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Unusually High Levels of Fluoride and Nitrate in Groundwater in Southern India: Water Quality Indices and Associated Health Hazard Implications

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Abstract

Groundwater is crucial for supporting the global population, with water quality having a significant impact on human health. In this study, we examined the groundwater geochemistry, health risks, and water quality index associated with consuming water contaminated by high levels of fluoride and nitrate in and around Gokak, Belgaum district, Karnataka. Fifty (50) groundwater samples were collected, and thirteen (13) physicochemical parameters were analysed following APHA methods. Results indicates that levels of pH, EC, TDS, fluoride, nitrate, and chloride exceed the WHO recommended standards. Fluoride concentrations range from 0.05 mg/L to 6.5 mg/L, while nitrate concentrations range from 2.66 mg/L to 118.8 mg/L. Excessive fluoride levels were observed in 14% of samples, and nitrate levels exceeded limits in 26%. Through Principal Component Analysis (PCA), four components explained 82.70% of the dataset variance. The water quality index (WQI) results categorize 26% of samples as excellent, 44% as good, 14% as poor, and 16% as unsuitable for any purpose, with 30% of samples overall being unfit for drinking. Health risk assessments for fluoride and nitrate indicate that 68% of samples had a hazard index (HI) value >1, highlighting a considerable health risk associated with groundwater consumption, particularly for women. Our findings suggest that both natural and human activities contribute to groundwater contamination. To further delineate pollution sources, stable isotopic studies are recommended.

Keywords: Fluoride, Nitrate, Health, Karnataka, South India

Introduction

Groundwater is a vital global resource, supplying nearly half the world's population with drinking water (Anisha *et al*., 2025). In India, it provides 60–85% of rural drinking water (Tanwar *et al*., 2023). Its quality is influenced by both geogenic (water–rock interaction) and anthropogenic factors (fertilizers, waste, industrial effluents) (Sinha *et al*., 2023). Over extraction, driven by population and industrial growth, threatens sustainability (Tanwar *et al*., 2023), and contaminated groundwater poses serious health risks (Sinha *et al.,* 2023). Fluoride (F^-) and nitrate (NO_3^-) are prominent contaminants in groundwater (Egbueri *et al*., 2023). While fluoride supports bone and dental health, excess levels cause fluorosis and other health issues (Dubey *et al.,* 2021). Its sources include geogenic inputs and phosphate fertilizers (Subba Rao, 2018). Elevated nitrate levels, largely from fertilizers, poor waste management, and runoff, are also a concern (Dai *et al.,* 2024). Nitrate exposure is linked to methemoglobinemia, thyroid disorders, and cancer (Subba Rao, 2018). Statistical tools like correlation analysis and PCA help reveal relationships between water quality parameters and underlying factors (Gaikwad *et al.,* 2020). Various indices such as HQ, HI, and WQI offer integrated assessments of water quality and related health risks (Patil *et al.,* 2024).

Following a recent study in southern Karnataka (Thabrez and Parimalarenganayaki, 2024), this research focuses on groundwater in the Gokak region, northern Karnataka. It aims to: 1) assess spatial variation and health risks of fluoride and nitrate using HQ and HI; 2) evaluate groundwater quality using WQI; and 3) identify factors influencing groundwater chemistry through PCA and correlation analysis.

Materials and Methods

Study Area

The study area (Fig.1) lies on the eastern edge of the Western Ghats (74°35'59" E - 75°19'59" E, 15°40'N - 16°25'N, ~4,146.40 km^2) with undulating terrain. It is a part of the Ghataprabha (Krishna tributary) basin, with a dendritic to sub-

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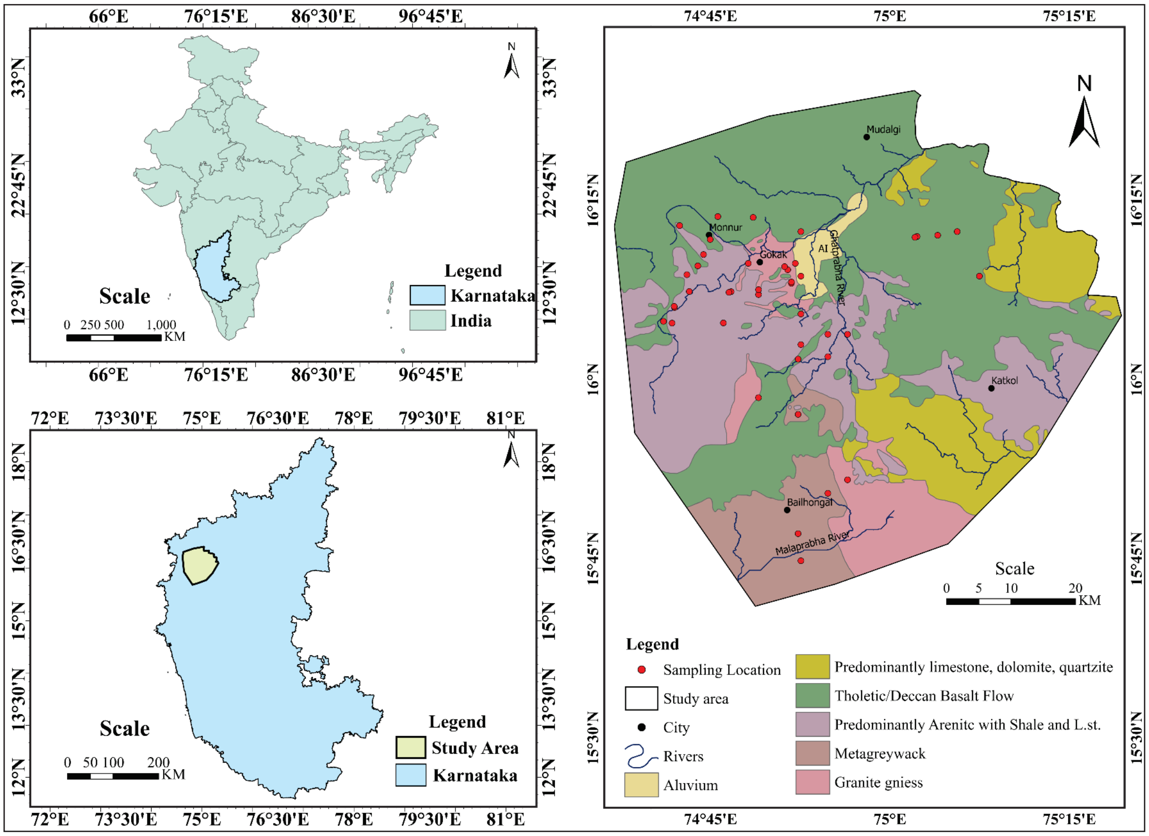

Fig.1. Location map of the Study area (Modified *after* GSI, 2005)

dendritic drainage (Herlekar *et al*., 2020). Elevation (453-920 m) affects runoff and groundwater in the region (CGWB, 2021).

Geology

The study area has a complex geological setup ranging in age from Archean to recent alluvial deposit (Fig.1; GSI, 2016). Dharwarian Schist, gneiss, and Banded Hematite Quartzite (BHQ) are the oldest lithologies of Archean age exposed in the study area (Nadagauda *et al.,* 2009). These are overlain by the Badami Group of rocks characterized by arenite, clastic sediments, and basic dykes. The Deccan Basalt, overlain by the Badami Group, acts as a primary aquifer (*i.e.*, fractured, jointed, and highly weathered zones) in the region (GSI, 2016; Patil *et al.,* 2020). Parent rock, geographic conditions, and climate influence soil types. Prominent soil types are black cotton and alkaline soil derived from the basaltic formations. The red sandy soil is a weathering product of sandstone of the Kaladgi formation (CGWB, 2023).

Methodology

Fifty groundwater samples (19 dug wells and 31 bore wells) were collected in May 2022 to represent shallow and deep aquifers. Polyethylene bottles were rinsed with distilled water before sampling of groundwater. On-site measurements for pH, electrical conductivity (EC), and total dissolved solids (TDS) were conducted using a HANNA handheld meter. Total alkalinity (TA), Total hardness (TH), and Chloride (Cl^-) concentrations were determined through volumetric titrations. Major cations including Calcium (Ca^{2+}), Potassium (K^+), Sodium (Na^+), and Magnesium (Mg^{2+}) were analysed using a Shimadzu ICPE-9000 ICP-AES at Savitribai Phule Pune University's Department of Geology. Anions such as Sulfate (SO_4^{2-}) and Nitrate (NO_3^-) were measured with a Shimadzu 1800 UV-spectrophotometer, and Fluoride (F^-) concentrations were determined using a Hanna ISE-5222 Ion Selective Electrode. The ionic balance error (IBE) was maintained within ±5%.

Statistical Analysis

Correlation analysis in statistical studies evaluates the interconnections among different water quality parameters. This method aids in identifying potential relationships between ions and their possible sources (Gaikwad *et al*., 2020). It condenses multiple variables into fewer "principal components," capturing the significant variations within the dataset (Gaikwad *et al*., 2022). By simplifying the data structure, PCA reveals key trends and relationships among various water quality parameters (Morovati *et al.*, 2024).

Water Quality Index (WQI)

It is derived from a mathematical formula that yields a single numerical value to represent the quality of water (Tanwar *et al.,* 2023). The WQI is generally classified into different categories:

To calculate WQI, the following equation (4) is used,

$$\text{Water Quality Index (WQI)} = (\Sigma Wn \times Qn) / \Sigma Wn \qquad (1)$$

Where Wn represents the unit weight of the nth parameter, and Qn denotes the quality rating of the nth parameter.

To calculate unit weight (Wn)

$$Wn = K/Sn \tag{2}$$

where K is Constant and Sn is the Permissible limit

For calculating constant proportionality value (k)

$$K = 1 / (\Sigma\ 1/Sn) \tag{3}$$

Quality rating (Qn) calculated by using equation (4)

$$Qn = [(Pn - Ci) / (Sn - Ci)] \times 100 \tag{4}$$

Pan- real concentration of the parameter, and Ci - ideal concentration, which is zero (0), and pH is 7 (Neutral).

WQI is a mathematical measure that quantifies the entire health of groundwater. It operates on a scale from 0 to over 100, with lower numbers signifying superior water quality.

WQI is classified into five categories: excellent (0-25), good (26-50), poor (51-75), very poor (76-100), and unsuitable for irrigation and drinking (<100).

Human Health Risk Assessment

High fluoride and nitrate in groundwater poses significant health risks to individuals of all ages, particularly in rural areas (Singh *et al.,* 2019). Although they are classified as non-carcinogenic, these contaminants can lead to various health complications (USEPA, 2014). This study assesses the risk associated with ingesting F^- and NO_3^- by calculating exposure dosage and hazard quotient.

Calculation of Exposure Dose

The chronic daily intake dose was calculated by following equation (Tanwar *et al.,* 2023),

Chronic Daily Intake Dose (CDID) =
$$(Cf \text{ or } Cn \times DWI \times AL \times EF) / (MBW \times MAED) \tag{5}$$

Cf - Concentration of fluoride; Cn - nitrate; DWI - Daily Water Intake; AL - Average lifetime; EF - Exposure Frequency; MBW - Exposure Body Weight; MAED - Mean Age Exposure Duration

The parameters used in the above equation are constructed from the standard literature (Tanwar *et al.* (2023; USEPA, 2014; Table 1a).

Hazard quotient (HQ)

The (HQ) for F^- and NO_3^- and is computed using Eq. 2. It is computed by dividing chronic daily intake of an element by the reference dose (Tanwar *et al.,* 2023). The following equation will be used to calculate the hazard quotient.

$$\text{Hazard Quoteint (HQ)} = \frac{\text{Chronic Daily Intake Dose (Mg/kg/day)}}{\text{Reference Dose (Mg/kg/day)}} \tag{6}$$

Hazard Index (HI)

The HI is a cumulative factor implemented in health risk assessment to estimate combined health risk causes owing to multiple chemical components (Tanwar *et al.,* 2023). By combining the HQs of individual components, the findings yield an HI linked to the intake of F^- and NO_3^- from drinking water. If HQ is higher than one, it indicates high risk, while it is less than one, indicating low risk (Sunitha and Reddy, 2022). To calculate HI, follow equation (7).

$$\text{Hazard Index (HI)} = \Sigma\ HQ_f + HQ_n \tag{7}$$

HQf is the hazard index of fluoride, and HQn is the hazard index of nitrate.

The HI is the summation of HQ for F^- and NO_3^-. If the HI of a particular sample is less than 1, it infers no chronic risk. A value exceeding 1 suggests that consuming this groundwater could be harmful to human health. The details of Chronic Daily Intake Dose (CDID), hazard quotient (HQ), Hazard Index (HI) are given in Table 3.

Results and Discussion

Hydro-geochemistry of Groundwater

Table 1(a) presents hydro-chemical data statistics, providing a basic understanding of regional hydro-chemical characteristics. The pH ranges between 5 and 9.4, averaging 7.18, reveal mildly alkaline nature. Excluding 2% of the samples, rest 98% are within the prescribed limit by WHO (2017).

Electrical conductivity (EC) measures water's ability to conduct electricity, influenced by temperature and the type and concentration of dissolved ions. (Malik *et al.,* 2024). In the groundwater samples, EC values range from 518 µS/cm to 4108 µS/cm, with an average of 1499 µS/cm. Elevated EC in water indicates increased ion concentrations, often resulting from leaching during infiltration and recharge, as well as the infiltration of agricultural chemicals (Moravati *et al.*, 2024). Approximately 32% of the samples exceed the permissible EC limit.

TDS in groundwater consist of total inorganic salts along with small amounts of organic matter (WHO, 2017). The average TDS level is 959 mg/L, and nearly 30% of the samples show TDS levels higher than the recommended limit of WHO (2017).

Sodium (Na^+) levels are lower (averaging 58.2 mg/L) than the permissible limit set by WHO. The presence of Na^+ in groundwater is influenced by the weathering and dissolution of plagioclase feldspar-rich host rock, as well as anthropogenic activities (Subba Rao, 2021). The average potassium (K^+) concentration in the study is 7.7 mg/L, which is within the WHO (2017). The main sources of potassium in groundwater are the weathering of K-feldspar and other soil minerals (Dhakate *et al.,* 2023). The concentration of calcium (Ca^{2+}) ranges from 20.04 mg/L to 160.2 mg/L, with an average of 53.03 mg/L. Forty-two percent of the samples exceedthe permissible limit of 200 mg/l. Plagioclase feldspar minerals are the primary source of calcium in water, released through dissolution and leaching (Marghade *et al.,* 2021). Magnesium (Mg^{2+}) concentrations in groundwater ranges from 6.4 mg/l to 500 mg/lwith a mean of 112.9 mg/l. Mg^{2+} is a dominant ion resulting from the weathering of ferromagnesian minerals in silicate rocks (Sarma and Singh, 2023).

The concentration of bicarbonate (HCO_3^-) among the major anions ranges between 100 mg/l and 950 mg/l), with an average of 379 mg/L. Approximately 22% of the samples exceed the WHO permissible limit. The HCO_3^- in water primarily result from the weathering of carbonate minerals and the decomposition of organic matter (Moravati *et al.,* 2024). Chloride (Cl^-) in groundwater ranges from 20.5 mg/L to 1043 mg/l. About 6% of samples are exceeding the permissible limit. The higher concentration is observed along the low-lying areas. Primary sources of elevated concentrations of Cl^- in water are domestic wastewater and irrigation return flow (Laxmankumar *et al.,* 2019).

The sulphate (SO_4^{-2}) ranges between (11.56 mg/l - 253 mg/l), averaging 97.3 mg/l. About 94% of samples are found within the prescribed limit given by WHO (2017). The sources of high SO_4^{-2} in groundwater are primarily due to anthropogenic activities (Gaikwad *et al.,* 2022).

Fluoride and Nitrate in Groundwater

The accumulation of F^- and NO_3 in groundwater is influenced by factors such as aquifer type with depth, porosity, hydraulic conductivity, and recharge rate (Alharbi and El-Sorogy, 2023). The F^- concentration varies from 0.05 mg/l to 6.5 mg/l. Highest fluoride concentration (6.5 mg/l) (Fig.2a) was found at the South of Parnatti village (Gokak-Kolavi Road) while lowest value was at Nandgaon (0.05 mg/l). The Fluoride-rich minerals dissolution and clay minerals are the major natural sources, while phosphatic fertilizers increase fluoride in groundwater (Subba Rao, 2018). The present study area is a part of semi-arid climatic regions with low rainfall together with high rock–water interactions at depth, which have elevated the fluoride in groundwater in the Pre-monsoon season (Rashid *et al.*, 2023).

The natural concentration of NO_3^- in groundwater is typically up to 10 mg/L, with levels exceeding this indicating anthropogenic pollution (Sinha *et al.,* 2023). In this study, nitrate concentrations ranged from 2.66 mg/l to 118.8 mg/l, averaging 33.89 mg/l. North of Vannur shows highest concentration (118.8mg/l), while Itnal shows lower concentration of 2.66 mg/l. About 74 % of the samples fall within the limit established by WHO (2017) (Fig. 2b). Potential sources of nitrate contamination include agricultural fertilizers, sewage, and animal waste (Ullah *et al.,* 2021).

Table 1: Statistical analysis

a) hydrochemical data along with the permissible limit of WHO (2017)

Sr. No.	Parameter	Minimum	Maximum	Mean	WHO Permissible limit (2017)
1	pH	5	9.4	7.18	6.5-8.5
2	TDS	331.00	2629.35	959	1000
3	EC	518.00	4108.00	1499	1500
4	F^-	0.05	6.50	0.95	1.5
5	NO_3^-	2.66	118.87	33.89	45
6	Cl^-	20.50	1043.00	222.85	500
7	SO_4^-	11.56	253.00	97.37	250
8	Total Hardness	60.00	2163.00	831.92	100
9	HCO_3^-	100.00	950.00	379.05	500
10	Ca^{2+}	20.04	160.28	53.03	75
11	Mg^{2+}	6.46	500.00	112.95	50
12	Na^+	15.63	99.60	58.25	600
13	K^+	2.00	10.00	7.75	12

b) Pearson's correlation matrix of water quality parameters

	pH	TDS	EC	HCO_3^-	F^-	Cl^-	NO_3^-	SO_4^-	TH	Ca^{2+}	Mg^{2+}	Na^+	K^+
pH	1												
TDS	-0.13	1											
EC	-0.13	1.00	1										
HCO_3^-	-0.14	0.78	0.78	1									
F^-	0.29	0.25	0.25	0.30	1								
Cl^-	-0.16	0.87	0.87	0.42	0.09	1							
NO_3^-	-0.24	0.67	0.67	0.51	-0.06	0.59	1						
SO_4^-	0.14	0.76	0.76	0.43	0.30	0.64	0.37	1					
TH	-0.34	0.84	0.84	0.51	-0.08	0.87	0.73	0.54	1				
Ca^{2+}	-0.22	0.33	0.33	0.37	-0.06	0.11	0.32	0.27	0.31	1			
Mg^{2+}	-0.11	0.93	0.93	0.58	0.20	0.95	0.60	0.71	0.86	0.15	1		
Na^+	0.10	0.71	0.71	0.52	0.38	0.56	0.37	0.71	0.49	0.27	0.56	1	
K^+	-0.08	-0.20	-0.20	-0.26	-0.15	-0.08	-0.16	-0.14	-0.12	-0.10	-0.23	0.02	1

c) PCA with eigenvalue, % variance and cumulative % variance

	Component			
	PC-1	PC-2	PC-3	PC-4
Ca^{2+}	0.12	-0.13	0.90	-0.01
Mg^{2+}	0.97	0.07	0.02	-0.14
Na^+	0.64	0.47	0.34	0.26
K^+	-0.11	-0.11	-0.06	0.95
HCO_3^-	0.56	0.17	0.55	-0.27
SO_4^-	0.72	0.42	0.20	0.08
Cl^-	0.97	-0.04	-0.07	0.02
NO_3^-	0.69	-0.28	0.27	-0.16
F^-	0.11	0.80	0.10	-0.12
TH	0.91	-0.28	0.15	-0.04
pH	-0.16	0.72	-0.28	-0.04
TDS	0.94	0.14	0.29	-0.10
EC	0.94	0.14	0.29	-0.10
Eigenvalue	6.83	1.76	1.15	1.01
%of Variances	47.71	13.86	12.48	8.64
Cumulative % variances	47.71	61.57	74.05	82.70

Statistical Analysis

Correlation Analysis

The strength of these correlations is represented by the correlation coefficient (Singh *et al.,* 2012). Table 1 (b) presents the relationships among 13 water quality parameters using correlation coefficients (r). A coefficient greater than 0.7 indicates a strong correlation, while values between 0.5 and 0.7 indicate a moderate correlation (Gaikwad *et al.,* 2020, 2022). A correlation coefficient less than 0.5 signifies a weak correlation between two parameters (Das *et al.,* 2022).

The correlation analysis reveals a strong positive correlation between TDS and several other parameters. Specifically, TDS demonstrates a perfect linear correlation with EC (1.0), and strong correlations with TDS-TA (0.78), TDS-Cl (0.87), TDS-SO_4 (0.76), TDS-TH (0.84), and TDS-Mg (0.94). Similarly, a strong positive correlation exists between EC and various parameters: EC-HCO_3 (0.78), EC-Cl (0.87), EC-TH (0.84), EC-Mg (0.93), and EC-Na (0.71). Additionally, significant correlations are noted between Cl-TH (0.87), Cl-Mg (0.95), NO_3-TH (0.73), SO_4-Na (0.71), and TH-Ca (0.86). These correlations suggest that the groundwater geochemistry is influenced by rock-water interactions and the infiltration of domestic wastewater (Sarma and Singh, 2023). No significant correlation was found for HCO_3, Ca, and F, indicating different sources and distinct processes affecting their concentrations in groundwater (Said *et al.,* 2022).

Principal Component Analysis (PCA)

The PCA is a powerful statistical method that helps simplify complex water quality datasets (Gaikwad *et al.,* 2020). In this study, PCA was conducted using varimax rotation and Kaiser's normalization to extract components with eigenvalues greater than 1 (Rao *et al.,* 2022). The analysis identified the first four principal components (PC 1, PC 2, PC 3, and PC 4) as the most significant, collectively accounting for 82.70% of the total variance (Table 1c).

PC1 explains 47.71% of the total variation, showing strong

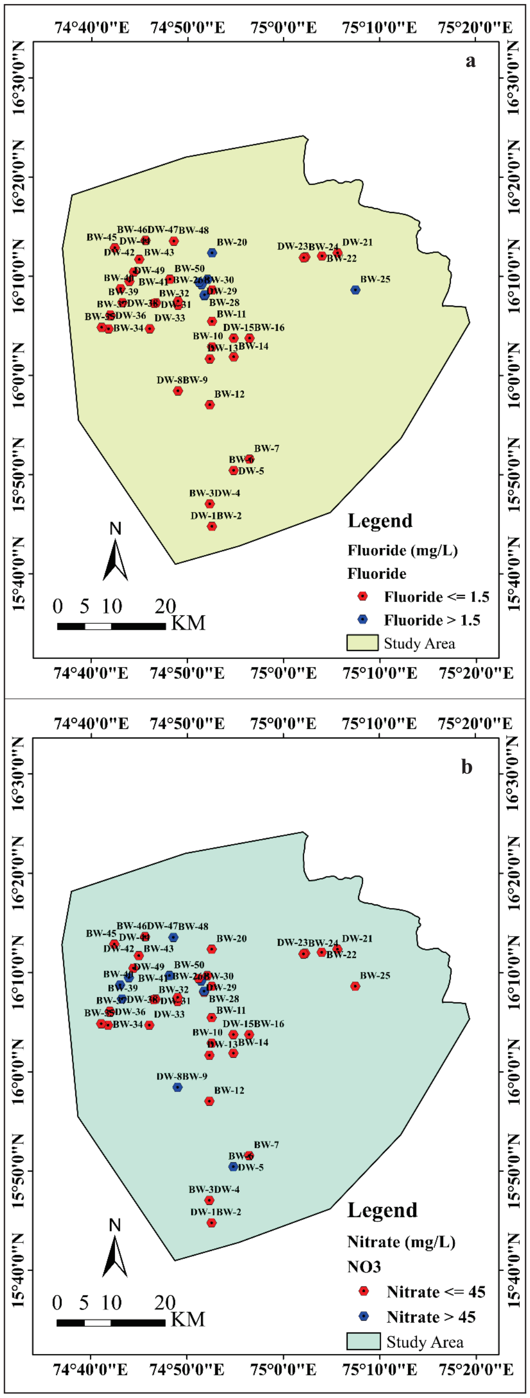

Fig.2. a) Fluoride distribution in groundwater of study area. b) Nitrate distribution in groundwater of study area.

positive correlations with Mg^{2+} (0.97), Cl^- (0.97), SO_4^{2-} (0.72), Na^+ (0.64), TDS (0.94), EC (0.94), and TH (0.91). It also demonstrates moderate positive correlations with NO_3^- (0.484) and K^+ (0.368), indicating that the first factor affecting groundwater quality is influenced by a combination of rock and anthropogenic sources, such as agricultural activities (Sarma and Singh, 2023). The second principal component (PC 2) has a lower eigenvalue of 1.76 and accounts for 13.86% of the total variance, displaying strong positive loadings for F^- (0.80) and pH (0.72). The source of fluoride is geogenic, and an alkaline pH is conducive to its dissolution in groundwater (Saxena and Ahmed, 2001). The third and fourth principal components have relatively lower eigenvalues of 1.15 and 1.01, respectively, with single dominant factor loadings of Ca (0.90) for PC-3 and K (0.95) for PC-4, indicating their natural origins (Gaikwad *et al.,* 2022). A scree plot illustrating the eigenvalue distribution for all four PCs helps identify the most significant components (Fig. 3). Scree plots showing first two component having ranges between values (2-6). Overall, the PCA indicates the combined effects of geogenic processes and human activities on groundwater chemistry.

Water Quality Index (WQI)

The Water Quality Index (WQI) is a comprehensive tool designed to assess the overall quality of water based on various physicochemical parameters (Mukate *et al.,* 2019). It produces a single numerical value that reflects the water's suitability for different uses, including drinking (Tanwar *et al.,* 2023). Figure 4 (a) illustrates that in northern and western regions, higher WQI values observed suggest favourable lithologies and anthropogenic influences on WQI (Gaikwad *et al*., 2020). Twenty-six percent (26%) of the samples fall within the "excellent" to "good" categories, indicating that the water is suitable for drinking, agriculture, and industrial applications. Approximately 14% of the samples are categorized as "poor," suggesting they are unsuitable for drinking but may be usable for certain industrial and agricultural purposes.

Approximately 16% of the samples are classified as "unsuitable," indicating that they require treatment before use. Figure 4b presents a histogram illustrating the WQI range for groundwater samples categorized accordingly. Water quality parameters, relative index and permissible limits are provided in Table 2.

Human Health Risk Assessment

High levels of (F^-) and (NO_3^-) in groundwater are linked to non-carcinogenic health risks. Prolonged consumption of such contaminated water poses health hazards across all age groups (Reddy and Sunitha, 2020). A health risk assessment was conducted, first calculating the hazard quotient (HQ) and subsequently the hazard index (HI) based on USEPA guidelines (2014). The data regarding Chronic Daily Intake Dose (CDID), HQ, and HI is summarized in Table 3.

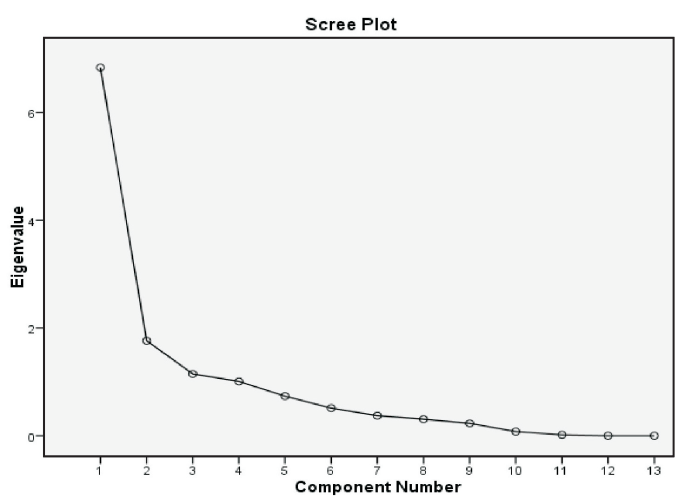

Fig.3. Scree plot with eigenvalues

Table 2: Water quality parameter relative weight index and permissible limits (Brown *et al.*, 1970; *Modified after* Tanwar *et al.*, 2023)

Sr. No.	Parameter	W_n=K/S_n	1/S_n	Permissible limit (WHO, 2017)
1	pH	0.142	0.118	8.5
2	TDS (mg/L)	0.001	0.001	1000
3	EC (µS/cm)	0.001	0.001	1500
4	F^- (mg/L)	0.802	0.667	1.5
5	Cl^- (mg/L)	0.005	0.004	250
6	NO_3^- (mg/L)	0.024	0.020	50
7	SO_4^- (mg/L)	0.005	0.004	250
8	Total hardness (mg/L)	0.002	0.002	500
9	Total Alkalinity (mg/L)	0.002	0.002	500
10	Ca^{2+} (mg/L)	0.004	0.003	300
11	Mg^{2+} (mg/L)	0.012	0.010	100

Table 3: Parameters used for chronic daily intake dose and estimating the hazard quotient (HQ) for F^- and NO_3. (*Modified after* Tanwar *et.al.,* 2023)

Sr. No.	Parametric Symbol	Parameter description	Unit	Values	Source reference
1	C_f	Concentration of fluoride in groundwater	(mg/L)		Observed in study area
2	C_n	Concentration of nitrate in groundwater	(mg/L)		Observed in study area
3	DWI	Daily Water Intake	L/day	Adult, 2.5 Children, 1.5	WHO (2017) USEPA (2019)
4	AL	Average life time	Years	Male, 65.5 Female, 70.2 children, 12	NITI Aayog (2020)
5	EF	Exposure frequency	Days/ year	365	USEPA (2014)
6	MBW	Mean body weight	Kg	Male, 60 Female, 55 Children, 35	Nair and Augustine (2018) NIN-ICMR (2011)
7	MAED	Mean age exposure duration	Days	Male, 23,908 Female, 25,623 Children, 4380	*Modified after* Tanwar *et al.* (2023)

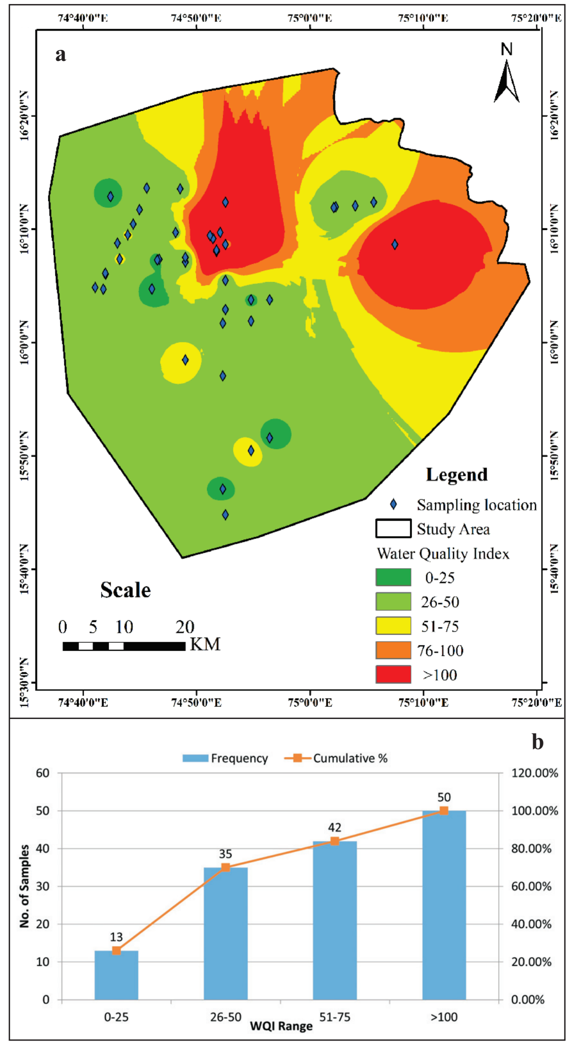

Fig.4. A) Water Quality Index type distribution in groundwater of study area. B) Histogram showing WQI range with respect to groundwater samples falls under respective categories.

Chronic Daily Intake Dose (CDID)

The highest Chronic Daily Intake Dose (CDID) values for (F^-) were reported at DW-27 (Village-Parnetti) for males and children, whereas females exhibited the highest CDID at BW-6 (Village-Chikkoppa). For nitrate (NO_3^-), the highest CDID values were found at BW-09 (Village-Vannur) for males, females, and children (Table 3).

Hazard Quotient (HQ)

The HQ_f values for males range from 0.0521 to 44.7345, with a mean of 1.7206. In females, it ranges between 0.0568 and 7.3867, with a mean of 3.377. In children, it ranges from 0.0536 to 6.9643 with a mean of 1.0188. The HQ_{NO3} values ranges between (0.069 to 3.096), (0.076 to 3.377), and (0.071 to 3.184) for male, female, and children, respectively (Table 4; Fig. 5).

Hazard Index (HI)

The (HI) is calculate by adding (HQ) values for fluoride (F^-) and nitrate (NO_3^-). The HI value exceeding 1 suggests potential health risks from consuming water contaminated with elevated levels of specific substances (Patil *et al.,* 2024). For the study, HI values ranged from 0.33 to 7.08 for males (mean: 1.82), 0.36 to 7.72 for females (mean: 1.99), and 0.34 to 7.28 for children (mean: 1.88) (Table 4). Samples with HI values above 1 are marked with red stars, while those below 1 are indicated with green stars (Fig. 5). The HI analysis revealed that 68% of the groundwater samples present a potential health risk for all three groups: males, females, and children (Patil *et al.,* 2024). Furthermore, the health risk assessment showed that HI values correlated spatially with fluoride concentrations in groundwater, indicating that fluoride contamination poses a significant health risk. Notably, the health risks associated with F^- and NO_3^- were most pronounced for females compared to males and children.

Conclusions

The groundwater geochemistry in and around Gokak, reveals that the predominant cations are $Mg^{2+} > Na^+ > Ca^{2+} > K^+$, while the dominant anions are $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^- > F^-$. The Fluoride ($F^-$) concentrations ranges from 0.05 mg/L to 6.5 mg/L, with a mean of 0.9 mg/,while the Nitrate (NO_3^-) concentrations range from 2.66

Table 4: CDID and Hazard Quotients and Hazard Index value for male, female and children

	Male			Female			Children		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
CDID (F^-)	0.0021	0.2708	0.0396	0.0023	0.2955	0.0432	0.0021	0.2786	0.0408
CDID (NO_3^-)	0.111	4.953	1.412	0.121	5.403	1.540	0.114	5.094	1.452
HQ (F^-)	0.0521	44.7345	1.7206	0.0568	7.3864	1.0806	0.0536	6.9643	1.0188
HQ (NO_3^-)	0.069	3.096	0.883	0.076	3.377	0.963	0.071	3.184	0.908
HI (F^-+ NO_3^-)	0.33	7.08	1.82	0.36	7.72	1.99	0.34	7.28	1.88

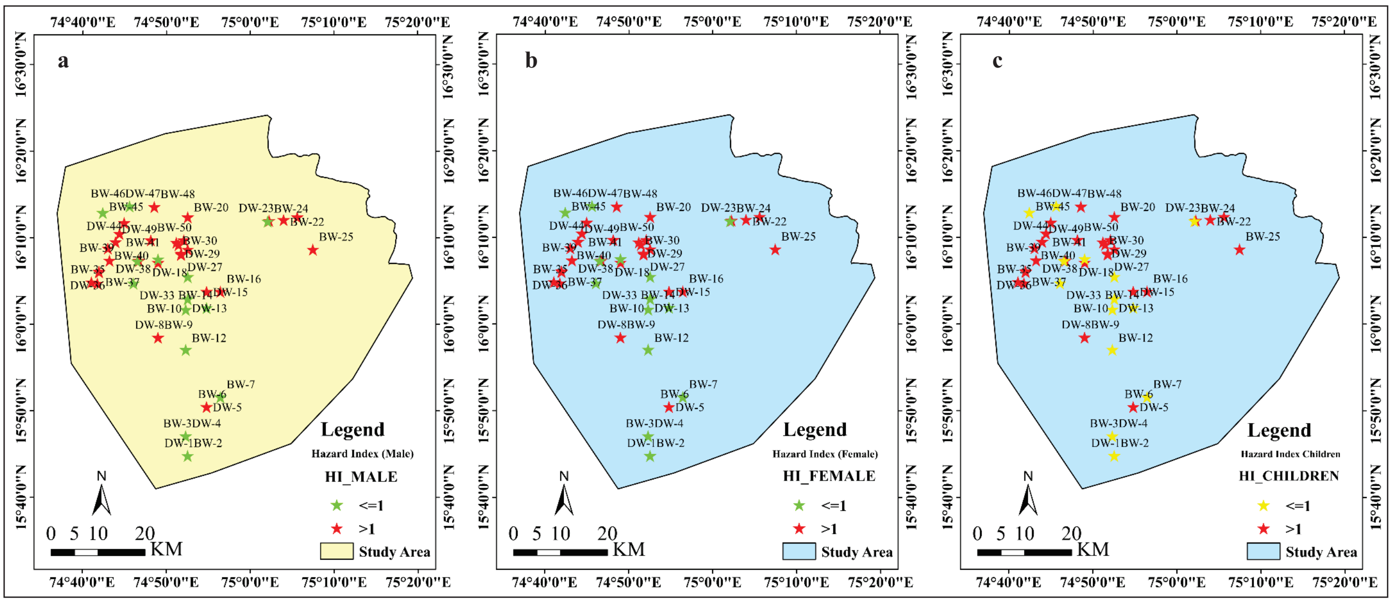

Fig.5. Hazard Index for (a) male, (b) female and (c) childern for fluoride and nitrate in study area.

mg/l to 118.8 mg/l, averaging 33.89 mg/L. Statistical analysis indicates a strong positive correlation between total dissolved solids (TDS) and electrical conductivity (EC), total alkalinity (TA), chloride (Cl), sulphate (SO_4), total hardness (TH), magnesium (Mg), and sodium (Na), suggesting rock-water interactions and the infiltration of domestic wastewater influencing groundwater geochemistry. Principal Component Analysis (PCA) identified four components that account for 82.70% of the variance in the dataset. It highlights the combined effects of natural processes and human activities on groundwater chemistry. The Water Quality Index (WQI) studies show 16% of water samples are unsuitable for drinking. The health risk assessment for fluoride and nitrate reveals that 68% of samples have a hazard index (HI) value greater than 1, indicating a significant health risk associated with the consumption of groundwater containing F^- and NO_3^-. In summary, the groundwater chemistry is influenced by both natural processes and anthropogenic activities. Stable isotopic studies of groundwater are recommended for deeper understanding geochemistry and sources of contamination.

Author contributions

PS: Conceptualization, Fieldwork, Analysis and Original Draft. **SG:** Conceptualization, Fieldwork, Discussions, Guidance, Writing Final Draft. **AD:** Conceptualization, Fieldwork, Discussions, Guidance, Writing Final Draft. **RM:** GIS maps. **AM**: Statistical Analysis. **AS:** Discussions, Guidance, Writing Final Draft. **AB:** Discussions, Guidance, Writing Final Draft.

Conflict of Interest

Authors declare that they have no conflict of interests.

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