.145	0.114
SO ₄	0.738	0.738	0.000	0.769	0.157	−0.272
NO ₃	0.811	0.811	0.000	0.198	−0.093	0.167
HCO ₃	0.874	0.874	0.000	0.037	0.085	0.921
CO ₃	0.829	0.829	0.000	−0.28	−0.126	−0.151
EC	0.714	0.714	0.000	0.677	0.334	−0.316
pH	0.819	0.819	0.000	−0.092	0.845	0.232
TH	0.895	0.895	0.000	0.926	0.179	0.025
TDS	0.942	0.942	0.000	0.953	−0.071	0.08

Factor I retains very high loadings on Ca, Mg, Cl, SO₄, EC, TH and TDS, consolidating the hardness-mineralization signal after rotation. Factor II sharpens to a dominant pH loading (0.845) with reduced cross-loading on Na. Factor III isolates HCO₃ (0.921) as an almost pure bicarbonate factor, with CO₃ retaining only weak negative loadings throughout. The comparatively lower communalities of Cl suggests that post-monsoon chloride variability is partly influenced by variable recharge dilution not fully captured by the retained three-factor model.

4.5. Spatial Variation of Factor Scores

Factor scores computed for each of the 58 sampled wells were interpolated and contoured to delineate the spatial distribution of each hydrogeochemical process

across the Varthur Catchment in both seasons (**Figures 1-7**).

High Factor-I scores (**Figure 1**) coincide with zones of intense urban development and deeper water tables in the south-central and northern catchment, promoting prolonged rock-water contact and mineral enrichment. Factor-II scores (**Figure 2**) show a scattered pattern with localised positive anomalies, consistent with point-source potassium enrichment from feldspathic-gneiss weathering and minor localised fertiliser application.

Factor-III scores (**Figure 3**) display a broadly distributed positive zone reflecting localised carbonate-pH equilibrium. Factor-IV scores (**Figure 4**) are highest in the northern and northeastern catchment, consistent with nitrate enrichment from sewage infiltration, septic-tank leakage and fertiliser application in areas of dense settlement and residual agriculture, concentrated during the dry season when dilution by recharge is minimal.

The post-monsoon Factor-I map (**Figure 5**) shows an overall reduction in the extent and magnitude of high-score zones relative to pre-monsoon, consistent with dilution of hardness indicators by seasonal recharge; a persistent high-score zone in the south-central catchment indicates lithologically sustained mineralization. Factor-II scores (**Figure 6**) show localised positive anomalies in the south-central and southwestern catchment, consistent with recharge-driven pH and alkalinity modification in zones of active infiltration.

Factor-III (bicarbonate) scores (**Figure 7**) are highest in the northwestern and southern catchment margins, reflecting zones of enhanced carbonate-mineral dissolution and recharge-related bicarbonate enrichment following monsoon infiltration.

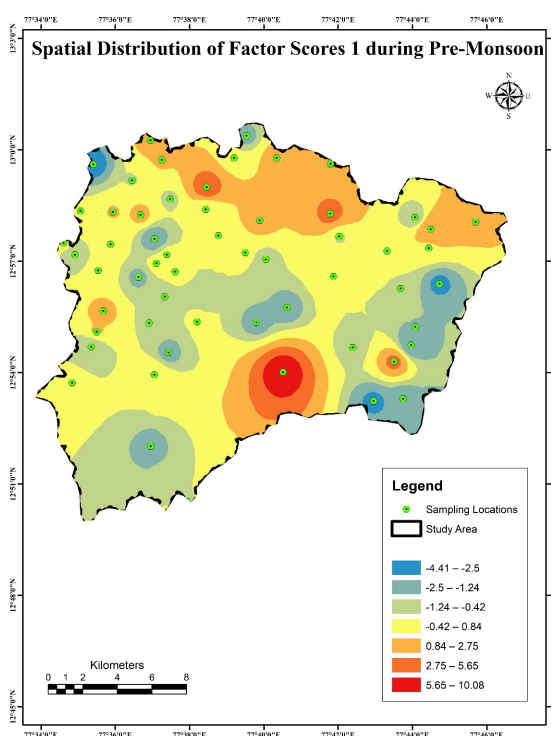


Figure 1. Factor-I (hardness-mineralization) pre-monsoon.

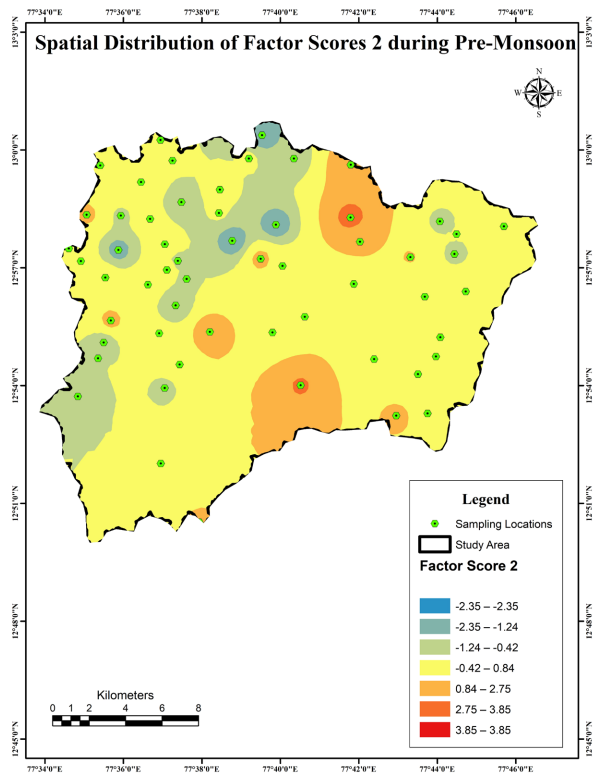


Figure 2. Factor-II (alkali enrichment) pre-monsoon.

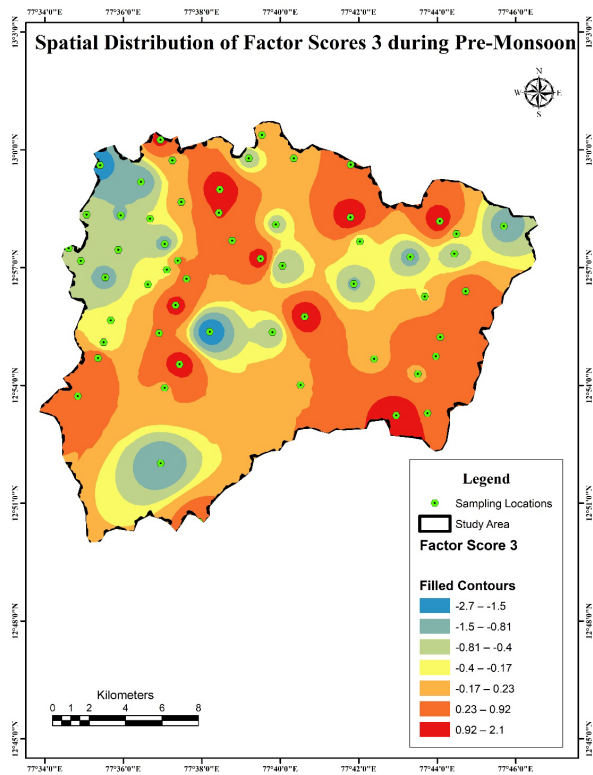


Figure 3. Factor-III (carbonate equilibrium) pre-monsoon.

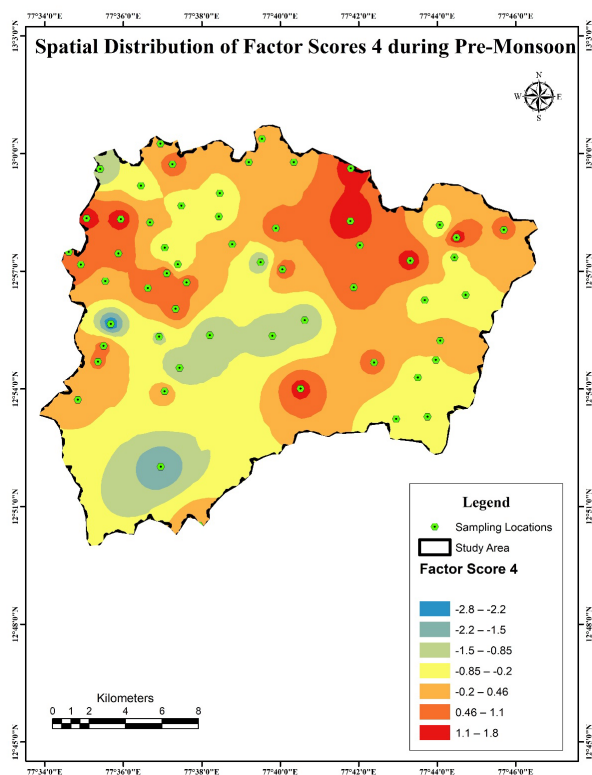


Figure 4. Factor-IV (nitrate/anthropogenic) pre-monsoon.

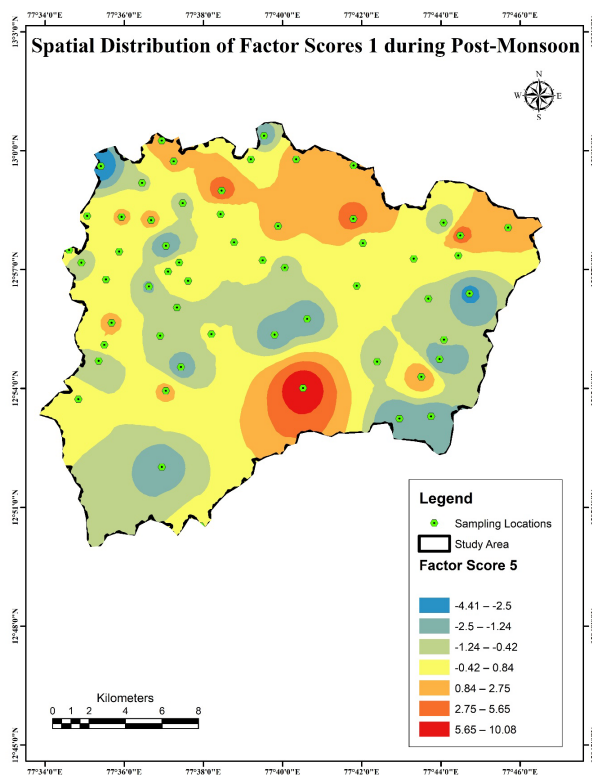


Figure 5. Factor-I (hardness-mineralization) post-monsoon.

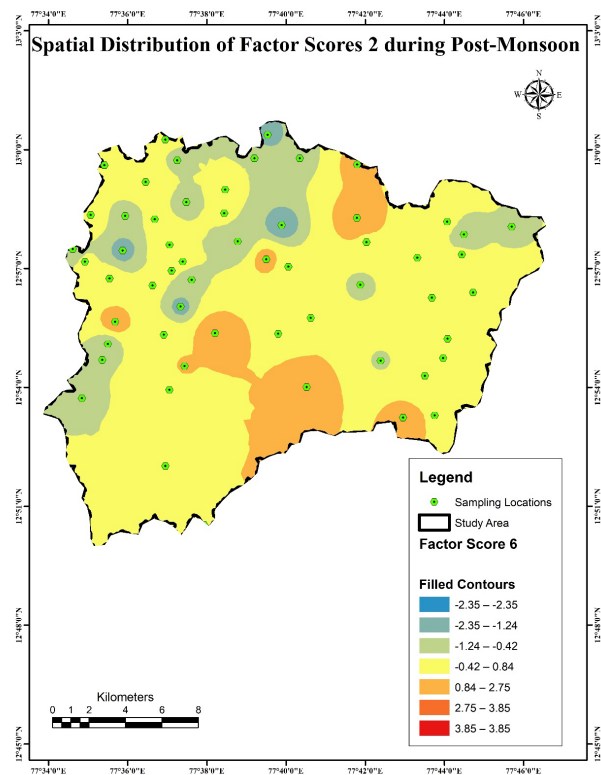


Figure 6. Factor-II (alkaline/carbonate buffering) post-monsoon.

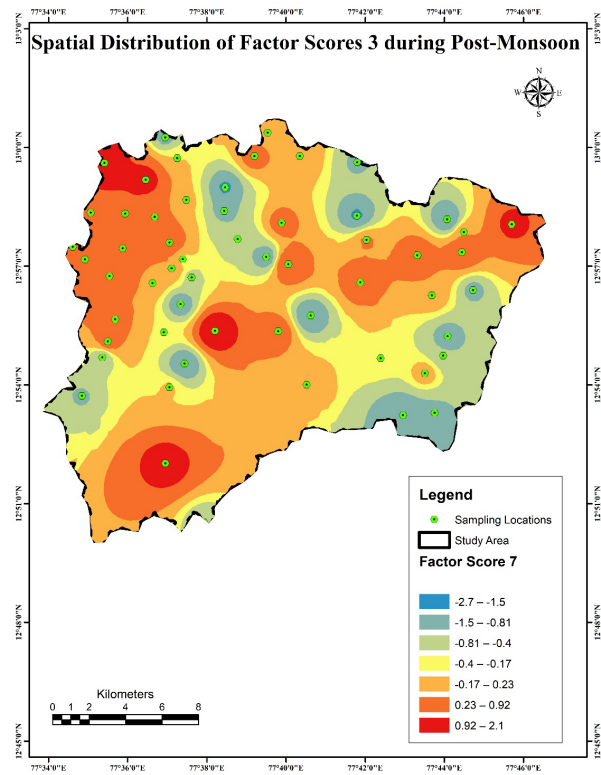


Figure 7. Factor-III (bicarbonate) post-monsoon.

4.6. Integrated Seasonal Hydrogeochemical Interpretation

Comparison of the independently derived pre- and post-monsoon factor structures reveals strong consistency in the dominant geogenic control alongside systematic seasonal differences in the secondary and anthropogenic factors. In both seasons, Factor I is dominated by Ca, Mg, Cl, SO_4 , EC, TH and TDS, demonstrating that geogenic rock-water interaction—principally weathering of plagioclase, biotite and hornblende within the Peninsular Gneissic Complex—is the seasonally invariant control on groundwater mineralization, consistent with the seasonally stable hardness factors reported for other Peninsular Gneissic terrains of Karnataka [7] and for comparable hard-rock and semi-arid Indian aquifers [1].

Carbonate-related variables reorganise seasonally: pH and CO_3 load together pre-monsoon, whereas post-monsoon this structure separates into a pH-dominated Factor II and an almost independent HCO_3 -dominated Factor III, consistent with recharge-driven carbonate dissolution and CO_2 -charged infiltration, a seasonal carbonate-equilibrium shift broadly analogous to the recharge-driven bicarbonate enrichment documented in other monsoon-influenced hard-rock settings [6].

The most pronounced seasonal contrast lies in the nitrate signature: NO_3 loads almost exclusively (0.972) on a dedicated pre-monsoon factor, indicating concentrated anthropogenic enrichment when minimal recharge limits dilution, whereas post-monsoon NO_3 loadings are modest across all retained factors (maximum $r = 0.198$), consistent with dispersal and dilution by monsoon recharge rather than elimination of the contamination source a pattern consistent with the seasonal nitrate attenuation reported for other urbanising and agriculturally influenced Indian aquifers [5]. Spatial factor-score mapping reinforces this pattern: hardness-mineralization scores contract post-monsoon while remaining persistently elevated in the south-central catchment, and nitrate-related scores (pre-monsoon) remain concentrated in the northern catchment near dense settlement and residual agriculture, underscoring the spatially fixed nature of anthropogenic sources relative to the seasonally mobile geogenic and carbonate signals.

5. Conclusions

R-mode factor analysis of pre- and post-monsoon hydrochemical datasets from the Varthur Catchment demonstrates that groundwater quality is governed by a consistent set of geogenic processes that persist across both seasons, modulated by seasonally variable secondary and anthropogenic influences. The principal findings are summarised below.

- Dominant hydrogeochemical process: In both the pre-monsoon (49.86% of variance) and post-monsoon (52.46%) datasets, the first and most important factor is consistently a hardness-mineralization factor dominated by Ca, Mg, Cl, SO_4 , EC, TH and TDS, confirming rock-water interaction within the Peninsular Gneissic Complex as the fundamental control on groundwater chemistry, irrespective of season.

- Seasonal factor variation: The pre-monsoon dataset retains four significant factors explaining 77.22% of total variance, whereas the post-monsoon dataset retains three factors explaining 72.70%. The reduction reflects dilution and statistical merging of the dry-season alkali-enrichment and carbonate-equilibrium axes into a more diffuse pH-bicarbonate structure, and the loss of nitrate as a separately resolvable factor.
- Carbonate equilibrium: Carbonate-related variables reorganise seasonally, from a combined carbonate-equilibrium factor (pre-monsoon) into separate alkaline (pH-dominated) and bicarbonate (HCO_3 -dominated) factors (post-monsoon), indicating intensified, recharge-driven carbonate-mineral dissolution following the monsoon.
- Anthropogenic influence: Nitrate constitutes a clearly anthropogenic, geochemically independent signal pre-monsoon (loading 0.972), most likely sourced from agricultural fertiliser application, sewage infiltration and septic-tank leakage. This signal becomes diffuse and statistically unresolved post-monsoon (maximum loading 0.198), consistent with dilution by recharge rather than elimination of the source.
- Spatial patterns: High hardness-mineralization zones coincide with deeper water tables and intensified urban development in the south-central catchment in both seasons, with some contraction post-monsoon. Nitrate-related scores (pre-monsoon) concentrate in the northern catchment near dense settlement and residual agriculture, highlighting spatially fixed anthropogenic source areas.
- Overall groundwater evolution: The integrated seasonal analysis indicates that groundwater hydrogeochemistry in the Varthur Catchment evolves through persistent lithogenic weathering and carbonate dissolution, with recharge-induced seasonal modification of secondary pathways and a superimposed, seasonally modulated anthropogenic nitrate signal, underscoring the need for continued seasonal groundwater monitoring in rapidly urbanising hard-rock catchments.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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