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Pritam Kumar Barik
Department of Geology, Fakir
Mohan University, Balasore,
Odisha, India

Nandita Mahanta
Department of Geology, Utkal
University, Bhubaneswar,
Odisha, India

Hydrochemical analysis and evaluation of groundwater quality for irrigation suitability in Baliapal block of Balasore district, Odisha, India.

Pritam Kumar Barik and Nandita Mahanta

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Abstract

The present study aims to approach the quality of groundwater of Baliapal Block of Balasore District, Odisha. The degradation of groundwater can put at risk for human consumption and irrigation purpose. Hence it is important to assess groundwater quality regularly. A study was conducted in a part of the coastline of North-Odisha to examine the hydrogeochemistry, spatial distribution, correlation with various ions and controlling factors of groundwater chemistry. Hence, a total of 100 groundwater samples were collected and analysed for EC, TDS, TH, HCO_3^- , CO_3^{2-} , Cl^- , SO_4^{2-} , NO_3^- , F^- , PO_4^{3-} , Ca^{2+} , Mg^{2+} , Na^+ and K^+ . To assess the groundwater quality for irrigation purpose, parameters like Sodium Adsorption Ratio (SAR), Soluble Sodium Percentage (SSP), Residual Sodium Carbonate (RSC), Magnesium Absorption Ratio (MAR), Permeability Index (PI), Potential Soil Salinity (PS) and Kelley's Ratio (KR) values were calculated. As per the U.S. Salinity diagram, most of the groundwater samples fall in C2-S1 and C3-S1 category indicating medium to high salinity which is safe for irrigation purpose for all types of soils. 10 number of samples were fall in C3-S2 category whereas one sample each fall in both C2-S2 and C4-S3 category. Piper diagram, Wilcox diagram, Gibb's diagram and Chadha diagram were plotted to know about the rock-water geochemistry and irrigation purpose of water.

Keywords: Groundwater quality, baliapal block, irrigational parameter, U.S. salinity diagram

Introduction

Groundwater is an essential natural resource that supports life in India and across the globe. India ranks among the highest consumers of groundwater, mainly for agriculture and household needs such as drinking water. Since agriculture is the backbone of the Indian economy, the demand for groundwater remains very high. In many rural regions, people depend largely on hand pumps and tube wells for both irrigation and daily water use. Data from the National Sample Survey shows that around 56% of households rely on hand pumps or tube wells for drinking water, while 14% use open wells and nearly 25% receive water through piped supply systems.

The degradation of groundwater can put at risk for irrigation purpose and human health. Hence it is important to assess groundwater quality regularly. Analysis of groundwater hydrogeochemistry, control characteristics, water quality, and nitrate-related health risks in Longkou Bay, has been studied in North China (Adimalla, 2019) ^[1]. Changes in water resources as a result of climate change will increase pressure for sustainable water management, especially in regions that are already water stressed and/or under pressure.

According to Pandey *et al.*, (2023) & Karunanidhi *et al.*, (2020) ^[12, 19], the demand for fresh water has significantly increased over the past few decades due to the fast industrialization and population rise, a case study in the Shanmuganadhi River basin of South India. Rapid urbanisation, particularly in emerging economies like India, has had an impact on groundwater accessibility and availability because of overuse and improper waste management, particularly in metropolitan areas of Uttarpradesh, India (Elumalai *et al.*, 2020) ^[8].

Several studies have been carried out to examine the pollution levels in the eastern and coastal portions of the Mahanadi Basin, Odisha. (Haque *et al.*, 2021) ^[10]. the groundwater state of a region is significantly influenced by the topography, including its geology, Geomorphology,

Corresponding Author:
Pritam Kumar Barik
Department of Geology, Fakir
Mohan University, Balasore,
Odisha, India

Soil, and hydraulic gradient (Mahanta & Goswami, 2024)^[14]. The research of groundwater development utilising RS and GIS approaches has been studied in the lower stretches of Subarnarekha River, Odisha (Jaishi *et al.*, 2024)^[11]. It is possible to evaluate the water quality of any given place or particular source using physical, chemical, and biological properties. According to Li *et al.*, (2024), if these metrics' values exceed certain thresholds, it could be harmful to people's health. The regulating factors that influence an aquifer's groundwater availability are its geographic area, infiltration index, and specific yield (Mahanta *et al.*, 2018)^[15]. But as anthropogenic groundwater withdrawals outpace natural recharge, groundwater supplies are running out in Baitarani River Basin of Odisha (Mahanta, 2017)^[16]. Droughts and rising temperatures are examples of climatic stresses that also have an impact on groundwater supplies (Rahman *et al.*, 2021; USEPA, 2012)^[21]. Groundwater depletion is linked to changes in the land-atmosphere energy feedback, saline water intrusion, and deteriorating water quality (Rajan & Nandimandalam, 2024)^[22]. Recharge of groundwater only happens when precipitation surpasses evapotranspiration. With the sloping topography and hard rock soil, the frequency and severity of intense rain fall events have increased recently (Naik *et al.*, 2022; Li *et al.*, 2024)^[17], which is anticipated to lead to increased runoff losses. Due to inappropriate groundwater use for agriculture, the GRACE (Gravity Recovery and Climate Experiment) satellite mission records show significant groundwater depletion in north and northwest India (Baruah *et al.*, 2024; Sahoo *et al.*, 2024)^[3, 23]. Approximately 80% of the 45 million people who live in Odisha rely on groundwater for their drinking water. Because of groundwater consumption for agriculture, groundwater levels in the heavily populated Balasore coastal basin are dropping and seawater intrusion has been observed (Das *et*

al., 2023; Haque *et al.*, 2021)^[6, 10]. The main cause of the lower number of research comparing studies on surface water to those on groundwater regarding the effects of anthropogenic and climatic stresses is a lack of data (Mahanta *et al.*, 2018; Mahanta, 2017)^[15, 16]. The main sources of data on the impact of anthropogenic and hydrological factors on groundwater systems, however, are time series of groundwater levels from monitoring networks (Rajan & Nandimandalam, 2024; Zafar *et al.*, 2022)^[22, 27].

This study aims to assess the groundwater quality of sandy aquifer of Balipal block in coastal area of Balasore district in north-eastern Odisha and determine whether the water is suitable for drinking water and for many purposes including irrigation. The main objective of this study is to monitor the groundwater in the study area using GIS technology and take necessary measures to improve the groundwater for drinking and for many other purposes.

2. Materials and Methods

2.1 Study area

The study area is located in the administrative unit of Balipal block of Balasore district in north coastal Odisha. The study area spans an area of about 202 km² and is marked by the Survey of India toposheet numbers F45P/2, F45P/3 and F45P/6. The area lies between 21°31'N to 21°42'N and 87°07'E to 87°22'E. The administrative blocks such as Jaleswar to the north, Bhograi to the east, Basta and Balasore sadar to the west, and the Bay of Bengal to the south (CGWB, 2016). The location map of the study area is shown in Fig. 1. The average daily temperature in this region is around 32.3 °C in summer and 16.5 °C in winter. The average precipitation in the pre-monsoon period in 2022 is estimated to be approximately 1429.21 mm. Sample location map of the study area is shown in Fig. 2.

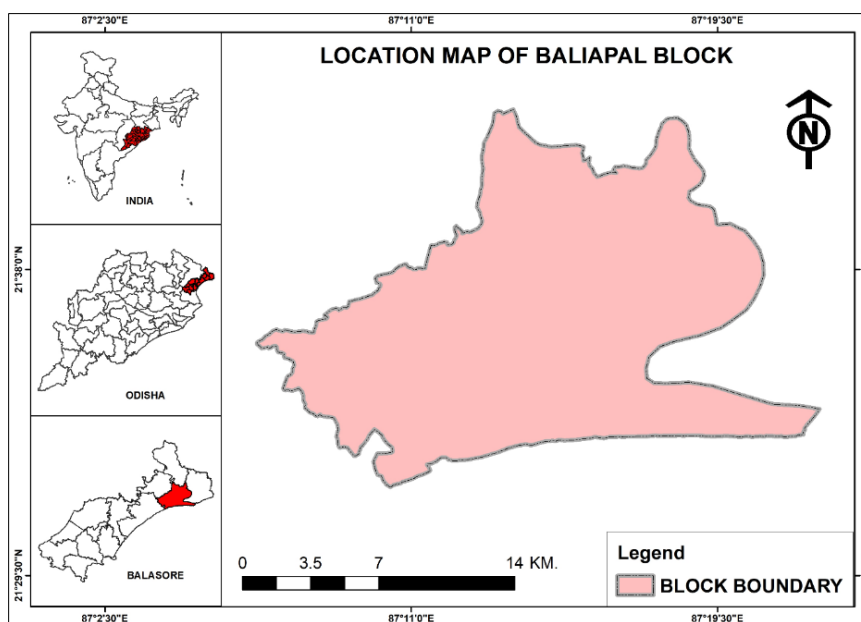


Fig 1: Location map of the study area.

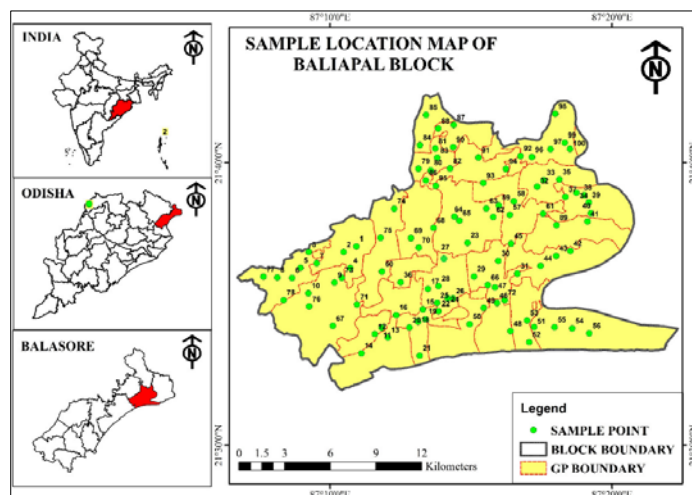


Fig 2: Sample Location map of the study area

2.2 Sample collection and physicochemical analysis

A total of 100 groundwater samples were collected from tube wells in various parts of the study area in the premonsoon of 2022 using the analysis method recommended by American Public Health Association (APHA), 2012. Before collecting the water samples, the tube wells were pumping for five to ten minutes for removing any stagnant water. Subsequently, 1 litre polyethylene bottles with a sterilized and pre-cleaned capacity stored the water samples and stored at 4 °C for analysis using standard procedures recommended by APHA. Every bottle had an accurate label with pertinent information written on it. At the sample collection site, measurements of pH, TDS, and temperature were made by using a portable device (Hanna HI 9811- 5). A GPS device is used to determine the coordinates of the sample. Sample bottles were filled with sample water. Wear gloves if collecting samples by hand. In the study region, most of the hand pumps used for irrigation and drinking were less than 40 meters deep.

The analysis of all chemical parameters was carried out in accordance with the procedures outlined by APHA (2012). Sulfate (SO_4^{2-}) and nitrate (NO_3^-) concentrations were quantified using a UV-Visible spectrophotometer. Chloride (Cl^-) content was determined by the argentometric titration method employing silver nitrate (AgNO_3). Total hardness (TH, expressed as CaCO_3) and calcium ion (Ca^{2+}) concentrations were measured through EDTA titration. Magnesium hardness (MgH) was obtained by calculating the difference between total hardness and calcium hardness ($\text{MgH} = \text{TH} - \text{CaH}$). The concentration of magnesium ions (Mg^{2+}) was then estimated from the magnesium hardness value using the equivalent weight of magnesium and the normality of the EDTA solution.

The concentrations of total hardness (TH, expressed as CaCO_3) and calcium (Ca^{2+}) were determined using the standard EDTA complexometric titration method. Sodium (Na^+) and potassium (K^+) concentrations were quantified with a Systronics flame photometer following standard analytical procedures. Bicarbonate (HCO_3^-) was analyzed by acid titration using sulfuric acid (H_2SO_4) as the titrant and methyl orange as the indicator.

Fluoride (F^-) concentration was measured using an ion-selective electrode (ISE) method employing an Orion fluoride electrode coupled with an Orion electrometer, in accordance with previously reported procedures (Adimalla, 2019; Rahman, 2021)^[1, 21]. Calibration of the instrument was

performed using a series of fluoride standards (0.1–10 mg L^{-1}) prepared by serial dilution of a 100 mg L^{-1} sodium fluoride stock solution. Prior to measurement, 2 mL of Total Ionic Strength Adjustment Buffer (TISAB III) was added to 20 mL of each sample to maintain a constant ionic strength and minimize potential interference during fluoride determination.

2.3 Statistical Method

Groundwater quality evaluation for irrigation purposes involves the systematic analysis of hydrochemical characteristics using statistical techniques. Water samples are collected from selected wells distributed across the study area to represent the spatial variability of groundwater conditions. The collected samples are examined for important physicochemical parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), major cations such as sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), major anions including chloride (Cl^-), sulfate (SO_4^{2-}), and bicarbonate (HCO_3^-), as well as trace metals where necessary. Descriptive statistical tools are applied to summarize the dataset by determining measures such as average values, standard deviations, and observed ranges. In addition, correlation analysis is used to investigate the degree of association among water quality variables and to identify factors influencing groundwater chemistry. The interpretation of these statistical results helps determine the suitability of groundwater for irrigation and supports the development of appropriate water management practices. Such an approach provides a reliable framework for understanding groundwater quality and contributes to the sustainable utilization of water resources in agricultural regions.

3. Results and Discussion

3.1 Hydrochemical results

The hydrochemical characteristics of the groundwater samples are presented in Table 1. The pH values range from 6.16 to 7.78, with a mean value of 7.13, indicating that the groundwater is generally neutral to slightly alkaline in nature. Total Dissolved Solids (TDS) concentrations vary between 267.52 and 1236.48 mg/L, with an average of 556.55 mg/L, suggesting that the groundwater predominantly falls within the freshwater category. Electrical conductivity (EC), which reflects the concentration of dissolved ions and the salinity

status of water, ranges from 418 to 1932 $\mu\text{mho/cm}$, with a mean value of 869.61 $\mu\text{mho/cm}$. Elevated EC values may be attributed to the dissolution and leaching of minerals from aquifer materials. Total hardness (TH) values range from 103.98 to 379.99 mg/L, with an average of 219.86 mg/L, indicating that the groundwater is generally hard to very hard in character. Fluoride concentrations vary from 0.04 to 0.99 mg/L, with a mean concentration of 0.40 mg/L, which may

be associated with the dissolution of fluoride-bearing minerals present in the alluvial deposits. Nitrate concentrations range between 1.06 and 86.50 mg/L, averaging 11.77 mg/L. The occurrence of elevated nitrate levels at certain locations is likely linked to intensive agricultural practices and the excessive application of nitrogen-based fertilizers.

Table 1: Statistical analysis of the data

Parameter	Min	Max	Mean	Std.dev
pH	6.16	7.78	7.13	0.23
EC	418	1932	869.61	311.99
TDS	267.52	1236.48	556.55	199.67
TH	103.98	379.99	219.86	65.28
Ca ²⁺	25.65	86.65	44.98	16.98
Mg ²⁺	9.23	48.25	26.19	8.43
Na ⁺	42.61	251.72	100.86	43.80
K ⁺	3.42	135.24	16.56	17.32
CO ₃ ²⁻	0	0	0	0
HCO ₃ ⁻	102	422	250.64	66.28
Cl ⁻	73.98	419.87	152.58	60.19
SO ₄ ²⁻	7.74	149.64	44.56	33.74
F ⁻	0.04	0.99	0.40	0.27
NO ₃ ⁻	1.06	86.5	11.77	17.06
PO ₄ ³⁻	0.01	1.21	0.07	0.13

All the samples are expressed in mg/l except pH and EC

3.2 Sodium Adsorption Ratio (SAR)

The Sodium Adsorption Ratio (SAR) is a widely used index for assessing the suitability of groundwater for irrigation. It indicates the relative concentration of sodium ions in comparison to calcium and magnesium ions and is used to evaluate the potential impact of irrigation water on soil structure, permeability, and infiltration characteristics (Mahanta, 2017; Mahanta *et al.*, 2018; Mahanta & Goswami, 2024) [16, 17, 18]. The results of the present study reveal that all 100 groundwater samples fall within the excellent category based on SAR values. This classification suggests that the groundwater poses no sodium-related hazard to agricultural soils and is therefore considered suitable for irrigation purposes.

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{(\text{Ca}^{2+} + \text{Mg}^{2+})/2}}$$

All values are expressed in meq/L.

The US Salinity Laboratory (USSL) diagram is widely used to evaluate the suitability of water for irrigation by assessing both salinity and sodium hazards. In this classification, the Sodium Adsorption Ratio (SAR) is plotted against Electrical Conductivity (EC) (Fig. 3). The results indicate that 47% of the groundwater samples fall within the C2S1 category, while 41% belong to the C3S1 category. Additionally, 10% of the samples are classified as C3S2, whereas only 1% each fall under the C2S2 and C4S3 categories. The predominance of samples in the C2S1 and C3S1 classes suggests low sodium hazard with medium to high salinity levels, making them generally suitable for irrigation under appropriate management practices. Overall, the groundwater quality of the study area is considered favourable for agricultural use.

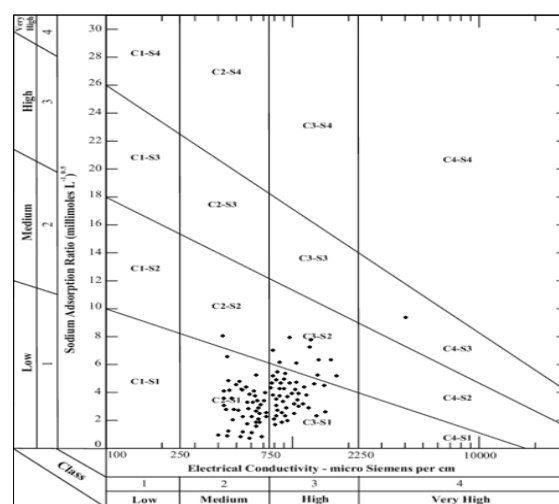


Fig 3: US salinity diagram of the sample

3.3 Sodium Percentage (Na %)

Percent Sodium (%Na) is a widely used indicator for evaluating the suitability of water for irrigation. It expresses the proportion of sodium ions relative to the total concentration of major cations present in water and is useful for assessing the potential impact of sodium on soil permeability, structure, and agricultural productivity (Mahanta *et al.*, 2018; USEPA, 2014) [17]. The analysis of groundwater samples from the study area revealed that 12% of the samples fall within the good category, 71% are classified as permissible, and 17% are categorized as doubtful for irrigation use. These results indicate that the majority of the groundwater samples are suitable for irrigation, although a considerable proportion may require careful management to prevent adverse effects on soil properties and crop growth.

$$\%Na = \frac{(Na^+ + K^+) \times 100}{Ca^{2+} + Mg^{2+} + Na^+ + K^+}$$

All values are expressed in meq/L.

The Wilcox diagram (Wilcox, 1948) [26] is widely employed to evaluate the suitability of groundwater for irrigation by relating sodium percentage (Na %) to electrical conductivity (EC) (Fig. 4). Based on these parameters, irrigation water is categorized into five classes: *excellent to good*, *good to permissible*, *permissible to doubtful*, *doubtful to unsuitable*, and *unsuitable*. Elevated sodium concentrations in irrigation water may adversely affect soil structure by promoting soil dispersion, which reduces permeability and water infiltration, ultimately impacting crop productivity. Therefore, the assessment of sodium percentage is essential for sustainable agricultural water management (Jaishi *et al.*, 2024) [11]. The results of the present study indicate that 46% of the groundwater samples belong to the excellent category, 49% fall within the good category, 4% are classified as permissible, and only 1% are categorized as doubtful. These findings suggest that the majority of the groundwater samples are suitable for irrigation purposes with minimal sodium-related hazards.

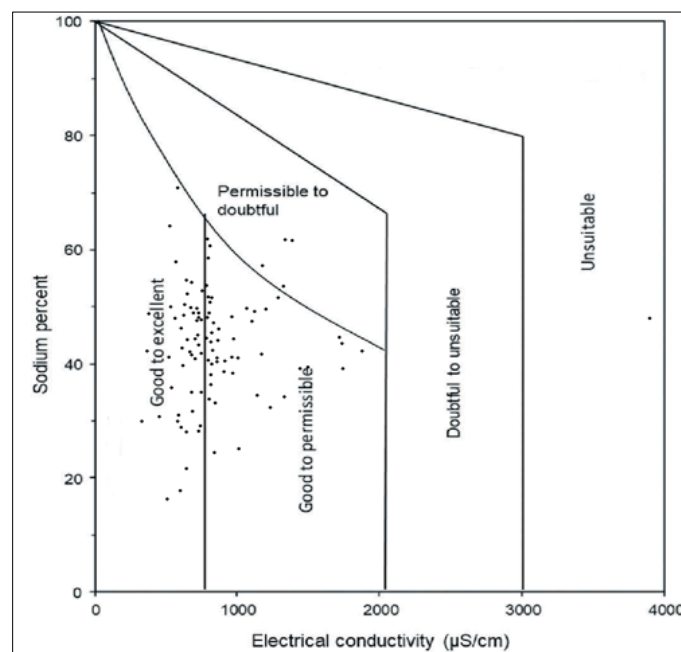


Fig 4: Wilcox diagram of the sample

3.4 Permeability Index (PI)

The Permeability Index (PI) is an important criterion for evaluating the suitability of groundwater for irrigation, as it reflects the influence of dissolved ions on soil permeability and the long-term maintenance of soil structure. This index helps assess the potential impact of irrigation water on soil degradation, particularly due to the presence of sodium and bicarbonate ions. The calculated PI values indicate that groundwater in the study area is generally appropriate for irrigation purposes. Based on the classification results, 48% of the samples fall within the suitable category, while the remaining 52% are classified as good. These findings suggest that the majority of groundwater samples are unlikely to adversely affect soil permeability and can be safely utilized for agricultural irrigation.

$$PI = \frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{2+} + Mg^{2+} + Na^+} \times 100$$

Here all values are in meq/L.

According to the Permeability Index (PI) classification proposed by Doneen (1964) [7], the irrigation suitability of groundwater samples was evaluated and illustrated in Fig. 5. The results indicate that the majority of the samples fall within Class II (permissible) and Class III (unsuitable) categories, while only one sample is classified under Class I (good) for irrigation use. The Permeability Index reflects the potential impact of irrigation water on soil permeability, which is primarily governed by the concentrations of sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and bicarbonate (HCO_3^-) ions. Elevated levels of these constituents can alter soil structure and infiltration characteristics, thereby influencing the long-term suitability of water for agricultural applications. The Permeability Index (PI) is an important parameter for evaluating the suitability of irrigation water, as it reflects the potential influence of water quality on soil permeability. Elevated PI values may alter soil physical properties, affecting water movement, infiltration capacity,

and drainage conditions. Continuous monitoring of PI is therefore essential for sustainable agricultural management, as adverse changes in soil permeability can reduce crop

productivity and increase the risk of surface runoff and soil degradation.

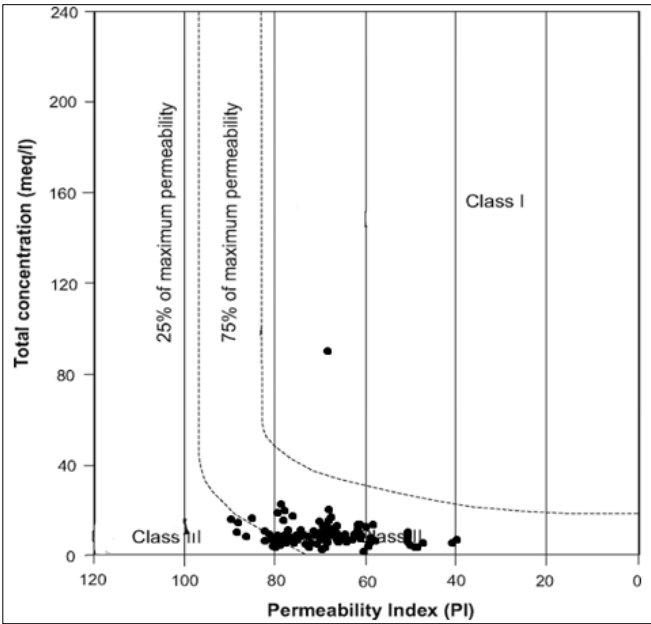


Fig 5: Permeability index diagram of the sample

3.5 Residual Sodium Carbonate (RSC)

Residual Sodium Carbonate (RSC) is an important parameter for assessing irrigation water quality, reflecting the potential for sodium and carbonate accumulation in the soil, which may impact soil structure and crop health. RSC is calculated based on the concentrations of sodium, calcium, and magnesium in the water. Elevated RSC values indicate a higher risk of sodium toxicity and soil dispersion, making it a critical factor in evaluating water for irrigation purposes.

3.6 Residual Sodium Carbonate (RSC) is a key indicator used to evaluate the suitability of water for irrigation. It measures the excess concentration of carbonate and bicarbonate ions relative to calcium and magnesium ions, which can influence soil properties and crop productivity. High RSC values promote the precipitation of calcium and magnesium, resulting in a relative increase in sodium concentration in the soil. This process can adversely affect soil structure, reduce permeability, and hinder water infiltration. Consequently, irrigation water with elevated RSC levels may contribute to sodium accumulation and soil degradation, making RSC an essential criterion for assessing irrigation water quality and its long-term impact on agricultural sustainability.

The formula of RSC is given below;

$$RSC = (HCO_3^- + Co_3^{2-}) - (Ca^{2+} + Mg^{2+})$$

All values are reported in meq/L.

The analysis of RSC values indicates that 97% of the groundwater samples have values below 1.25 meq/L, classifying them as suitable for irrigation use. Approximately 3% of the samples fall within the range of 1.25–2.5 meq/L, indicating a moderate level of suitability for irrigation. No sample recorded an RSC value greater than 2.5 meq/L, the threshold generally considered unsuitable for agricultural irrigation. These findings suggest that the majority of the

groundwater in the study area can be safely utilized for irrigation without posing significant risks to soil quality (Table 2).

Table 2: Residual Sodium Carbonate (RSC)

Classification Of Groundwater Based On RSC		
RSC	Category	No of Samples
< 1.25	Suitable	97
1.25-2.5	Moderate	03
> 2.5	Unsuitable	-

3.7 Kelley’s Ratio (KR)

Kelley’s Ratio (KR), proposed by Kelly (1940), is a widely used index for assessing the suitability of groundwater for irrigation. It evaluates the relative abundance of sodium ions with respect to calcium and magnesium ions in water. The ratio is determined by dividing the concentration of sodium (Na⁺) by the combined concentrations of calcium (Ca²⁺) and magnesium (Mg²⁺). Higher KR values indicate a greater sodium hazard, which may adversely affect soil structure and crop productivity, whereas lower values suggest better irrigation suitability (Baruah *et al.*, 2024)^[3].

$$KR = \frac{Na^+}{Ca^{2+} + Mg^{2+}}$$

Here all values are in meq/l.

Kelley’s Ratio (KR) is widely used to evaluate the suitability of water for irrigation by assessing the relative concentration of sodium with respect to calcium and magnesium ions. A KR value less than 1 indicates that sodium levels are comparatively low, making the water suitable for irrigation. Conversely, values greater than 1 reflect sodium dominance, which may promote soil dispersion, reduce permeability, and adversely affect crop productivity. Therefore, KR serves as an important indicator of the potential impact of irrigation water on soil quality and agricultural sustainability. In the

present study, 50% of the groundwater samples exhibited KR values below 1.0, indicating suitability for irrigation, whereas the remaining 50% showed KR values greater than 1.0, suggesting potential unsuitability due to sodium-related hazards (Table 3).

Table 3: Kelly's Ratio (KR)

Classification Of Groundwater Based On KR		
KR	Category	No of Samples
< 1	Good	50
> 1	Unsuitable	50

3.8 Potential Soil Salinity (PS)

Potential Salinity (PS) is an important criterion for assessing the suitability of water for irrigation. According to Doneen (1964)^[7], the salinity hazard of irrigation water is influenced not only by the concentration of dissolved salts but also by several other factors that affect its overall suitability for agricultural use. Potential Salinity is expressed in milliequivalents per liter (meq/L) and is determined by the combined contribution of chloride (Cl⁻) ions and one-half of the sulfate (SO₄²⁻) concentration. This index is widely used to evaluate the long-term impact of irrigation water on soil salinity and crop productivity (Haque *et al.*, 2021; Elumalai *et al.*, 2020)^[8, 10].

$$PS = Cl^{-} + \frac{1}{2} SO_4^{2-}$$

All values are given in meq/L.

The analysis revealed that 69% of the groundwater samples exhibited Potential Salinity (PS) values below 5, classifying them as *excellent to good* for irrigation purposes. Additionally, 28% of the samples had PS values ranging from 5 to 10, indicating a *good to injurious* category for irrigation. Only 3% of the samples recorded PS values greater than 10, placing them in the *injurious to unsatisfactory* category. These results suggest that the majority of the groundwater samples are suitable for irrigation, although a small proportion may pose salinity-related risks to soil and crop productivity (Table 4).

Table 4: Potential Soil Salinity (PS)

Classification Of Groundwater Based On Ps		
PS	Category	No of Samples
< 5	Excellent to Good	69
5-10	Good to Injurious	28
> 10	Injurious to Unsatisfactory	03

3.9 Magnesium Ratio (MR)

The Magnesium Ratio (MR) is an important index used to evaluate the suitability of groundwater for irrigation. It reflects the relative concentration of magnesium in comparison to calcium and helps determine the potential impact of irrigation water on soil quality and crop productivity. Excessive magnesium in irrigation water can adversely affect soil structure by increasing alkalinity and

reducing soil permeability, thereby limiting water infiltration and nutrient availability to plants. Consequently, elevated MR values may lead to reduced crop growth and yield. Assessment of MR is essential for sustainable agricultural management, as it provides valuable information on soil fertility and nutrient balance. High MR values may indicate a potential risk of magnesium-induced toxicity and deterioration of soil physical properties. Knowledge of MR also assists farmers in selecting crops that are more tolerant to elevated magnesium concentrations and in formulating appropriate fertilization and irrigation strategies. Regular monitoring of MR can help prevent soil degradation, optimize water management practices, and support long-term agricultural productivity and sustainability.

$$MR = \left[\frac{Mg^{2+}}{Mg^{2+} + Ca^{2+}} \right] \times 100$$

All values are expressed in meq/L.

The Magnesium Ratio (MR) assessment revealed that 54% of the groundwater samples exhibited values below 50, indicating their suitability for irrigation. Conversely, 46% of the samples recorded MR values greater than 50, suggesting potential limitations for irrigation use due to the adverse effects of excess magnesium on soil quality and crop productivity (Table 5).

Table 5: Magnesium ratio (MR)

Classification Of Groundwater Based On Mr		
MR	Category	No of Samples
< 50	Suitable	54
> 50	Unsuitable	46

Gibbs Diagram (Mechanism controlling groundwater quality)

Gibbs (1970) provided a schematic for understanding the mechanism of major ion chemistry in groundwater samples. Grapher software was used to draw Gibbs plot. The Gibbs diagram explains the three different fields: rock dominance, evaporation dominance, and precipitation dominance (Pandey *et al.*, 2023)^[19].

The following formula was used to get the Gibbs ratio:

$$\text{Gibbs ratio 1 (anion)} = \frac{Cl}{(Cl + HCO_3)}$$

$$\text{Gibbs ratio 2 (cation)} = \frac{Na}{(Na + Ca)}$$

The concentration of all ions was taken in meq L⁻¹.

Gibbs plots (cation plots and anion plots shown in Fig. 6) determined the hydrogeochemistry of water. The Gibbs plot shows that most of the samples are "rock-dominated", illustrated that the local rocks in the area control the chemical composition. Therefore, the geogenic agents of the study area also affect the increase in nitrate concentration (Pal *et al.*, 2024)^[18]

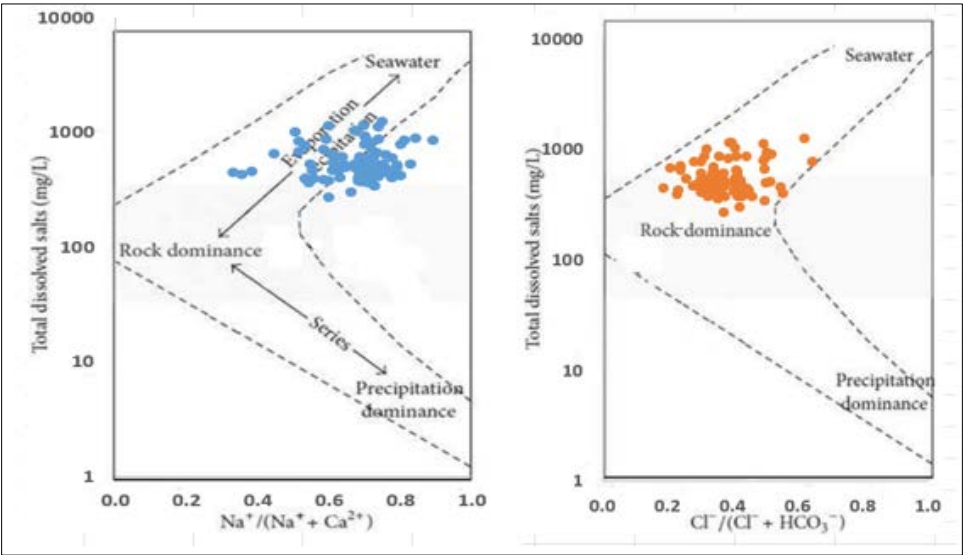


Fig 6: Gibbs Diagram of the study area

Piper Diagram (Geochemical evaluation of groundwater)
To understand the hydrochemical facies, different water types, and geochemical evolution of the region, the Piper (1944)^[20] diagram was plotted (Li *et al.*, 2024). According to

the classification, the predominant water types are in "Field 5" (magnesium bicarbonate type), "Field 9" (mixed type), "Field 7" (sodium chloride type) and "Field 8" (sodium bicarbonate type) which is depicted in Fig. 7.

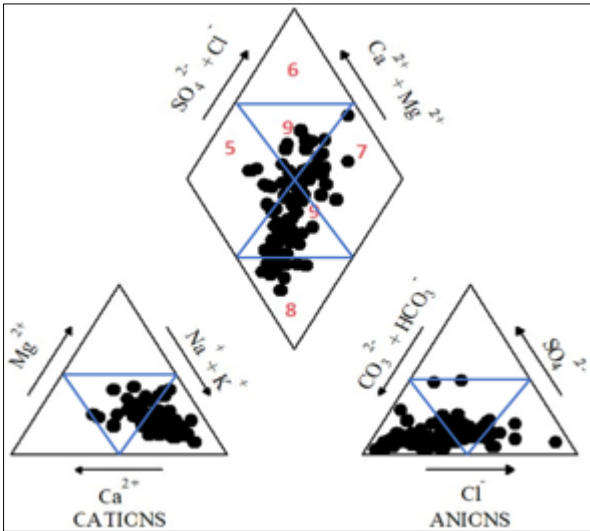


Fig 7: Piper Diagram of the study area

Correlation Matrix

Correlation analysis is an important statistical tool used to evaluate the relationships among different water quality parameters and to understand their combined influence on irrigation suitability. It helps identify the degree of association between hydrochemical constituents, thereby providing insights into the geochemical processes governing groundwater quality. The correlation matrix among Sodium Adsorption Ratio (SAR), Permeability Index (PI), Residual Sodium Carbonate (RSC), Potential Salinity (PS), Kelley's Ratio (KR), Percentage Sodium (%Na), and Magnesium Ratio (MR) is presented in Table 6. The results indicate a strong positive correlation between SAR and KR ($r = 0.92$), as well as between SAR and %Na ($r = 0.86$), suggesting that sodium concentration plays a significant role in controlling these irrigation water quality indices. Similarly, KR exhibits a strong positive correlation with %Na ($r = 0.93$), reflecting their common dependence on sodium content. A weak positive correlation is observed between PI and PS ($r = 0.15$),

indicating a limited association between soil permeability characteristics and salinity hazards. In contrast, RSC shows a weak negative correlation with PS ($r = -0.14$), suggesting a slight inverse relationship between carbonate hazard and potential salinity in the studied groundwater.

Table 6: Correlation of water quality

	SAR	PI	RSC	KR	Na%	PS	MR
SAR	1						
PI	0.653	1					
RSC	0.383	0.799	1				
KR	0.925	0.843	0.556	1			
Na%	0.863	0.887	0.583	0.938	1		
PS	0.791	0.157	-0.148	0.548	0.530	1	
MR	-0.024	-0.012	0.108	-0.066	0.024	0.003	1

4. Conclusion

The present groundwater investigation highlights the hydrochemical characteristics and governing processes

influencing groundwater quality in the study area. Elevated chloride concentrations observed in certain locations may adversely affect aquatic ecosystems, contribute to vegetation stress, and cause corrosion and scaling in household appliances. Comprehensive hydrogeochemical assessments, including Piper and Gibbs diagrams, correlation analysis, and statistical evaluations, were employed to identify the factors controlling groundwater chemistry and quality. The major findings and conclusions derived from the study are summarized below.

- From piper diagram, the dominant hydrochemical facies are $\text{Na}^+\text{-K}^+\text{-HCO}_3^-$ type followed by $\text{Ca}^{2+}\text{-Mg}^{2+}\text{-HCO}_3^-$ type.
- The average pH of the groundwater is 7.13, indicating that the water is slightly alkaline in nature. The mean Total Hardness (TH) is 219.86 mg/L, suggesting that most groundwater samples fall within the moderately hard to hard water category. Chloride (Cl^-) concentrations range from 73.98 to 419.87 mg/L, with relatively higher concentrations observed in the eastern and southern parts of the study area. Elevated chloride levels in these zones may be attributed to factors such as mineral dissolution, agricultural return flow, domestic wastewater infiltration, and evaporation processes. According to the standards prescribed by the Bureau of Indian Standards (BIS), only 1% of the groundwater samples exceed the permissible chloride limit, indicating that the majority of the samples remain within acceptable limits for drinking purposes, while the affected locations may require periodic monitoring and management due to their potential salinity risk.
- In permeability index diagram all the samples belong to class -II (permissible) and III (unsuitable) type except 1 sample, which lie class-I (good) for irrigation.
- The statistical analysis revealed significant relationships among the irrigation water quality indices. Sodium Adsorption Ratio (SAR) exhibited a strong positive correlation with both Kelley's Ratio (KR) and percentage sodium (%Na), indicating that an increase in sodium concentration relative to calcium and magnesium leads to higher SAR values. Similarly, KR showed a strong positive correlation with %Na, reflecting their common dependence on sodium content in groundwater. The Permeability Index (PI) demonstrated a weak positive correlation with Potential Salinity (PS), suggesting a limited influence of salinity on soil permeability characteristics. In contrast, Residual Sodium Carbonate (RSC) exhibited a negative correlation with PS, indicating that higher carbonate and bicarbonate concentrations are generally associated with lower potential salinity levels. These correlations provide valuable insights into the hydrochemical processes controlling groundwater quality and its suitability for irrigation purposes.
- From Gibbs diagram it concluded that all samples belong to rock dominance type.
- The area primarily consists of oxidized sand, silt, gravel and clay, interspersed with calcium nodules. It features diverse geomorphology, including small water bodies, rivers, active flood plains, older alluvial plains, older coastal plains, older flood plains, young alluvial plains, and younger coastal plains. Most of the area is covered with dense vegetation. Chloride dissolution in this region is significantly influenced by the sea water intrusion.

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