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Research Article
ISSN : 2455-1953
JGSR
Journal of Geosciences Research
Vol. 10, No.2, July, 2025, pp. 123-130

Water Potential and Modeling Studies of Kollam and Adjoining Region of Kallada Basin, South India: Insights into Drinking and Irrigation Suitability

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Abstract

Groundwater resources within river basins are gaining global attention due to their critical role in sustaining human and agricultural needs. Preserving groundwater quality is essential for agricultural productivity and public health, as it serves as the primary source of drinking and irrigation water for billions of people worldwide. This study focuses on the hydrochemical characterisation and quality evaluation of groundwater in the lower urbanized regions of the Kallada River Basin (LKRB), covering Kollam town and its surrounding areas. This study aimed to assess water quality for drinking and irrigation purposes while also evaluating the underlying hydrogeochemical processes. The major cations and anions in groundwater follow the order: $Ca^{2+} > Na^{+} > Mg^{2+} > K^{+}$ and $HCO_3^{-} > Cl^{-} > SO_4^{2-}$. The dominant groundwater type is Ca-HCO_3, followed by Na-Cl. The Water Quality Index (WQI) was employed to evaluate groundwater suitability for drinking. WQI analysis revealed that 80% of samples fell within the 'good to excellent' range, indicating suitability for drinking and domestic use, while 20% were classified as poor quality. Several indices, such as the Magnesium Hazard (MH), Sodium Adsorption Ratio (SAR), Residual Sodium Carbonate (RSC), Sodium Percentage (Na%), and Kelley's Ratio (KR), were used to assess the suitability of groundwater for irrigation. The findings indicate that although most samples are safe for irrigation, a few areas have problems with their water quality that render them harmful. This study helps with the sustainable management of groundwater resources in the LKRB by providing important insights for policymakers and urban planners.

Keywords: Groundwater Chemistry, Hydro-chemical Facies, Drinking Suitability, Irrigation Suitability, Water Quality Index, Lower Kallada River

Introduction

Water is the lifeblood of our planet, and groundwater, stored beneath the surface, plays a vital role in supporting human civilization (Loganathan and Sathiyamoorthy, 2024; Kumar *et al.,* 2024). It is an essential resource for drinking, irrigation, industrial uses and ecological balance (Khadri and Moharir, 2016; Pramoda *et al.,* 2022; Meghanad *et al.,* 2025). Groundwater quality assessment is particularly important in regions experiencing rapid urbanization and industrial growth, where contamination risks from industrial effluents, agricultural runoff, and urban wastewater continue to rise (Jain *et al.,* 2019). In many developing nations, water pollution and its management require urgent attention, as unsafe water is linked to nearly 80% of disease outbreaks and fatalities. According to Shayo *et al.* (2023), 2.2 million people die yearly from waterborne illnesses, and around 2.1 billion people worldwide lack access to clean drinking water. India has the highest groundwater extraction rate globally, surpassing China and the United States (NGWA, 2016). Groundwater hydrochemistry is influenced by geological formations, rock-water interactions, mineral dissolution, evaporation, precipitation, and anthropogenic activities such as industrialization and large-scale agriculture (Singh *et al.,* 2011; Rajesh *et al.,* 2012; Manjare and Pophare, 2020; Panigrahi and Das, 2022; Raheja *et al.,* 2024). Furthermore, hydrogeochemical processes such as weathering, ion exchange, and dissolution play a crucial role in determining the concentration of major and minor ions in groundwater. Approximately 15% of the world's groundwater is used for industrial purposes, 20% for irrigation, and 65% for drinking (Adimalla *et al.,* 2018; Gani *et al.,* 2023). Additionally, nearly one-third of the global population relies entirely on groundwater for their drinking water needs (Adimalla and Venkatayogi, 2018). However, excessive groundwater exploitation and recurring droughts have led to declining water tables and declining water quality (Hosseinifard and Mirzaei Aminiyan, 2015). Continuous monitoring is necessary for sustainable water resource management in the Kallada River Basin (KRB), as groundwater serves as a major source for irrigation and drinking. This study investigates groundwater quality in the Kallada River Basin's lower urbanized regions, focusing on Kollam town and nearby areas to evaluate its suitability for irrigation and drinking while assessing hydrochemical properties. Hydrogeochemical investigations help in formulating strategies to protect

(Received : 11 March 2025 ; Revised Form Accepted : 02 June 2025)
https://doi.org/10.56153/g19088-025-0252-85

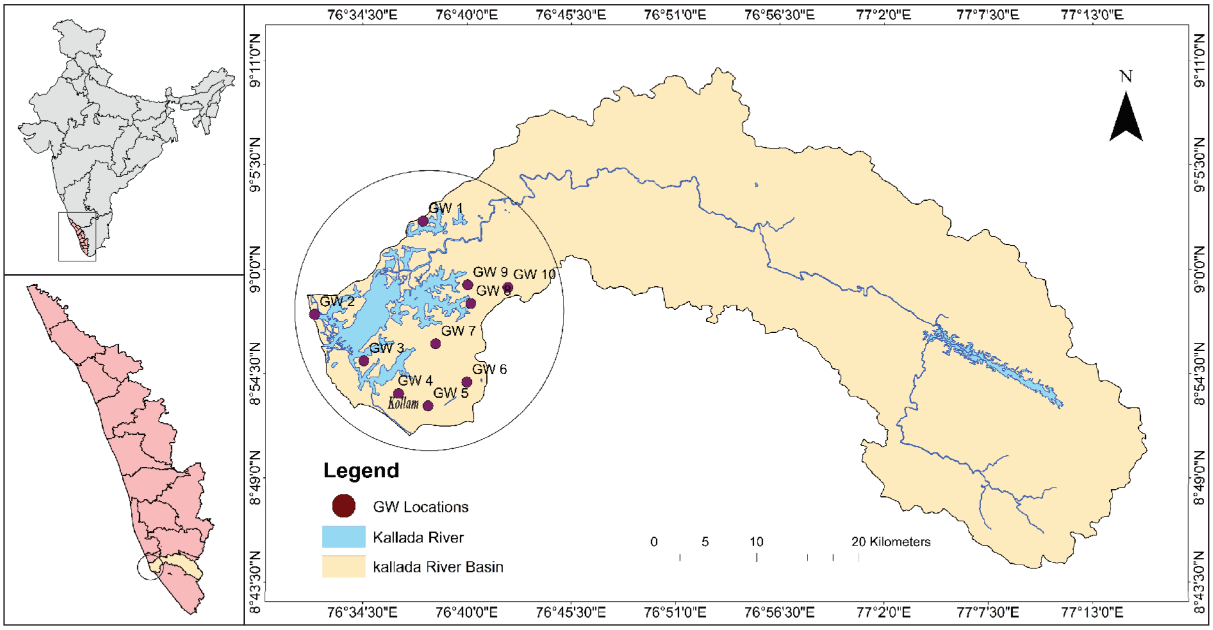

Fig.1. Study area map with sampling well points

aquifers from contamination caused by natural and human-induced factors. The Water Quality Index (WQI) is often used to evaluate drinking water quality from groundwater, providing a simplified approach based on WHO guidelines (Roy *et al.,* 2023; Kumar and Augustine, 2022). Irrigation water quality is assessed using various indices, including the Permeability Index (PI), Sodium Adsorption Ratio (SAR), Kelley's Ratio (KR), Sodium Percentage (Na%), and Magnesium Adsorption Ratio (MAR) (Pophare and Sadawarti, 2019; Guo *et al.,* 2021; Kumar *et al.,* 2021; Safari *et al.,* 2021; Kouser *et al.,* 2022; Hakim *et al.,* 2024). The results of this study will enhance understanding of local groundwater quality issues and aid in developing sustainable management strategies to protect public health and improve agricultural productivity.

Study Area

Kollam town has historically been a key trading hub since the 12^{th} century, with its black pepper trade gaining significant prominence. Today, it is one of the fastest-developing cities, recognized by the Economist Intelligence Unit (EIU) survey (2015-2020). The region is well known for its abundant mineral sand deposits and diverse marine ecosystem, supporting nearly 45 seaweed species and commercially valuable crustaceans such as prawns, lobsters, and shrimp (Manilal *et al.,* 2010). The LKRB in Kollam exhibits varied land use, with much of the basin comprising urban settlements, mixed tree plantations, reclaimed land, and clustered habitations. Among all zones of the KRB, this lowland region experiences the highest degree of urbanization. The Kallada River, a significant watercourse in southern Kerala, originates from Karimalaikottai (1,854 m AMSL) in the Western Ghats and flows into Ashtamudi Lake near Kollam (Fig. 1). Covering a length of 121 km and a drainage basin of 1,614 km², this river plays a crucial role in Kerala's largest irrigation project, supplying water to 92 local self-government bodies in the southern part of the state. Due to its significance in regional water supply, assessing the groundwater quality in the area is essential. Precambrian crystallines, Tertiary sedimentaries, laterites, and Quaternary sediments are the main geologic units found in the KRB (Aju *et al.,* 2019). The KRB is dominated by Precambrian crystalline rocks, including charnockites, migmatites, and the khondalite group, with younger Tertiaries found in the western regions (Aju *et al.,* 2024). The region experiences an annual average rainfall of 2,428 mm (CGWB, 2013), with 63% of precipitation occurring during the southwest monsoon, while the northeast monsoon contributes about 27%. The coastal climate in this region is typically hot and humid, influencing groundwater availability and quality.

Materials and Methods

Groundwater samples were gathered from ten sites in January 2021 (post-monsoon period), following strict precautions to prevent contamination during sampling and storage. On-site measurements of important hydrochemical parameters were made using a Portable Water Quality Analyzer (Aqua Read 2000 D, Germany), including dissolved oxygen (DO), electrical conductivity (EC), pH, and total dissolved solids (TDS). A Continuous Flow Analyzer (CFA, Skalar SAN++ 1052, The Netherlands) was used to examine nutrients. Microwave Plasma Atomic Emission Spectrophotometer (MP-AES, Agilent 4210, USA) was used to identify the major cations. Furthermore, bicarbonate, sulfate, and chloride concentrations were measured using the APHA (2017) approach. The results were then compared against BIS (2012) and WHO (2017) drinking water guidelines.

To ensure data reliability and accuracy, the cation-anion balance method was applied. Ion concentrations were given in mEq/L, and the Hem (1985) equation was used to compute the ionic balance error. The error remained within ±10% for all sampling locations.

$$NICB\,\% = 100 \times [(\sum TZ^{+} - \sum TZ^{-}) / (\sum TZ^{+} + \sum TZ^{-})] \qquad (1)$$

Where, NICB represents the normalized inorganic charge balance, and TZ^{+} and TZ^{-} denote the total sum of cations and anions, respectively.

Evaluation of Water Quality for Drinking

The Water Quality Index (WQI) is a widely used tool for assessing groundwater suitability for drinking. It was first presented by Horton (1965) and later improved by Brown *et al.* (1972). This study employs the five-step WQI method:

Step 1 : Data Collection – Gathering relevant parameters for the physicochemical quality of water.

Step 2 : Proportionality Constant Calculation (K) – Determined using:

$$K = 1/(1/\sum nisi) \quad (2)$$

Where, 'si' is the standard permissible limit for the n^{th} parameter.

Step 3: Quality Rating Calculation (Qn) – The quality rating for each parameter is computed as:

$$Qn = 100 \times [(Vn - Vi)/(Sn - Vi)] \quad (3)$$

Here, Vn is the estimated value at a sampling site, Vi is the ideal value for pure water, and Sn is the permissible limit for the parameter.

Step 4: Unit Weight Calculation (Wn) for n^{th} parameter

$$Wn = K/Sn \quad (4)$$

Step 5: Final WQI Calculation – The overall index value is obtained using:

$$WQI = (\sum Wn \times Qn)/\sum Wn \quad (5)$$

The WQI values are categorized based on Brown *et al.* (1972) to determine drinking water suitability.

Evaluation of Water Quality for Irrigation

Clay minerals in soil have the ability to adsorb divalent cations such as calcium and magnesium from irrigation water. When these exchange sites in the clay are occupied by divalent cations, the soil texture remains suitable for plant growth. However, sodium in irrigation water can negatively impact soil permeability. If there is a lot of sodium in the water, sodium ions replace calcium and magnesium through ion exchange, leading to compacted and impermeable soil that hinders cultivation. This process, though, is reversible and can be managed by modifying water composition or applying gypsum, which introduces calcium ions to restore soil structure. The extent to which sodium replaces calcium and magnesium can be quantified using the Sodium Adsorption Ratio (SAR) (Richards, 1954; Todd and Mays, 2005).

$$SAR = Na^+ / \sqrt{[(Ca^{2+} + Mg^{2+})/2]} \quad (6)$$

When irrigation water contains high levels of bicarbonates but low concentrations of calcium and magnesium, calcium and magnesium tend to precipitate as carbonates. This process alters the remaining water composition, increasing sodium concentration and forming sodium bicarbonate in solution. This phenomenon is called Residual Sodium Carbonate (RSC) (Raghunath, 1987).

$$RSC = (HCO_3^- + CO_3^-) - (Ca^{2+} + Mg^{2+}) \quad (7)$$

Percentage sodium (%Na) indicates the concentration of soluble sodium in groundwater and is a key indicator for evaluating sodium hazards (Wilcox, 1955). Since sodium interacts with soil, potentially reducing its permeability, %Na is commonly used to assess water suitability for irrigation from natural sources.

$$\%Na = [(Na^+ + K^+)/(Ca^{2+} + Mg^{2+} + Na^+ + K^+)] \times 100 \quad (8)$$

Kelly (1940) and Paliwal (1967) introduced a new parameter to assess and classify irrigation water quality, focusing on the ratio of sodium (Na^+) to the concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}).

$$KR = Na^+ / (Ca^{2+} + Mg^{2+}) \quad (9)$$

KR > 1 signifies an elevated concentration of Na^+ in water. As a result, water with KR ≤ 1 is deemed suitable for irrigation, whereas KR ≥ 1 is considered unsuitable due to potential alkali hazards (Ramesh and Elango, 2012; Rawat *et al.,* 2018).

Szabolcs and Darab (1964) introduced the concept of Magnesium Hazard (MH) values for irrigation water, which can be determined using the following equation:

$$MH = [Mg^{2+}/(Ca^{2+} + Mg^{2+})] \times 100 \quad (10)$$

An MH value exceeding 50 is considered inappropriate for irrigation, as it may negatively impact soil properties and crop growth (Khodapanah *et al.,* 2009).

The Permeability Index (PI) is a crucial factor in assessing groundwater suitability for irrigation. Long-term irrigation can influence soil permeability due to Na^+, Ca^{2+}, Mg^{2+}, and HCO_3^- presence. Ragunath (1987) and Doneen (1964) developed a classification system for irrigation water based on PI, categorizing it into three classes: Class 1, Class 2, and Class 3.

$$PI = [100 \times (Na^+ + \sqrt{HCO_3^-})] / [Ca^{2+} + Mg^{2+} + Na^+] \quad (11)$$

To calculate irrigation indices, all ion concentrations are expressed in milliequivalents per litre (mEq/L).

Results and Discussion

The groundwater samples were analyzed for hydrochemical characteristics, WQI, and irrigation water quality indices to assess their suitability for drinking and irrigation. The findings were compared with recommended standard values to provide a comprehensive evaluation. Table 1 provides the groundwater quality parameters, descriptive statistics, and a comparison with the BIS (2012) and WHO (2017) guideline values.

In the present study, the pH of the groundwater varies from 5.2 to 8.7, indicating variability from slightly acidic to slightly alkaline conditions. Groundwater samples in the study location had EC values ranging from 72.39 to 1033.48 µS/cm. The average EC value was 343.02 µS/cm. TDS levels in the samples ranged from 43.44 to 633.52 mg/L, with an average of 209.49 mg/L. The total hardness of samples ranged from 7.55 to 351.66mg/L. The dominant cation is in the $Ca^{2+} > Na^+ > Mg^{2+} > K^+$ order. The Ca^{2+} ion concentration varied from 1.87 to 80.27 mg/L, averaging 21.39 mg/L. Sodium concentration varied from 5.25 to 32.36 mg/L with an average of 16.46 mg/L. The concentration of Mg^{2+} in the groundwater of the study area ranged between 0.70 and 36.75 mg/L, with an average value of 7.70 mg/L. Potassium is the least prominent cation in the research area, ranging from 0.78 to 13.33 mg/L, having an average of 5.41mg/L. The dominant anion order is $HCO_3^- > Cl^- > SO_4^{2-}$ HCO_3^- ranging from 15.76 - 334.24 mg/L, averaging 86.72 mg/L. The concentration of Cl^- ranged from 5.87 to 45.50 mg/L, with an average value of 22.62 mg/L. SO_4^{2-} ranges from 0.25 - 20.36mg/L

Table 1: Statistical analysis of groundwater samples in the study region

Sl. No.	Parameter	Post-monsoon						WHO 2017	BIS 2012
		Min	Max	Average	SD	Skewness	Kurtosis		
1	pH	5.2	8.7	6.51	1.25	1.05	-0.08	6.5-8.5	6.5-8.5
2	EC (µS/cm)	72.39	1033.48	343.02	288.95	2.15	4.94	500	500
3	TDS (mg/L)	43.44	633.52	209.49	177.66	2.14	4.90	500	500
4	DO (mg/L)	2.46	6.99	5.22	1.33	-0.96	1.34	5	5
5	BOD (mg/L)	1.69	5.50	4.04	1.14	-1.05	1.16	-	-
6	Ca^{2+} (mg/L)	1.87	80.27	21.39	24.06	2.39	5.97	100	75
7	Mg^{2+} (mg/L)	0.70	36.75	7.70	11.04	3.10	9.73	50	30-100
8	Na^{+} (mg/L)	5.25	32.36	16.46	9.36	0.44	-1.05	200	-
9	K^{+} (mg/L)	0.78	13.33	5.41	4.87	1.08	-0.38	20	-
10	Cl^{-} (mg/L)	5.87	45.50	22.62	14.97	0.55	-0.84	250	250-1000
11	HCO_3^{-} (mg/L)	15.76	334.24	86.72	96.12	2.84	8.36	200	600
12	SO_4^{2-} (mg/L)	0.25	20.36	5.96	6.49	1.82	2.92	250	200-400
13	Hardness (mg/L)	7.55	351.66	85.09	103.96	2.8	8.14	200	200
14	NO_3^{-} (mg/L)	0.10	10.38	4.99	4.65	0.01	-2.45	-	-
15	NO_2^{-} (mg/L)	0.0	0.09	0.02	0.03	2.86	8.52	-	-

with an average value of 5.96 mg/L. The average values of all parameters fall within the limits set by the BIS and WHO.

The groundwater quality of the KRB (as examined in this study) is compared with that of other river basins in India and around the world (see Table 2). This comparison is based on key parameters, including pH, TDS, and EC, as well as major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (Cl^{-}, SO_4^{2-}, HCO_3^{-}). The KRB has lower TDS, EC, and major ion concentrations than many Indian and global river basins, making it fresher and less mineralized. Compared to groundwater in Periyar River Basin, KRB has similar characteristics, but Bhavani and Shanmuganadhi are more mineralized and alkaline. KRB have less silicate weathering or anthropogenic impact than other basins.

The Water Quality Index (WQI) is a common method used to assess and measure groundwater quality for drinking purposes (Adimalla, 2021; Dashora *et al.,* 2022). It assesses individual water quality parameters such as pH, DO, EC, BOD, TDS, TH, Ca^{2+}, Na^{+}, Cl^{-}, K^{+}, NO_3^{-}, Mg^{2+}, SO_4^{2-}, NO_2^{-}, and HCO_3^{-} to determine overall water suitability.

In this study, WQI values were calculated for different sampling stations and classified into five categories as proposed by Brown *et al.* (1972): excellent, good, poor, very poor, and unsuitable for human consumption. The WQI values in the study area ranged from 14.60 to 57.17 during the post-monsoon season. Among the 10 samples analyzed, 30% were classified as excellent, 50% as good, and 20% as poor (Fig. 2). It was observed that groundwater pollution in certain areas was primarily caused by saltwater intrusion and the illegal discharge of industrial effluents and sewage (Krishnakumar *et al.,* 2022). According to the WQI classification (Table 3), two sites were found to have low water quality, making them unsuitable for drinking purposes. This demonstrates the necessity of ongoing groundwater monitoring and efficient management techniques to guarantee the area's clean drinking water.

Groundwater Assessment for Irrigation

After assessing groundwater quality for drinking purposes, this study also focused on evaluating its suitability for

Table 2: Comparison of present study with selected river basins of the Western Ghats and other part of world

Sl. No.	Study Area	pH	TDS (mg/L)	EC (µS/cm)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	Cl^{-} (mg/L)	SO_4^{2-} (mg/L)	HCO_3^{-} (mg/L)	References
1	Kallada River Basin, Kerala, India	6.51	209.49	343.02	21.39	7.70	16.46	5.41	22.62	5.96	86.72	Present Study
2	Kallada River Basin, India	6.4	232.8	-	8.25	2.81	18.7	4.68	3142	2.59	40.3	Mohan and Krishnakumar (2021)
3	Periyar River Basin, Kerala, India	5.78	232.91	423.47	13.28	4.77	8.47	3.87	70.54	4.24	67.08	Krishnakumar *et al.* (2022)
4	Bhavani River Basin, TN, India	8.49	859	1420	52	58	140	42	190	113	263	Sajil Kumar *et al.* (2020)
5	Shanmuganadhi River Basin, TN, India	7.59	899	1285	74	34	136	16	123	184	233	Aravinthsamy *et al.* (2021)
6	Satluj River Basin, Punjab, India	7.74	-	710	53	28	63	12	48	52	-	Chaudhry *et al.* (2019)
7	Shivaganga river basin, Maharastra, India	7.48	394	612	54	25	21	0.7	47	37	204	Kadam *et al.* (2022)
8	Kanavi Halla Sub-Basin, Belagavi, India	7.3	916	1420	145	31	126	23	243	56	320	B Patil *et al.* (2020)
9	Blue Nile Basin, Northwestern Ethiopia	7.08	394.04	627.55	30.18	20.72	30.79	4.99	9.26	6.60	273.48	Bawoke and Anteneh (2020)
10	Xincai River Basin, Northern China	7.03	1217.83	1522.28	175.25	56.27	84.27	6.33	158.24	108.14	586.54	Zheng *et al.* (2017)
11	Ordos basin, northwest China	7.89	2484.57	-	83.72	148.90	566.83	3.69	602.05	791.54	308.16	Wu *et al.* (2020)
12	Bazman basin, southeastern Iran	7.80	2035.5	3906.0	154	40	572	14	392	487	95.9	Rezaei *et al.* (2019)

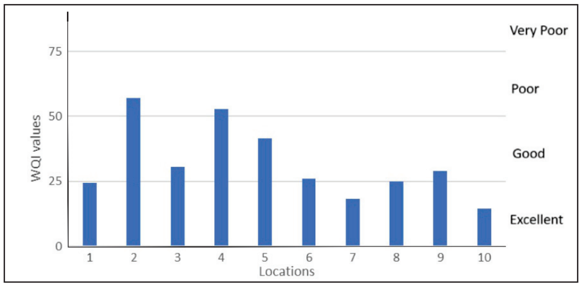

Fig.2. Variation of water quality index with locations

Table 3: WQI of the sampling locations

Sample Locations	WQI rating	Water Quality Status
GW1	24.36	Excellent
GW2	57.17	Poor
GW3	30.47	Good
GW4	52.74	Poor
GW5	41.53	Good
GW6	25.98	Good
GW7	18.18	Excellent
GW8	25.04	Good
GW9	29.01	Good
GW10	14.60	Excellent

irrigation. Several criteria were applied to categorize groundwater characteristics for irrigation use, as outlined in the following sections.

The Sodium Adsorption Ratio (SAR) and Residual Sodium Carbonate (RSC) values of all the samples were within safe limits, indicating suitability for irrigation. Another key parameter, the Permeability Index (PI), was used to assess groundwater suitability (Doneen, 1964). According to this classification, water is divided into Class I, II, and III, where Class I and Class II are considered suitable for irrigation. In the study area, 80% of the samples fell into Class I, while the remaining 20% belonged to Class II, confirming their irrigation suitability.

Todd and Mays (2005) emphasized that excessive sodium in groundwater can decrease soil permeability, hinder plant growth, and lower crop productivity. Based on sodium percentage (% Na), 10% of the samples were classified as "excellent," 30% as "good," 20% as "permissible," and 40% fell into the "doubtful" category (Fig. 3). The presence of higher sodium levels in some locations suggests potential long-term soil degradation risks, highlighting the need for careful groundwater management in agricultural activities.

Kelley's Ratio (KR) is used to classify water quality for irrigation. A KR value below 1 signifies suitability, whereas a value exceeding 1 indicates unsuitability for irrigation use. In the study area, KR values range from 0.20 to 3.48. Of the total groundwater samples analyzed, 60% (6 samples) were deemed suitable for irrigation, while the remaining 40% (4 samples) were considered unsuitable. Higher KR values in certain locations may be attributed to elevated sodium concentrations, which can negatively impact soil permeability and crop yield.

The Magnesium Hazard (MH) values range from 14.18 to 54.31 mEq/L. Approximately 90% of the samples have MH values below 50, signifying their suitability for irrigation. However, some samples exceed this threshold, suggesting potential concerns regarding soil permeability and crop productivity in certain locations.

Hydrogeochemical Characteristics of Groundwater

A Piper trilinear diagram (Piper, 1944) was utilized to analyze the hydrogeochemical characteristics of groundwater in the study area. This graphical tool helps visualize the similarities and variations among groundwater samples, facilitating the classification of hydrochemical facies based on predominant ions. Major cations and anions were plotted to determine the groundwater type, revealing that the predominant water type in the area is mixed Ca-HCO_3, followed by Na-Cl. Additionally, one sample exhibited a mixed Ca-Na-HCO_3 composition (Fig. 4). Overall, the groundwater in the study area is primarily influenced by alkaline earth elements (Ca^{2+} and Mg^{2+}) and weak acids (HCO_3^-). The observed dominance of Na-Cl species in certain locations may be attributed to excessive groundwater extraction, particularly during warm seasons, leading to saline water intrusion (Subba Rao, 2008; Mohan and Krishnakumar, 2022).

Hydrogeochemical Processes of Groundwater

A Gibbs diagram is a graphical representation used in hydrogeology to interpret the chemical composition of groundwater. It plots the relative concentrations of major cations (Ca^{2+}, Na^+, K^+) and anions (Cl^-, HCO_3^-) in a diagram. The Gibbs diagram is particularly useful for distinguishing the primary processes controlling groundwater chemistry, particularly the influences of precipitation, rock weathering, and evaporation (Gibbs, 1970). The Gibbs diagram (Fig. 5) suggests that groundwater chemistry in the LKRB during the post-monsoon season is primarily controlled by rock-water interactions, particularly weathering of silicate minerals. Only a few samples appear near the precipitation

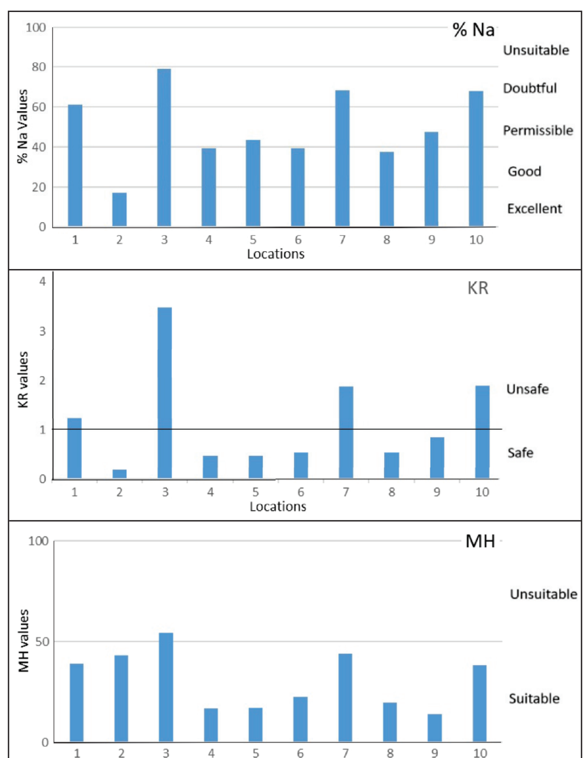

Fig.3. Variation of % Na, KR, MH with locations

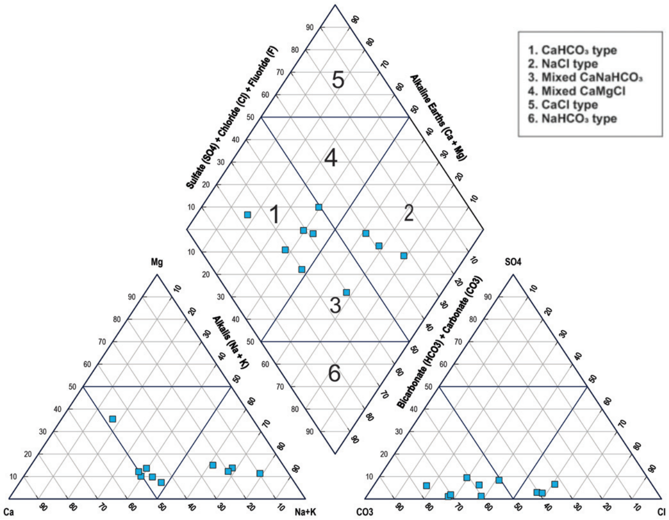

Fig.4. Piper diagram of the groundwater samples of the study area

dominance zone, indicating that direct rainfall contribution to groundwater chemistry is minimal in this season.

Conclusions

Groundwater quality is a crucial factor in sustainable resource management, directly influencing water availability and usability for drinking, agriculture, industry, and ecosystem maintenance. Ensuring safe and clean groundwater aligns with Sustainable Development Goal (SDG) 6: Clean Water and Sanitation, which highlights the importance of sustainable water management. This study evaluated the groundwater quality of the LKRB in Kollam town and its surrounding areas for drinking and agricultural purposes using the Water Quality Index (WQI) method and various hydrochemical indicators.

The WQI evaluation categorized three of the ten samples examined during the post-monsoon period as excellent, five as good, and two as poor. For irrigation suitability, indices such as Na%, KR, and MH exceeded permissible limits in certain locations, indicating potential risks to soil quality and agricultural productivity. These findings are closely linked to SDG 2: Zero Hunger, as groundwater quality directly impacts food security and sustainable agriculture. The dominant groundwater types in the area were identified as mixed $CaHCO_3$ and NaCl types. While most groundwater sources were deemed suitable for drinking and irrigation, some samples showed contamination risks, highlighting the need for immediate intervention. The limitation of the study is the relatively small sample size, which may not fully capture the spatial variability of groundwater quality in the region. Nevertheless, the study provides preliminary insights into the hydrogeochemical status and can serve as a baseline for more detailed investigations in the future.

To ensure long-term sustainability, the following measures should be implemented in alignment with SDGs:

Regular monitoring and early warning systems (SDG 6: Clean Water and Sanitation): Conduct continuous groundwater quality assessments to detect contamination early and develop early warning systems for potential risks such as saltwater intrusion and agricultural runoff spikes. Enhancing groundwater recharge: Implement rainwater harvesting and managed aquifer recharge techniques to replenish natural groundwater. Sustainable water use and reduced over-extraction (SDG 12: Responsible Consumption and Production): Implement efficient irrigation techniques and water conservation policies to reduce over-extraction. Reducing agricultural pollution (SDG 15: Life on Land): Promote the use of organic fertilizers and reduce reliance on chemical inputs to prevent groundwater contamination. Crop rotation and sustainable farming practices can help minimize nutrient leaching. Strengthening industrial wastewater regulations (SDG 14: Life Below Water): Establish and enforce strict effluent discharge standards for industries near coastal lowlands. Require industries to treat wastewater before disposal, removing heavy metals, hazardous chemicals, and organic pollutants. Improving wastewater treatment infrastructure (SDG 9: Industry, Innovation, and Infrastructure): Upgrade existing wastewater treatment facilities to ensure removal of nitrates, heavy metals, and pathogens before discharge into the environment. Community education and awareness (SDG 4: Quality Education): Educate local communities on groundwater conservation, safe waste disposal, and household wastewater management to reduce contamination risks.

By integrating these sustainable groundwater management strategies, we can ensure the long-term resilience of groundwater resources, supporting present and future generations while achieving multiple SDGs. Policymakers and stakeholders must prioritize conservation measures to mitigate risks and enhance groundwater sustainability in Kollam town and similar regions.

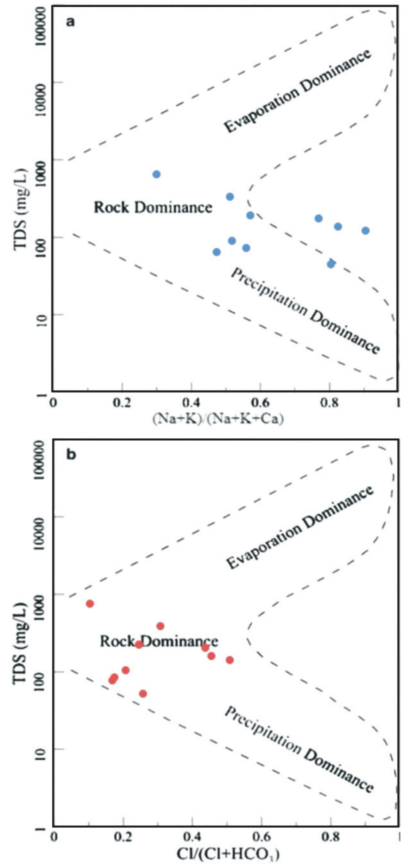

Fig.5. Gibbs diagram showing controlling mechanisms of water quality

Authors' Contributions

JJ: Conceptualization, Formal Analysis, Writing-Original

Draft, Methodology, Data Curation, Visualization, Reviewing and Editing, Software. **AK:** Investigation, Supervision, Conceptualization, Reviewing and Editing, Validation.

Data Availability

The data supporting this study's findings are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare no competing interests.

Acknowledgements

The authors sincerely thank the Director of NCESS, Thiruvananthapuram, for providing the necessary laboratory and fieldwork facilities for this research. The instrumental support from the Central Chemical Laboratory (CCL) is also gratefully acknowledged. The authors extend their heartfelt gratitude to the Ministry of Earth Sciences, Government of India, for financial support through the core program "River and Groundwater Hydrology in Peninsular India." Additionally, Mrs. Jeenu Jose expresses her sincere appreciation to Cochin University of Science and Technology (CUSAT) for the opportunity to pursue her PhD research.

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