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HYDROCHEMICAL CHARACTERISATION OF GROUNDWATER IN BHUBANESWAR CITY USING MULTIVARIATE STATISTICAL TECHNIQUES

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Abstract

Bhubaneswar, the smart city of Odisha, is where water quality deterioration is a major concern due to the huge population growth and rural-to-urban migration. This study includes three types of land use patterns, such as high population density areas, industrial areas, and the vicinity of solid waste dumping sites. Five samples were collected from each category of vulnerable areas, totalling fifteen samples. Physico-chemical parameters such as pH, Electrical Conductivity (EC), DO, Hardness, Alkalinity, Cl^-, TDS, F^-, NO_3^-, SO_4^{2-}, Fe^{2+}, Ca^{2+}, Mg^{2+}, Na^+, K^+ and HCO_3^- were tested for each sample. The concentration of iron is exceeding the permissible limit at 45% of the sample locations due to geogenic processes. Most of the parameter's concentration is within the permissible limit as stated in IS:10500 (2012). Factor 1 of Principal Component Analysis (PCA) suggests positive loadings for Ca^{2+} (0.962), total hardness (TH) (0.946), TDS (0.894), and HCO_3^- (0.876), indicating that this factor is predominantly associated with groundwater mineralisation and water–rock interaction. Factor 2 of PCA indicates strong positive loadings of Na^+ (0.952) and Cl^- (0.952), inferring the influence of salinity-related processes and ion exchange. Factor 3 of PCA interprets strong positive loadings for NO_3^- (0.907) and SO_4^{2-} (0.813), inferring a possible influence of anthropogenic activities such as domestic wastewater and other surface-derived inputs. Factor 4 was dominated by Mg^{2+} (0.866) and F^- (0.716), suggesting geochemical interactions. Factor 5 shows strong positive loadings for K^+ (0.866) and pH (0.532. This component may reflect a relatively distinct influence of potassium-bearing minerals and anthropogenic sources, especially where potassium is associated with domestic inputs. Hierarchical cluster analysis (HCA) recommends classification of the physicochemical parameters into five groups at a phenon line at 0.65, which is mostly related to the mineralisation and hardness characteristics of groundwater. The current study suggests that the government needs to develop a policy *for the consumption of groundwater in view of rapid urbanization and protect the fresh water from anthropogenic contamination.*

Keywords: Factor analysis, Bivariate correlation matrix, Groundwater contamination, Hierarchical cluster analysis

I. Introduction

Groundwater is the backbone of urban water security, and in developing countries, the contribution of groundwater for sustainable development is highly crucial. It's very important to maintain the quality as well as quantity throughout all the seasons. The major threat for contamination of ground water is rapid urbanization and its impact on groundwater. Groundwater contains ionic parameters that are dissolved from agricultural activity, industry, and solid waste disposal (Khan et al., 2023; Igboama et al., 2022; Niedbalska, 2022; Brindha et al., 2013; Wiemer et al., 1998). Contaminated groundwater may cause human health effects, change the color of water, and change the taste of water (Das et al., 2022). It has been studied that groundwater contamination occurs through the process of recharge in contaminated soil (Rao et al., 2024). In urban areas, groundwater is primarily contaminated due to population growth, industrialization, and urbanization (Tyagi et al., 2020). Groundwater is an important source of safe water, especially in dry climatic regions of the world (Rao et al., 2020). Human health is very important, and therefore the quality of groundwater must be ensured, which is influenced by physical and chemical parameters of the geo-environment (Das et al., 2022). The precious resource has been pressured by anthropogenic-induced factors, geogenic factors, including global warming. Rapid industrialization, population growth, application of chemical fertilizers, lack of wastewater management system, and inadequate water management resources for several years have increased groundwater pollution (Samal et al., 2023; Rajan et al., 2024; Navaneeth et al., 2024; Foster et al., 2013) Several studies have been conducted using the Water Quality Index (WQI) method to interpret suitability of groundwater for domestic or drinking purpose (Sarwar et al., 2020; Uddin et al., 2023). Researchers have conducted an analysis on the water quality index of the present study area, which suggests that water quality is classified as good and excellent (Samal et al., 2025). Due to the rapid growth of population and the demand for water, the importance of groundwater is very high for major domestic purposes. Therefore, it is essential to apply an innovative way of groundwater quality monitoring, propose mitigation for contamination, and reduce the health risk. With this background, monitoring and identification of groundwater in sensitive areas is essential for ensuring public health and wellness. Researchers have applied multivariate statistical analysis such as principal component analysis (PCA), Hierarchical cluster analysis (HCA), correlation matrix, multiple regression, and ANOVA to group the locations having similar groundwater contamination, as well as it assesses the factors that influence the concentration of different physicochemical parameters (Wu et al., 2020; Di et al., 2020).

Bhubaneswar, being the capital of Odisha state and a smart city, has highly increased in industrial growth. This urbanization thus increased the demand for fresh water. The existing water supply system would be inadequate to meet the demand; therefore, fresh available groundwater is mostly preferred. The geographical pattern of the city indicates that its breadth increases in directions such as the eastern part growing towards Cuttack city, north part expanding towards Cuttack, south part expanding towards Khurda, and the western area expanding towards Bhubaneswar's new smart city. As per the Central Ground Water Board, the Bhubaneswar block has been classified as semi-critical, indicating significant stress on its groundwater resources. This classification has been identified as the annual groundwater extraction is between 70% and 90% of the annually rechargeable quantity (CGWB 2023). The Mann-Kendall and Sen's slope analysis of groundwater quality of the study area revealed that iron concentration at a few places in the northern part is higher than the permissible limit (Tarai et al., 2023).

II. Materials and methods

II.i. Groundwater sampling and analysis

The study aimed to assess the quality of groundwater, especially in the zone of high population density, vicinity of solid waste dumping sites, and industrial belts. The number of locations identified was fifteen, out of which five locations were in the zone of high population density, five locations in the vicinity of solid waste dumping sites, and five locations at industrial sites. Geographic coordinates of each sampling location have been taken using the handheld Geographic Positioning System (GPS) instrument. The locations of each sampling point are shown in Fig. 1. The depth of tub wells varies from 45 m to 60 m below ground level, situated in a confined aquifer, and the distance of these tube wells is up to 500 m from the suspected land use sites.

From each sampling location, 500 ml samples have been collected either from hand tube wells or boreholes through pumping. Water was pumped continuously for five minutes before collection. The sample collection bottles were rinsed three times with the tube well or borehole water prior to collection of water samples. The pH, TDS, Electrical Conductivity (EC), and temperature data of groundwater samples were determined through a portable pocket-size TDS/Conductivity/Temperature tester (HANNA Combo HI98130 Model) that was immersed in the water sample bottle. Through the flame photometric method, potassium was determined, while Chloride and Sodium concentrations were analyzed in the laboratory through titration of silver nitrate with potassium chromate as an indicator. The absorption mode of the Atomic Absorption Spectrophotometric (AAS) technique was utilized to determine the concentrations of Magnesium and Calcium. The determination of Sulphate, Iron, Nitrate, and Fluoride were determined using a UV–visible spectrophotometer instrument, i.e., Systronics Model No. 2701. The results from the collected samples were compared with WHO (WHO 2007). The physicochemical parameter pH has no units, EC is measured in (µS/cm), and other parameters are expressed in milligrams per litre (mg/L). The ion balance (IBE) error was calculated using Equation-1 (Hota et al., 2023), and it is found within ±10%, conforming reasonably accuracy of analyses.

$$\text{IBE} = \frac{\sum \text{TCC} - \sum \text{TCA}}{\sum \text{TCC} + \sum \text{TCA}} \times 100 \qquad (1)$$

Where, ΣTCC and ΣTCA are the total concentrations of cations and anions, respectively, in meq/L.

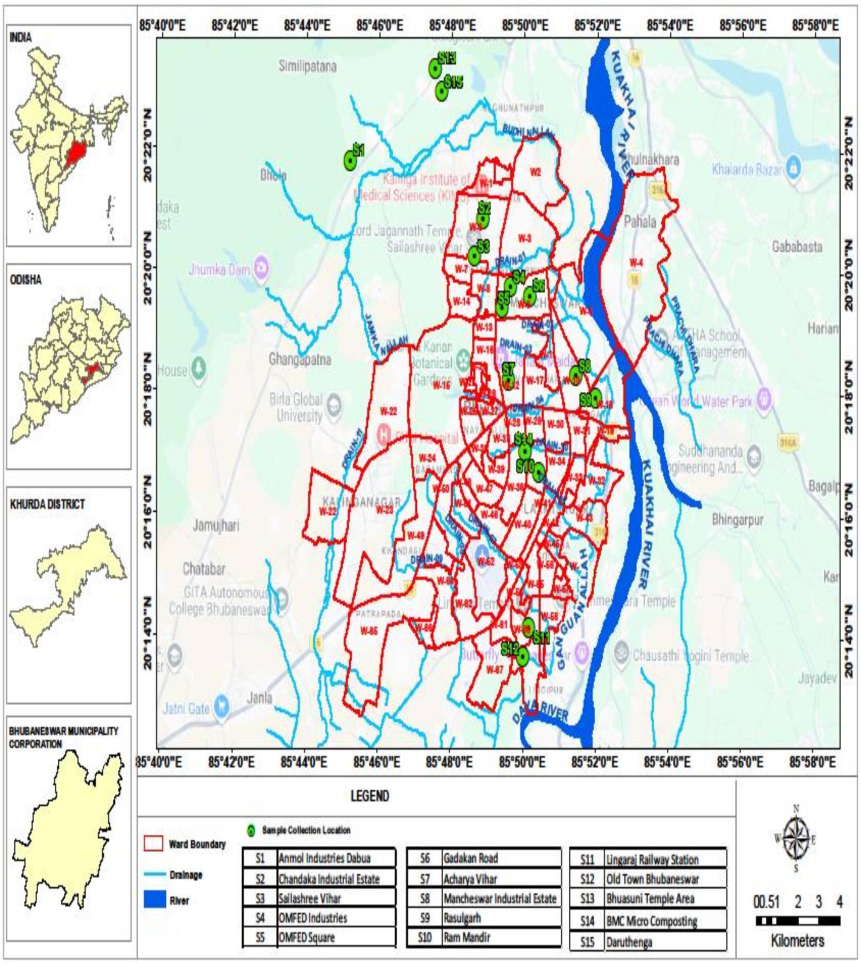

Fig. 1. Sample collection location map

II.ii. Statistical analyses and techniques

The different statistical methods used for analysis are descriptive statistics, bivariate correlation matrix, factor analysis, hierarchical cluster analysis (HCA), and ANOVA. Factor analysis is a multivariate statistical technique applied to analyse and also to reduce the several groups of original data to smaller groups of similar variables. In the current study, EC has been removed from the analysis as EC and TDS are highly correlated. The methodology implies that there is dependency existing within the physicochemical parameters (Rezaei et al., 2019; Jianqin et al., 2010). The HCA analysis was applied to categorize data into groups based on features, sources, and characteristics that are dissimilar or similar (Hajigholizadeh et al., 2017; Hamid et al., 2016). The HCA results are produced in the pictorial form of dendrograms. The standardisation applied to the variables, the distance metric (Euclidean distance on standardised variables), and the linkage method (Ward's method used) in the HCA analysis (Hair et al., 2019).

III. Results and Discussion

III.i. Descriptive Statistics

The statistical analysis was applied to analyse the mean, minimum, maximum, and standard deviation of each groundwater quality parameter.

Table 1: Descriptive Statistics Analysis

Variable*	Maximum	Minimum	Mean	CV (Coefficient of Variance in %)
pH	6.58	5.68	6.18	3.88
EC	619.00	316.00	453.40	25.14
TDS	396.00	202.00	290.13	25.16
TA	104.00	10.00	55.87	55.47
TH	236.00	60.00	140.67	35.00
Ca^{2+}	64.62	12.08	39.26	42.24
Mg^{2+}	19.95	2.40	10.38	57.74
Na^{+}	41.37	18.64	29.10	23.33
K^{+}	10.23	1.43	6.03	42.54
Fe^{+}	0.54	0.05	0.29	50.86
HCO_3^-	173.03	15.16	92.91	59.81
Cl^-	76.38	33.73	51.84	26.63
SO_4^{2-}	34.78	7.50	19.44	49.17
NO_3^-	62.73	8.73	33.62	56.83
F^-	0.24	0.03	0.13	54.67

*pH is unitless, and all other parameters having unit mg/l except conductivity, µS/cm.

pH value of the sample has a minimum value of 5.68 and a maximum value of 6.58, with a mean value of 6.18, which indicates the water quality is slightly acidic to near-neutral condition. Conductivity ranges from a minimum of 316 µs/cm to a maximum of 619 µs/cm, with a mean value of 453.40 µs/cm, which indicates total ionic concentration (dissolved salts) in water. The minimum value of hardness is 60 mg/l and the maximum value is 236 mg/l. Alkalinity of the parameters is a minimum of 10 mg/l and the maximum value is 104 mg/l. Chloride of the parameters has a minimum value of 33.73 mg/l and a maximum value of 76.38 mg/l. TDS of the tested parameters has a minimum value of 202 mg/l and a maximum value of 396 mg/l which indicates the concentration of groundwater falls within the freshwater category. The TDS concentration indicates moderate mineralization, which indicates groundwater constituents of dissolved minerals due to soil-water interaction and the geological leaching processes. The samples tested show a fluoride concentration with a minimum value of 0.03 mg/l and a maximum value of 0.24 mg/l which is within the permissible limit as stated in BIS (2012). Nitrate concentration has a minimum value of 8.73 mg/l and a maximum value of 62.73 mg/l possible due to anthropogenic contamination in certain locations. Sulphate concentration has a minimum value of 7.5 mg/l and a maximum value of 34.78 mg/l due to weathering and mineralization of sulphate minerals present in soil and rock with limited anthropogenic activities. Iron concentration has a minimum value of 0.05 and a maximum value of 0.54 mg/l with a mean value of 0.29 mg/l. Iron concentration was higher than the permissible limit (BIS 2012) due to geochemical processes. The calcium parameter has a minimum value of 12.08 mg/l and a maximum value of 39.26 mg/l. Magnesium concentration has a minimum value of 2.4 mg/l and a maximum value of 10.38 mg/l. Sodium concentration has a minimum value of 18.64 mg/l and a maximum value of 29.10 mg/l which indicates relatively low sodium content in the groundwater. Such levels generally suggest limited salinization and moderate mineral dissolution. Potassium concentration has a minimum value of 1.43 mg/l and a maximum value of 6.03 mg/l. Bicarbonate concentration has a minimum value of 15.16 mg/l and a maximum value of 92.91 mg/l which indicates that groundwater chemistry is largely influenced by natural rock–water interaction and carbonate weathering processes. The unit of all the physicochemical parameters is mg/l except pH and conductivity. pH has no unit, whereas conductivity is measured in µS/cm. The concentration of parameters indicates that the quality is influenced by natural geochemical processes such as carbonate weathering and mineral dissolution.

III.ii. Bivariate Correlation Matrix

The bivariate correlation matrix indicates the relationship between the physicochemical parameters of groundwater, which shows the influence of anthropogenic and geogenic processes. The ions having influence over the increase in TDS. EC and TDS are also correlated with Ca^{2+}, Mg^{2+}, and Na^{+}, which indicates that these positive cations influence salinity and mineralization and show an almost perfect positive correlation ($r = 0.999$, $p < 0.01$), which indicates that dissolved ions are the primary contributors to conductivity. Hardness has a positive correlation with $Ca^{2+}$and Mg^{2+} , which signifies that hardness is influenced by alkaline earth material produced from weathering of carbonate and silicate. pH has a negative correlation with Na+, which indicates that an increase in ions and sulphate concentration reduces pH value. The process of mineral dissolution or anthropogenic activities is the prime reason. The correlation matrix indicates that Iron is negatively correlated with Ca^{2+}, $Mg^{2+,}$ $Na^{+,}$ and $K^{+,}$ which implies that Iron concentration is controlled by redox conditions rather than the cation of physicochemical parameters. At the outset, the correlation matrix indicates the hydrochemistry of groundwater is controlled by mineral dissolution, and limited locations have geogenic exchanges such as salinity inputs from chloride and sodium. The cophenetic correlation coefficient (0.57) highlights a reasonable dependency on other groundwater chemical properties. But this hydraulic procession having poor clustering structure, which suggests a mixed geochemical control process across the parameters.

Table 2 : Bivariate Correlation Matrix

	pH	TDS	TA	TH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	F^-
pH	1	.028	-.259	.136	.007	.259	-.349	.187	.030	-.418	.250	.206	.038
TDS	.028	1	.351	.921**	.800**	.498*	.388	.429	.869**	.430	-.023	-.039	.460*
TA	-.259	.351	1	.245	.151	.243	.411	-.087	.078	.343	.257	.380	.513*
TH	.136	.921**	.245	1	.867**	.541*	.082	.167	.915**	.151	-.080	-.169	.396

Ca^{2+}	.007	.800**	.151	.867**	1	.051	-.066	.131	.742**	.053	.017	-.007	.148
Mg^{2+}	.259	.498*	.243	.541*	.051	1	.280	.113	.582*	.215	-.189	-.327	.546*
Na^{+}	-.349	.388	.411	.082	-.066	.280	1	.466*	.150	.943**	-.215	.015	.445*
K^{+}	.187	.429	-.087	.167	.131	.113	.466*	1	.279	.439	.131	-.001	-.144
HCO_3^-	.030	.869**	.078	.915**	.742**	.582*	.150	.279	1	.174	-.299	-.460*	.246
Cl^-	-.418	.430	.343	.151	.053	.215	.943**	.439	.174	1	-.259	.028	.414
SO_4^{2-}	.250	-.023	.257	-.080	.017	-.189	-.215	.131	-.299	-.259	1	.544*	-.037
NO_3^-	.206	-.039	.380	-.169	-.007	-.327	.015	-.001	-.460*	.028	.544*	1	.308
F^-	.038	.460*	.513*	.396	.148	.546*	.445*	-.144	.246	.414	-.037	.308	1

**. Correlation is significant at the 0.01 level (1-tailed). *. Correlation is significant at the 0.05 level (1-tailed).

III.iii. Factor Analysis

Factor analysis (FA) was applied to identify the key factors controlling the geogenic and anthropogenic variability of groundwater. The analysis reduces the dimensionality of the dataset. The standardized groundwater-quality variables were subjected to principal component extraction, followed by varimax rotation to obtain a structured grouping of parameters with similar characteristics of the parameter.

Table 3: Factor analysis developed through principal component analysis

	Factor Components				
	1	2	3	4	5
pH	-.002	-.568	.247	.479	**.532**
TDS	**.894**	.319	.060	.257	.152
TA	.213	.459	**.495**	.261	-.439
TH	**.946**	.005	-.054	.306	.004
Ca^{2+}	**.962**	-.056	.090	-.150	-.046
Mg^{2+}	.273	.109	-.258	**.866**	.083
Na^{+}	.015	**.952**	-.031	.202	.143
K^{+}	.209	.395	.070	-.072	**.866**
HCO_3^-	**.876**	.062	-.363	.254	.113
Cl^-	.101	**.952**	-.054	.096	.105
SO_4^{2-}	-.009	-.208	**.813**	-.085	.172
NO_3^-	-.133	.069	**.907**	.001	-.061
F^-	.206	.365	.255	**.716**	-.327

Extraction Method: Principal Component Analysis. **Rotated Component Matrix[a]**: Varimax with Kaiser Normalization.
a. Rotation converged in 13 iterations.

Five components were extracted based on the rotated component matrix, indicating distinct bonding among each factor's measured physicochemical parameters.

Factor 1 shows strong positive loadings for Ca^{2+} (0.962), total hardness (TH) (0.946), TDS (0.894), and HCO_3^- (0.876), indicating that this factor is predominantly associated with groundwater mineralisation and water–rock interaction. The strong association between Ca^{2+}, TH, HCO_3^- and TDS suggests dissolution of carbonate-bearing minerals.

Factor 2 was grouped by strong positive loadings of Na^+ (0.952) and Cl^- (0.952), having a strong negative loading of pH (−0.568), inferring the influence of salinity-related processes and ion exchange,

Factor 3 indicates strong positive loadings for NO_3^- (0.907) and SO_4^{2-} (0.813), inferring a possible influence of anthropogenic activities such as domestic wastewater and other surface-derived inputs.

Factor 4 was dominated by Mg^{2+} (0.866) and F^- (0.716), suggesting that mineral dissolution and geochemical interactions involving magnesium- and fluoride-bearing minerals could contribute towards groundwater chemistry.

Factor 5 shows strong positive loadings for K^+ (0.866) and pH (0.532), while TA (−0.439) and F^- (−0.327) exhibited moderate negative loadings. This component may reflect a relatively distinct influence of potassium-bearing minerals and anthropogenic sources, especially where potassium is associated with domestic inputs.

Further eigenvalue and loading stability have been evaluated by leaving one sample out, i.e., iron (Fe), and are shown in Table 4

Table 4 : Eigenvalues after leaving iron (Fe) parameter

Component	Initial Eigenvalues			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	4.569	35.146	35.146	3.622	27.863	27.863
2	2.476	19.047	54.193	2.805	21.577	49.440
3	2.045	15.729	69.921	2.077	15.974	65.414
4	1.434	11.032	80.953	1.869	14.378	79.792
5	1.290	9.926	90.879	1.441	11.087	90.879
6	.633	4.869	95.748			
7	.284	2.182	97.931			
8	.137	1.056	98.986			
9	.091	.703	99.689			
10	.032	.249	99.938			
11	.008	.062	100.000			
12	3.012E-005	.000	100.000			
13	4.641E-006	3.570E-005	100.000			

The component plot in rotated space was developed and shown in Fig. 2. The 3-D diagram shows similarity to factor analysis, where the physicochemical parameters are reduced to five components.

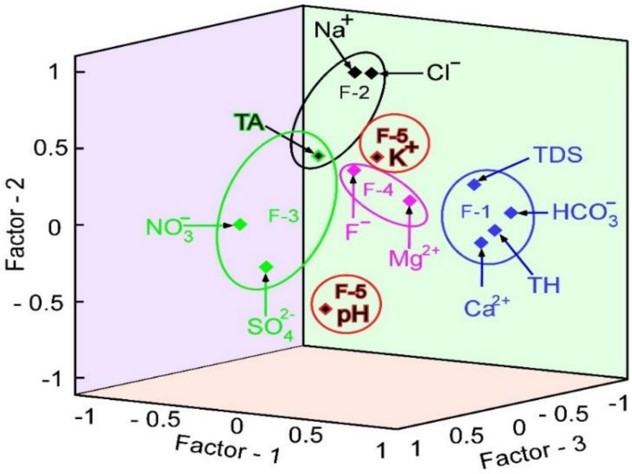

Fig. 2. Component plot in rotated space.

III.iv. Dendrogram

The hierarchical cluster analysis-generated dendrogram has grouped physicochemical parameters into five groups at a phenon line of 0.65, as shown in Fig. 3. These clusters signify their contribution to groundwater quality as well as inter-influence.

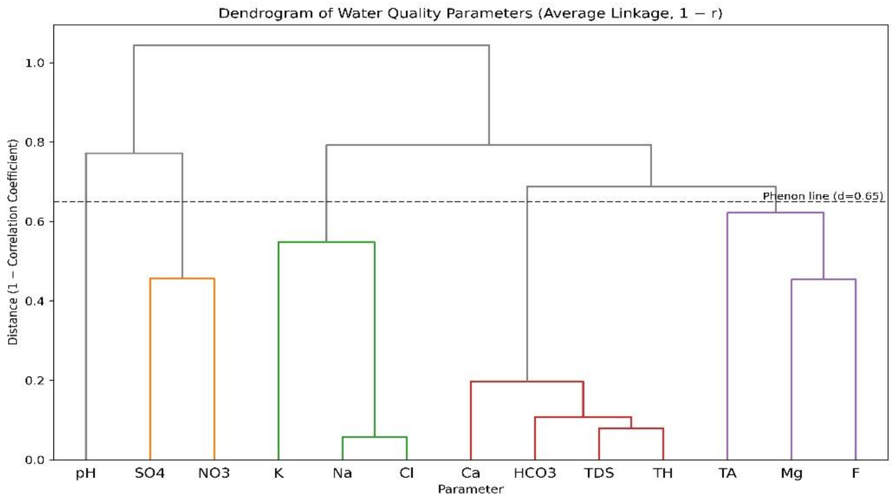

Fig. 3. Hierarchical cluster analysis (Dendrogram) of physicochemical parameters

The cluster (SO_4–NO_3) is most likely of anthropogenic origin, since nitrate is predominantly derived from agricultural fertilizers, septic effluent, or domestic waste, while sulphate can originate from fertilizer application, gypsum dissolution, or atmospheric/industrial deposition.

The cluster (Na–K–Cl) infers either the dissolution of alkali-bearing minerals (e.g., silicate weathering, cation exchange) or anthropogenic contamination such as domestic sewage, irrigation return flow, all of which are associated with elevated Na–Cl loads. The strength of the Na–Cl association in particular is a commonly used indicator of saline or evaporitic influence, or could be ion-exchange processes in the aquifer matrix.

The cluster (Ca–HCO_3–TDS–TH) represents the dissolution of carbonate minerals (calcite/dolomite). Because Ca^{2+} and HCO_3^- are the principal products of carbonate weathering and are the main contributors to both total hardness and total dissolved solids. The strong bonding of these parameters indicates that water–rock interaction with carbonate lithology is the primary control on the overall mineral content of the sampled waters.

The cluster (TA–Mg–F) groups total alkalinity with magnesium and fluoride. The dissolution of dolomite releases Mg^{2+}; this association may reflect a dolomitic (Mg-rich carbonate) weathering process distinct from the calcite-dominated process. Fluoride's presence in this cluster is associated with the weathering of fluoride-bearing minerals (e.g., fluorite, apatite, biotite) under alkaline conditions, and its co-clustering with alkalinity is considered geogenic contamination.
pH is considered independent of the other clusters, as underscored in this dataset. The alkalinity nature works as a catalyst for mineral dissolution.

III.v. Regression coefficients (TDS as dependent)

Table 4: Regression coefficient of TDS

Intercept	17.1328
Chloride	1.1239
Fluoride	-17.4647
Nitrate	1.1226
Sulphate	0.8665
Iron	9.4697
Ca^{2+}	0.8564
Mg^{2+}	0.7011
Na^+	0.3155
K^+	1.4143
HCO_3^-	1.1159

Table 4 indicates TDS is depended over the concentration of ions having positive coefficients, such as chloride (1.1239), nitrate (1.1226), sulphate (0.8665), calcium (0.8564), magnesium (0.7011), sodium (0.3155), potassium (1.4143), and bicarbonate (1.1159), which implies that the increase in concentration of these ions contribute directly to increase in TDS value. The processes of mineral dissolution, weathering of rocks, and certain anthropogenic processes are predominant. Iron indicates the highest positive coefficient (9.4697), which possibility due to redox geochemical processes. Fluoride shows an inverse relationship with TDS since the regression coefficient is negative (-17.4647).

The dependent equation is:

$$TDS=17.1328+1.1239(Cl^-)-17.4647(F^-)+1.1226(NO_3^-)+0.8665(SO_4^{2-}) +9.4697(Fe)+0.8564(Ca^{2+}) +0.7011 (Mg^{2+}) +0.3155 (Na^+) +1.4143 (K^+) +1.1159 (HCO_3^-) \quad (2)$$

III.vi. ANOVA

Table 5: ANOVA table of groundwater parameters

Sources of Variation	Degree of freedom	Sum Square	Mean Squares	F value	Pr(>F)
Chloride	1	19103.1967	19103.1967	376.146	4.1666E-05***
Fluoride	1	7648.78933	7648.78933	150.606	0.00025***
Nitrate	1	41.1203474	41.1203474	0.809	0.41909
Sulphate	1	124.985361	124.985361	2.460	0.19178
Iron	1	79.7609758	79.7609758	1.570	0.27838
Ca^{2+}	1	25049.2026	25049.2026	493.225	2.4334E-05***
Mg^{2+}	1	111.631656	111.631656	2.198	0.21232
Na^{+}	1	1007.66167	1007.66167	19.841	0.01120*
K^{+}	1	1433.14917	1433.14917	28.219	0.00603**
HCO_3^-	1	1035.57122	1035.57122	20.390	0.01069*
Residuals	4	203.14618	50.786545		

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

The ANOVA Table 5 indicates that there is a significant difference in characteristics between the physicochemical parameters of the sampled groundwater. F-values of parameter Chlroide, Fluoride, and Calcium are 376.15, 150.61, and 493.23, respectively, with p-values less than 0.001 ($p<0.001$), which indicates that the parameters have highly significant differences and high control on the characteristics of groundwater. Parameters like sodium, potassium, and bicarbonate have moderate significance, where $p<0.05$ indicates these parameters express notable contribution to hydro-chemical variability, which may be due to mineral dissolution and ion exchange processes. The remaining parameters, such as nitrate, sulphate, iron and magnesium, calculate low F-values, and high p-value ($p > 0.05$) implies that variations are not significant and remain almost similar across the sample locations. The summary of ANOVA tables indicates that ions such as Ca^{2+}, Cl^- and F^- make a dominant contribution to groundwater quality.

3.7 Piper Diagram

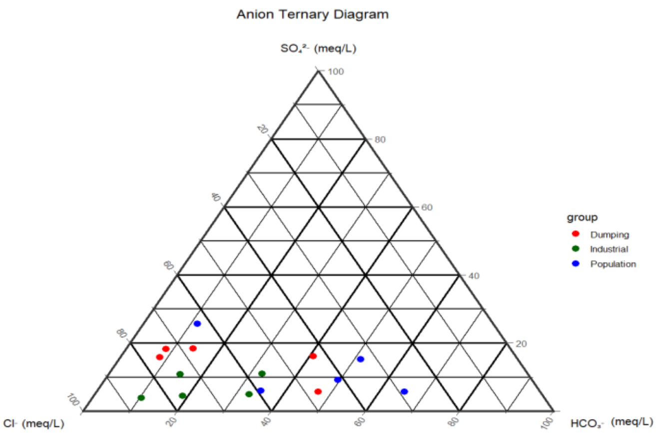

Fig. 4. Piper diagram of the anion physicochemical parameter

J. Mech. Cont. & Math. Sci., Vol.-21, No.-09, September (2026) pp 184-199

The Piper diagram for anion physicochemical parameters distributes the three land use patterns, such as high population density area, soil waste dumping sites, and industrial area, by relative concentrations (meq/L) of Cl^-, SO_4^{2-}, and HCO_3^-. The piper diagrams trilinear visualization indicates anions of groundwater change due to hydrogeochemical processes, which aligns with prior regression and ANOVA data on these ions. Fig. 4 indicates high density populated areas have groundwater inclined towards HCO_3^- interaction between water, rock, soil, and anthropogenic activities. The locations near solid waste dumping (red) and industrial developed area (green) spread toward Cl, which is indicating salinity or pollution from anthropogenic sources like soil waste leaching. Samples collected from high population density areas inclined towards HCO_3^-, which implies that groundwater points are affected due to rock weathering or biogenic CO_2 sources.

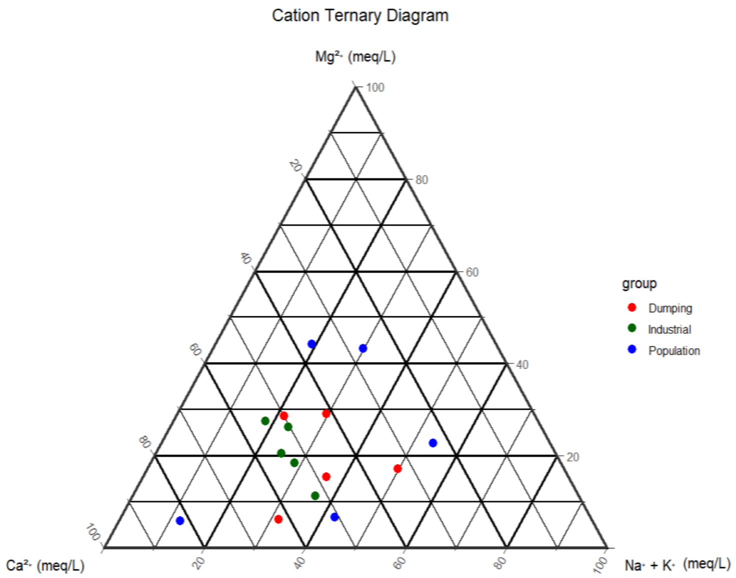

Fig. 5. Piper diagram of the cation physicochemical parameter

The Piper diagram for physicochemical parameter especially have been presented in Fig. 5. This diagram classifies water samples by relative meq/L concentrations of Ca^{2+}, Mg^{2+}, and Na^++K^+ throughout the three land use pattern areas, which indicates that the high population density area in blue color solid circle, the solid waste dumping site as green color solid circle, and the industrial area is represented by the red solid circle. This plot complements the piper diagram prepared for anions in Fig. 6, revealing cation dominance to define hydro-chemical facies and pollution signatures. High Population density locations cluster toward the Ca^{2+} apex (often >60%), which indicates calcium-dominant waters typical of limestone or gypsum dissolution in natural recharge areas. Dumping and industrial locations clustered toward Na^++ K^+ and Mg^{2+} regions, suggesting alkali or magnesium influence from solid waste dumping sites, also implying mixed chemistry possibly from effluents. The combined anion and cation plot shows high-density population locations where groundwater is likely of Ca-HCO3 types (fresh, geogenic), while affected groups trend to Na-Cl/SO4 or Mg-SO4, implying anthropogenic contamination.

IV. Conclusion

The current study was undertaken to study the physicochemical characteristics of groundwater in three classified vulnerable land use types, such as high population density areas, industrial areas, and areas in the vicinity of solid waste dumping sites, to evaluate the contamination of groundwater within the smart city Bhubaneswar of Odisha in India.

1. The physicochemical parameters of the 15 sample locations are within the permissible standards stated in BIS 10500:2012 and the WHO guidelines. However, 7 out of 15 locations, which is nearly 45% of the sampled location where iron concentration is beyond the permissible limit. Therefore, periodic groundwater monitoring and remedial procedures should be implemented to reduce critical health risks.
2. pH of the groundwater shows groundwater is acidic to neutral in nature, which signifies that there is a geochemical process influenced by silicate rock weathering.
3. The high loadings of conductivity and TDS indicate that this factor is primarily associated with the overall ionic strength of groundwater.
4. The association of Ca^{2+}, hardness, and bicarbonate further suggests that water–rock interaction and carbonate weathering are dominant processes influencing groundwater chemistry.
5. PCA analysis indicates that elevated nitrate and sulphate concentrations often originate from domestic wastewater or industrial activities. The presence of sodium further suggests contributions from human activities such as sewage infiltration or urban wastewater discharge.
6. Finally, rapid urbanization has increased stress on groundwater quality due to anthropogenic activities as well as relative geogenic process which increase contamination of groundwater. Accordingly, artificial recharge, applicative remediation, and natural attenuation approaches can be implemented to evade growing stress of the degrading groundwater quality regime.

Conflicts of Interest:

The authors declare that they have no conflicts of interest.

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