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Hydrogeochemical Characterization and Evolution of Groundwater in Hemgir Block, Sundargarh District, Odisha, India

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Abstract

A comprehensive geochemical assessment of groundwater and its suitability for drinking and agricultural applications was conducted in and around the Hemgir block of Sundargarh district, Odisha. A total of 85 groundwater samples were systematically collected during the pre-monsoon season (May 2024) and analyzed for key physico-chemical parameters, including pH, electrical conductivity, total dissolved solids, calcium, magnesium, sodium, potassium, bicarbonate, sulphate, and chloride. The analytical results revealed that the predominant ionic concentrations generally follow the order: $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$ among cations, and $HCO_3^- > Cl^- > NO_3^- > SO_4^{2-}$ among anions. The suitability of groundwater for both drinking and irrigation was evaluated using various water quality standards and established classification systems. Hydrochemical facies identified through Piper's Trilinear diagram and Stiff's plot indicated that most groundwater samples belong to the Ca^{2+}–Mg^{2+}–HCO_3^- facies, followed by Ca^{2+}–Mg^{2+}–Cl^-–HCO_3^- facies. Calcium and magnesium emerged as the dominant cations, while bicarbonate and chloride were the major anions in the study area. The elevated presence of Ca^{2+}, Mg^{2+}, and HCO_3^- suggests that the groundwater chemistry is primarily influenced by alkaline earth elements and weak acids. Gibbs plot confirmed that sediment/rock-water interaction is the major process governing groundwater composition. Overall, the groundwater quality was found to be suitable for both drinking and agricultural purposes, with calcite dissolution being the primary geochemical process, followed by silicate mineral weathering.

Keywords: Groundwater Quality, Geochemical Characterization, Hadrochemical Facies, Rock-Water Interaction, Calcite Dissolution, Silicate Weathering

Introduction

Ground water is the most important fresh water sources, which help in provider of drinking water, agriculture and industries universally (Bakshe *et al.,* 2024). Groundwater is the main source of drinking water in most places, especially in developing countries. But natural processes and human activities are putting both the quality and long-term health of groundwater at risk (Gao *et al.,* 2020; Patra *et al.,* 2021). To manage water properly we need to know what chemicals are in groundwater and how they change over time (Zhang *et al.,* 2025). The hydrogeochemical characterization is the study of physical and chemical properties of groundwater to see how it can be used and to find out what geochemical processes are happening that affect the chemistry of water (Promilton *et al.,* 2025). They include things like rock water interaction, mineral dissolution and precipitation, ion exchange, evaporation, and human activities like farming runoff, industrial discharge, and urbanization (Wen *et al.,* 2025; Divya *et al.,* 2026; Jena *et al.,* 2025). Integrating hydrochemical data with geological and hydrological contexts can yield insights into the origin and transformation of groundwater (Islam, 2023; Chatterjee *et al.,* 2022). The chemistry of groundwater is a dynamic process which depends on lithology, residence time, recharge conditions, and climatic variations. During the process of flowing through different geological structures, the chemistry of the groundwater changes considerably resulting in different hydrochemical facies (Jodhani *et al.,* 2025; Tiwari *et al.,* 2026; Jena *et al.,* 2026), these changes are often understood by using instruments such as piper diagrams, Gibbs plots and geochemical modeling in order to understand processes which control the quality of groundwater. In recent years, growing concerns regarding groundwater pollution, such as salinization, heavy metal, and nitrate enrichment have resulted in a need to carry out more hydrogeochemical studies in detail (Onwe *et al.*, 2023; Chatterjee *et al.,* 2023). These studies are essential in determining the source of contamination and the health hazards, and in coming up with sustainable management of ground water. Thus, this study is dedicated to hydrogeochemical characterization and evolution of groundwater to estimate its quality, the ruling geochemical processes, and offer a scientific background of sustainable use and management of groundwater resources. The current study targets on the hydrogeochemical characterization and evolution of groundwater. To determine the quality of groundwater, identify the

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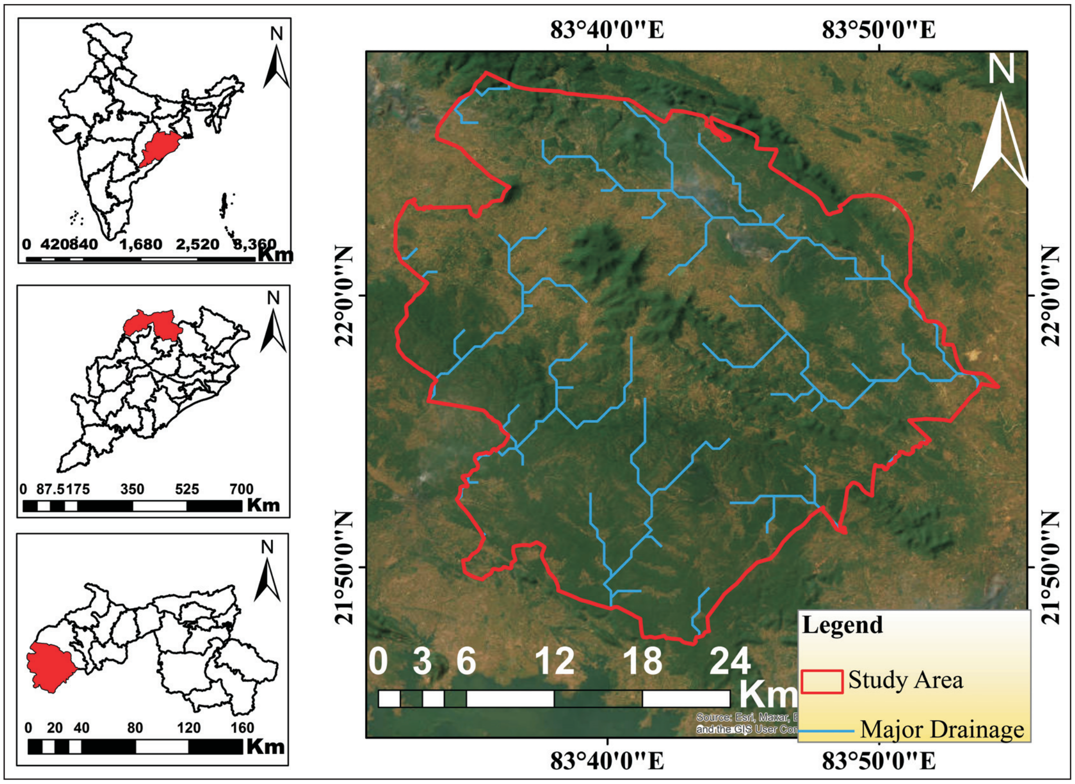

Fig. 1. Location Map of the Study Area

controlling geochemical processes, and provide a scientific background of the sustainable use and management of the groundwater resources of Sundargarh district, Odisha, using an interactive method of satellite data and comprehensive hydrogeological field survey.

Geological Setting

The study area, Hemgir block, is situated in Sundargarh district, located in the northwestern sector of the district, approximately 80 km from the district headquarters. This block falls within Survey of India Toposheet No. 64 O/9 and is geographically positioned between longitudes 83°32'00"E to 85°22'00"E and latitudes 21°36'00"N to 22°32'00"N. The nearest railway station is about 1 km from Kanika. The region is well connected by a network of metalled and unmetalled roads along with numerous footpaths, which facilitate convenient access to geological outcrops. Sundargarh district covers a total geographical expanse of 9712 sq. km, accounting for approximately 6.23% of Odisha's total land area. Positioned in the northwestern part of Odisha, Sundargarh ranks as the second largest district in the state and is categorized under the Fifth Schedule of the Indian Constitution. It shares its boundaries with Raigarh district (Chhattisgarh) to the west, Jashpur district (Chhattisgarh) to the northwest, Simdega district (Jharkhand) to the north, West Singhbhum district (Jharkhand) and Keonjhar district (Odisha) to the east, and Jharsuguda, Sambalpur, Deogarh, and Angul districts (Odisha) to the south (Fig.1). Geologically, the area is composed of rock units from both the Precambrian (Gangpur Supergroup) and the Lower Gondwana formations, with predominant lithologies including sandstones, shales, and clays of the Barakar, Talchir, and Kamthi formations, along with mica schists, phyllites, and acid intrusives such as granites and pegmatites. The Barakar Formation is notably interbedded with coal seams (Goswami *et al.*, 2006). Groundwater in the region is primarily sourced from large-diameter dug wells and both shallow and deep bore wells, which are extensively used for drinking and irrigation purposes.

Methodology

Groundwater samples were systematically collected from 85 wells across various locations in Hemgir Block, Sundargarh district, Odisha, during May 2024. Among these, 37 samples were obtained from dug wells, while 48 samples were sourced from tube wells. These wells were primarily used for drinking and irrigation purposes and the collected samples were analyzed to assess their suitability for these applications. The geographic coordinates of each sampling site were recorded using a Global Positioning System (GPS) device. In-situ measurements of key physicochemical parameters, including electrical conductivity (EC), pH, temperature (T), and total dissolved solids (TDS), were conducted using a multi-parameter probe (Systronics). Samples were securely sealed in clean polypropylene bottles, following storage and preservation protocols as outlined by various workers (Trivedi and Goel, 1984; Saxena, 2006; Gupta et al., 2004; Jaiswal, 2004; Chowdhury *et al.*, 2021; APHA, 2012). Major hydrochemical parameters such as total hardness (TH), chloride (Cl^-), sulphate (SO_4^{2-}), bicarbonate (HCO_3^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+) and fluoride (F^-) were analyzed. Electrical conductivity (EC) and pH were measured using digital meters immediately after sampling. Ca^{2+}, Mg^{2+}, HCO_3^- (bicarbonate) CO^{2-}, and Cl^- were analyzed by volumetric titrations.TDS was measured using a water analyzer kit. Flamephotometer was used to measure Na^+ and K^+ ions. SO_4^{2-} and F^- were determined by spectrophotometric technique. Fe and As were determined by Atomic Absorption Spectroscopy technique. Ion Balance Error (Charge balance error, CBE) was calculated to assess the accuracy of the chemical analysis. The ionic concentration was converted into milliequivalents per Lit (meq/L) and the charge balance error was determined using the following equation-

$$CBE\% = [(\sum Cations - \sum Anions)/(\sum Cations + \sum Anions)] \times 100$$

The calculated values for all groundwater samples were found to be within the permissible limit *i.e.* ±5 indicating good analytical accuracy and reliability of the data.

Results and Discussion

Physicochemical Characteristics and Major Ion Chemistry

The groundwater chemistry was analyzed to evaluate its suitability for both drinking and agricultural use. The ranges, mean and SD of the analytical results are presented in Table 1**.** The interpretation of groundwater quality for drinking purposes followed the guidelines of Ayers (1977) and Christiansen *et al.* (1977)**.** With respect to hydrogen ion concentration (pH), the ground water of the study area ranges from 5.2 to 8.8 implies the fact that it varies from acidic to slightly alkaline, with a near-neutral mean in nature. Electrical conductivity (EC) reflects the ionic conduction capacity of groundwater, while total dissolved solids (TDS) indicate the overall concentration of dissolved substances. EC and TDS in the samples ranged from 132.2 to 1076.3 µS/cm and 84.6 to 688.9 mg/L**,** with mean values of 410.17 µS/cm and 262.51 mg/L, respectively. Notably, 96% of the samples had TDS values within the acceptable limit of 500 mg/L, as per BIS (2012), since water exceeding this limit may cause gastrointestinal discomfort. The sequence of major cation concentrations was observed as $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$**,** while the anion order was $HCO_3^- > Cl^- > NO_3^- > SO_4^{2-}$ (Table 1). The concentration ranges (in mg/L) were: Ca^{2+}: 11.22–184.37**,** Mg^{2+}: 0.69–94.65**,** Na^{+}: 0.73–104.41, and K^{+}: 0.16–10.76 was the most dominant alkali metal, likely sourced from halite and silicate weathering**,** though agricultural runoff may also elevate sodium levels (Saha *et al.,* 2019). The higher Na^{+} concentration relative to K^{+} is due to sodium's greater dissolution rate. Potassium (K^{+}) levels may result from potassium-rich fertilizers and the decay of organic waste **(**Saha *et al.,* 2019**).** Among alkaline earth metals, calcium (Ca^{2+}) was most prevalent, while magnesium (Mg^{2+}) likely originated from the weathering of dolomite and ferromagnesian minerals **(**Saha *et al.,* 2019). Concentrations of Na^{+}, K^{+}, Ca^{2+}, and Mg^{2+} in all samples were within WHO acceptable limits for drinking and irrigation. Chloride (Cl^-), typically derived from rock dissolution, minor seawater intrusion, or contamination from domestic and industrial sources, was observed at low levels, indicating low groundwater salinity **(**Saha *et al.,* 2019). Organic matter oxidation in the aquifer can produce carbon dioxide, enhance mineral weathering and increase bicarbonate (HCO_3^-) levels **(**Khashogji and El Maghraby, 2013**).** Additional bicarbonate enrichment can result from silicate mineral weathering **(**Gastmans *et al.,* 2010; Saha *et al.*, 2019**).** The groundwater exhibited noticeable enrichment of Ca^{2+}, Mg^{2+}, and HCO_3^- due to active weathering processes. Bicarbonate concentrations ranged from 35 to 300 mg/L**,** while chloride levels varied between 10.65 and 347.9 mg/L**,** both within WHO permissible limits. Chloride was a significant contributor to EC and TDS variations in the aquifer. Sulfate (SO_4^{2-}) concentrations ranged from below detection limit to 10.3 mg/L**,** remaining well within the WHO and BIS safety limits for drinking and agricultural use. All groundwater samples also conformed to the BIS guidelines for bicarbonate content**.** To determine the drinking suitability of the groundwater, the measured concentrations were compared against the standards set by WHO (2004) and BIS10500 (ISI, 1995). The comparison indicates that most shallow and deep aquifer samples are suitable for drinking and domestic purposes, with only a few minor exceptions where select parameters slightly exceed the recommended thresholds **(**Table 1**).**

Hydrochemical Facies

The groundwater samples from the study area were plotted on the Piper (1944) Trilinear Diagram (Fig. 2). The distribution pattern indicates that most groundwater samples belong to the mixed $Ca^{2+}–Mg^{2+}–HCO_3^-$ water type. Specifically, the samples cluster in fields 4 and 5 of the Piper diagram (Fig. 2), which signifies that alkaline earth elements (Ca^{2+} and Mg^{2+}) dominate over strong acid anions**.** In this region, calcium and magnesium collectively contribute 75–90% of the total cation concentration**,** while bicarbonate (HCO_3^-) serves as the principal anion.

The Piper diagram confirms the dominance of Ca^{2+} and Mg^{2+}**,**

Table 1: Ranges of physicochemical parameters & their comparison to permissible limits set by World Health Organization (WHO, 2024) and Bureau of Indian Standards (BIS, 1995)

Parameter	Ranges	Mean	Standard Deviation	WHO(2004)	BIS10500 (ISI,1995)	
					Highest desirable	Maximum desirable
pH	5.2-8.8	6.91	0.86	6.5-8.5	6.5	8.5
EC	132.2-1076.3	410.17	193.76	400-2000	-	-
TDS	84.6-688.9	262.51	124.02	500-1000	500	2000
Total Hardness	125-600	288.15	100.71	-	300	600
Calcium	11.22-184.37	68.09	31.25	100-200	75	200
Magnesium	0.69-94.65	28.83	22.57	30-50	30	100
Sodium	0.73-104.41	23.75	22.37	20-200	-	-
Potassium	0.16-10.76	5.46	7.49	10-12	-	-
Bicarbonate	35-300	118.82	59.96	-	200	600
Sulphate	0-10.3	1.28	2.58	25-250	200	400
Nitrate	0-39	2.59	7.24	50	45	-
Chloride	10.65-347.9	65.9	54.55	25-600	250	1000
Iron	0.021-0.072	0.025	0.036	0.3	0.3	-
Fluoride	0.003-0.91	0.28	0.25	1.5	1.0	1.5
Arsenic	0.001-0.004	0.003	0.002	0.01	0.01	0.05

which exceed the influence of alkali metals, indicating a groundwater chemistry inclined towards alkalinity. The insignificant levels of chloride (Cl^-) and sulfate (SO_4^{2-}) further emphasize the prevalence of bicarbonate ions. The high concentration of HCO_3^- suggests that weak acids exceed strong acids in the groundwater system, leading to a prominent cluster near the alkalinity apex. The diamond-shaped field of the Piper diagram confirms that Ca^{2+}–Mg^{2+}–HCO_3^- is the predominant hydrogeochemical facies in the study area. Additionally, it was observed that in most samples, more than 80% of the total cation content is contributed by calcium and magnesium, while bicarbonate alone accounts for over 90% of the total anion concentration (Fig. 2). To further support these observations, Stiff diagrams, which graphically represent the major ion composition of individual water samples as per Stiff (1951), were constructed. The Stiff plots reinforced that calcium and magnesium are the dominant cations, while bicarbonate is the most abundant anion in the groundwater system.

Given the dominance of bicarbonate, its source was further examined. Generally, the ratio of HCO_3^- to (HCO_3^- + SO_4^{2-}) in groundwater provides insights into the primary proton sources during weathering, distinguishing between carbonation and sulfide oxidation processes (Mostafa *et al.,* 2017). Based on the study of Pandey *et al.* (2001), a higher ratio of HCO_3^- indicates that carbonic acid-driven weather in gis the major proton-generating process in the system. In this study, the HCO_3^- / (HCO_3^- + SO_4^{2-}) ratio was found to be approximately one (~1), strongly indicating that bicarbonate formation is overwhelmingly dominant due to the negligible sulfate concentrations (often below detection limits) across the region.

These points to carbonic acid weathering as the principal geochemical process influencing groundwater chemistry in the study area. This finding aligns with Marandi and Shand (2018), who noted that groundwater typically evolves along the bicarbonate pathway due to the abundant presence of carbonate minerals, particularly calcite, in sedimentary rocks and soils. The dissolution of calcite is often a controlling factor in groundwater chemistry, even when present in small quantities, because of its high solubility and widespread occurrence (Appelo and Postma, 1993).

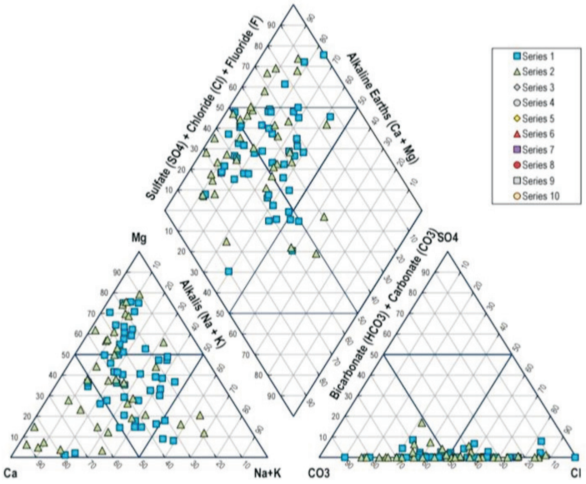

Fig. 2. Piper's Trilinear Plot

Overall, the Ca^{2+}–Mg^{2+}–HCO_3^- facies emerged as the dominant hydrochemical signature in the majority of groundwater samples, indicating that the water is fresh and low in salinity. Based on the combined concentrations of calcium and magnesium, the water samples were classified according to hardness. The analysis revealed that over 80% of the groundwater samples in the study area fall within the moderately hard water category (Fig. 3).

Source-Rock Deduction

The Gibbs diagram is a useful tool to evaluate the primary sources of dissolved ions in groundwater by analyzing the

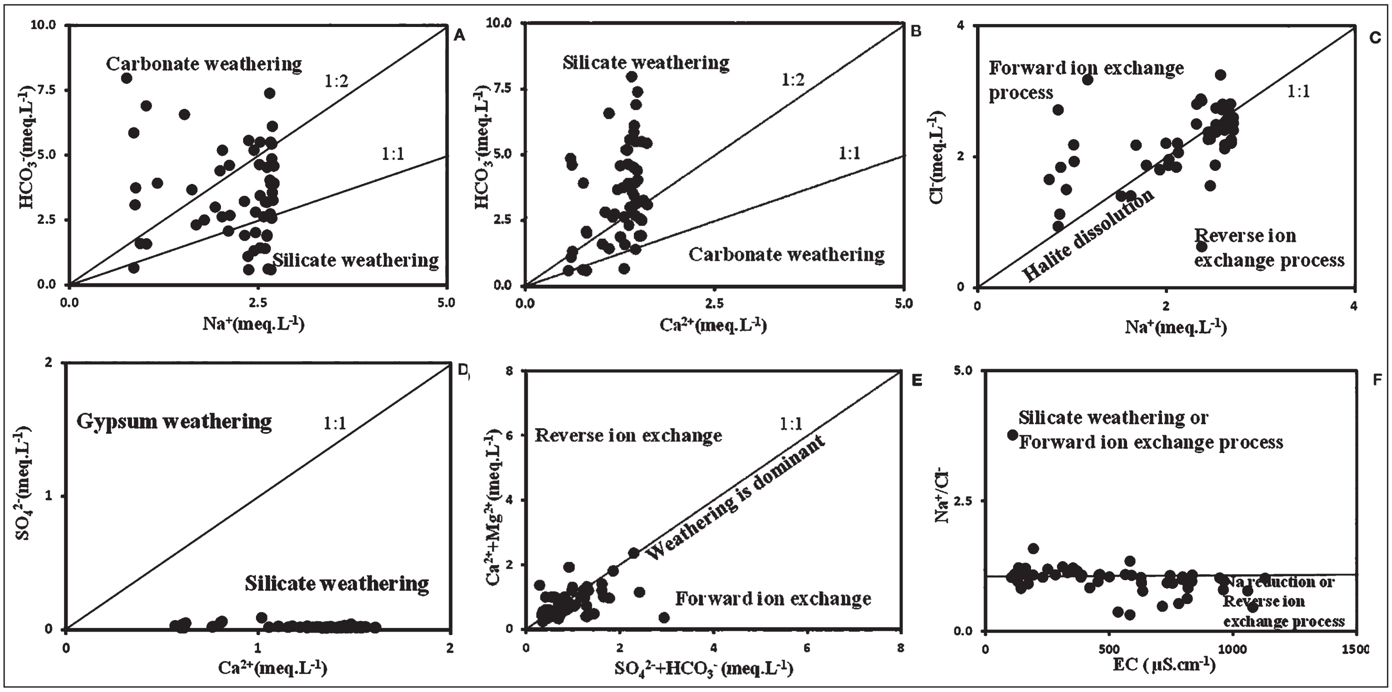

Fig. 3. Scatter plots used for source-deduction (A) HCO_3^- *vs.* Na^+(B) Ca^{2+}vs. HCO_3^- (C) Na^+ *vs.* Cl^-(D) Ca^{2+}*vs.* SO^{2-}_4 (E) Ca^{2+}+Mg^{2+}*vs.* HCO_3^-+SO^{2-}_4 and (F) EC *vs.* Na^+/Cl^-.

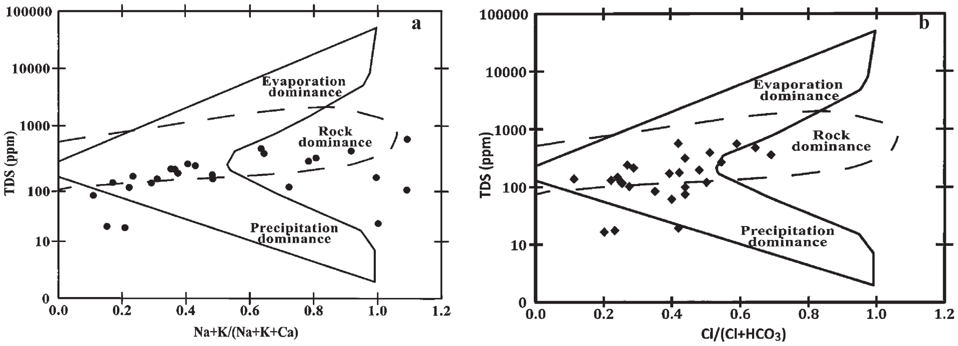

Fig. 4 a. Gibbs plot for cation; **b.** Gibbs plot for anion

relationship between major cation and anion ratios and total dissolved solids (TDS). The Gibbs ratios are calculated using the following expressions:

$$\text{Gibbs ratio Anion} = (Cl^-) / (Cl^- + HCO_3^-) \tag{1}$$

$$\text{Gibbs ratio Cation} = (Na^+ + K^+) / (Na^+ + K^+ + Ca^{2+} + Mg^{2+}) \tag{2}$$

By plotting these ratios against TDS, Gibbs diagrams help determine whether groundwater chemistry is primarily influenced by rock–water interaction, evaporation, or precipitation processes **(**Lanjwani *et al.,* 2021**).** In this study, the Gibbs plots (Fig. 3) reveal that rock–water interaction is the dominant process controlling groundwater chemistry in the region, indicating that the geochemical composition of the aquifer rocks is the principal source of dissolved ions. The concentration of various ions in groundwater largely depends on their abundance in the parent rock and their solubility rate **(**Dash, 1996; Dash and Sahoo, 1999; Saha *et al.,* 2019; Sahu, 2018). The mechanism governing groundwater chemistry in relation to aquifer lithology has been extensively studied by Gibbs (1970) and Viswanathaiah *et al.,* 1978**.** The Gibbs diagram categorizes groundwater genesis into three hydrogeochemical fields: precipitation dominance, evaporation dominance, and rock–water interaction dominance.

For anions, the majority of the samples-80 out of 85-fall within the rock dominance field (Fig. 4a), suggesting that the aquifer lithology strongly influences groundwater chemistry. The remaining samples lie in the precipitation dominance zone. Similarly, for cations**,** 80 samples also plot within the rock dominance field (Fig. 4b), with only five samples positioned in the precipitation dominance field. The combined interpretation of both cation and anion plots from the Gibbs (1970) diagrams clearly demonstrate that the groundwater chemistry of the study area is primarily controlled by the rock–water interaction processes governed by the mineralogical composition of the aquifer rocks**.**

Conclusions

The chemical analysis indicates that the groundwater in the study area is generally weakly acidic to slightly alkaline in nature. The Piper Trilinear Diagram confirms that calcium and magnesium are the dominant cations**,** while bicarbonate is the principal anion, reflecting a Ca^{2+}–Mg^{2+}–HCO_3^- hydrochemical facies**.** The elevated bicarbonate concentrations suggest active chemical weathering of the host rocks within the aquifer. The presence of Ca^{2+}, Mg^{2+}, and HCO_3^- contributes to temporary hardness, moderate alkalinity, and a dominance of alkaline earth elements and weak acids in the groundwater system. Interpretation of the Gibbs diagrams further demonstrates that the groundwater chemistry is predominantly controlled by the lithological characteristics of the aquifer, with rock–water interactions playing a significant role in shaping the hydrogeochemistry of the region. The overall chemical quality of the groundwater is found to be within the permissible limits set for drinking and agricultural use by WHO and BIS standards. Given the increasing dependence on groundwater due to irregular monsoon patterns and growing water demand linked to population expansion**,** it is essential to establish a program for regular groundwater quality monitoring**.** Continuous assessment will help safeguard the sustainability of the groundwater resource and ensure the long-term availability of safe water for the region.

Data Availability Statement

All data generated or analyzed during this study are included in this published article.

Authors' Contributions

RP: Conceptualization, Data Curation, Analysis, Map Preparation and Manuscript Writing. **DB**: Conceptualization, Manuscript Writing and Editing. **SKD**: Investigation and Methodology. **KMJ**: Reviewed and Editing. **SD**: Review, Map Preparation and Editing.

Conflict of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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