

Research Article

Evaluation of saline water intrusion along the coastal aquifers of Vadakara, Kerala, South India, using hydrogeochemistry and GIS

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Abstract

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The hydrogeochemical characteristics and evaluation of saline water intrusion of shallow groundwater in the coastal aquifers of Vadakara have been investigated using geochemical analysis and spatial interpolation techniques. Major ion analysis of groundwater samples was employed to identify saltwater intrusion status. The major ions dissolved in water are Ca, Mg, Na, K, Cl, HCO₃, and SO₄. Groundwater zones in coastal areas have to be delineated in terms of quality. To identify the origin of saline groundwater in the coastal reaches of Vadakara Taluk, Kozhikode district, Kerala, six different major ionic ratios viz. Na/Cl, (Ca+Mg)/Cl, K/Cl, SO₄/Cl, Na/Ca, and Ca/SO₄ and Base Exchange Index (BEX) were computed from physio-chemical analysis of open wells in the study area. Groundwater aquifers, which have a direct connection to tide-influenced river stretches and the sea, are more susceptible to salinization due to seawater intrusion, according to the spatial representation of the ionic ratios.

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Introduction

Water is vital for the existence of humanity, agriculture, and the industrial sector. Groundwater is the main source of water for domestic purposes in Kerala, and dug wells are the major groundwater extraction structures (Sreeja et al., 2015). It is a crucial source of freshwater for more than two billion individuals globally (Gimenez and Morell, 1997; Todd and Mays, 2005) and is facing escalating challenges due to population growth and enhanced living standards. These challenges encompass the spatial and temporal fluctuations in precipitation, excessive exploitation resulting in diminished river discharges and intrusion of saltwater in coastal regions, as well as the degradation of water quality due to pollutants.

The sustainable management of water necessitates a profound comprehension of the intricate interactions among geology, topography, and climate. A fresh perspective is imperative, perceiving groundwater as a communal asset and taking into

account diverse hydrogeological contexts and socio-economic conditions. This perspective mandates revisions in resource evaluation, delineation of aquifers, monitoring of quality, and structures of governance.

Coastal aquifers encounter distinct obstacles, with the infiltration of seawater representing a significant environmental apprehension (Werner et al., 2013). Impacts of climate change, such as elevated sea levels and prolonged continental dry spells, influence the interface between fresh groundwater and seawater (Ferguson and Gleeson, 2012). Grasping the chemical mechanisms causing salinity is pivotal for the efficient management of coastal aquifers (Post, 2005).

Given that approximately half of the global population resides in coastal regions, a figure projected to escalate to 75% within this century (Finkl, 1994), numerous research endeavors have concentrated on seawater intrusion. The extraction of groundwater in these regions can result in diminishing water tables, thus facilitating the migration of saline water (Kumar

et al., 2015). The degree of intrusion is contingent upon geological configurations, hydraulic gradients, rates of withdrawal, and replenishment (Choudhury et al., 2001). Recognizing the dispersion and source of saline waters is imperative for regulating extraction and mobility within coastal aquifers.

The present study aimed to evaluate the saline water intrusion status of the coastal reaches of Vadakara Taluk, Kozhikode District, Kerala State, South India.

Materials and Methods

Study area

Vadakara, situated at 11.60' N-75.58' E in Kozhikode district, Kerala, India, is a coastal Taluk (Figure 1) with an average elevation of 15 m (49 ft) (KSLUB, 2021). Encompassing an area of 576 km², it comprises 27 panchayaths (local bodies) and is delineated by the Mahe River in the north and the Kuttiady River in the south (WRD, GoK, 2020). Vadakara Taluk, bordering Wayanad district along the Western Ghats section and bordered by the Arabian Sea in the west, witnesses the

confluence of the Kuttiady River with the sea to the south, resulting in the formation of small islands and sandbanks near the river mouth.

The geological composition of the area includes basic rocks, charnockite group of rocks, migmatite complex, and Tertiary sediments (GSI, 2018). Within the hydrological context, a well-developed canal system in the Kuttiady River basin facilitates aquifer recharge through seepage, ensuring a sustainable water supply (CGWB, 2019). Groundwater is present in weathered, fractured, crystalline, and alluvial formations, exhibiting phreatic conditions in weathered formations and semi-confined conditions in deep fractures. Groundwater storage and movement are predominantly regulated by the fracture system (GWD, GoK, 2020). The existing climatic conditions in the region are defined by a humid climate, with a hot season experienced from March to May, reaching its highest temperatures in May. High moisture levels are observed in the coastal regions, with the main wet season happening during the southwest monsoon (June to September) and the northeast monsoon following thereafter (second half of October through November) (IMD, 2022).

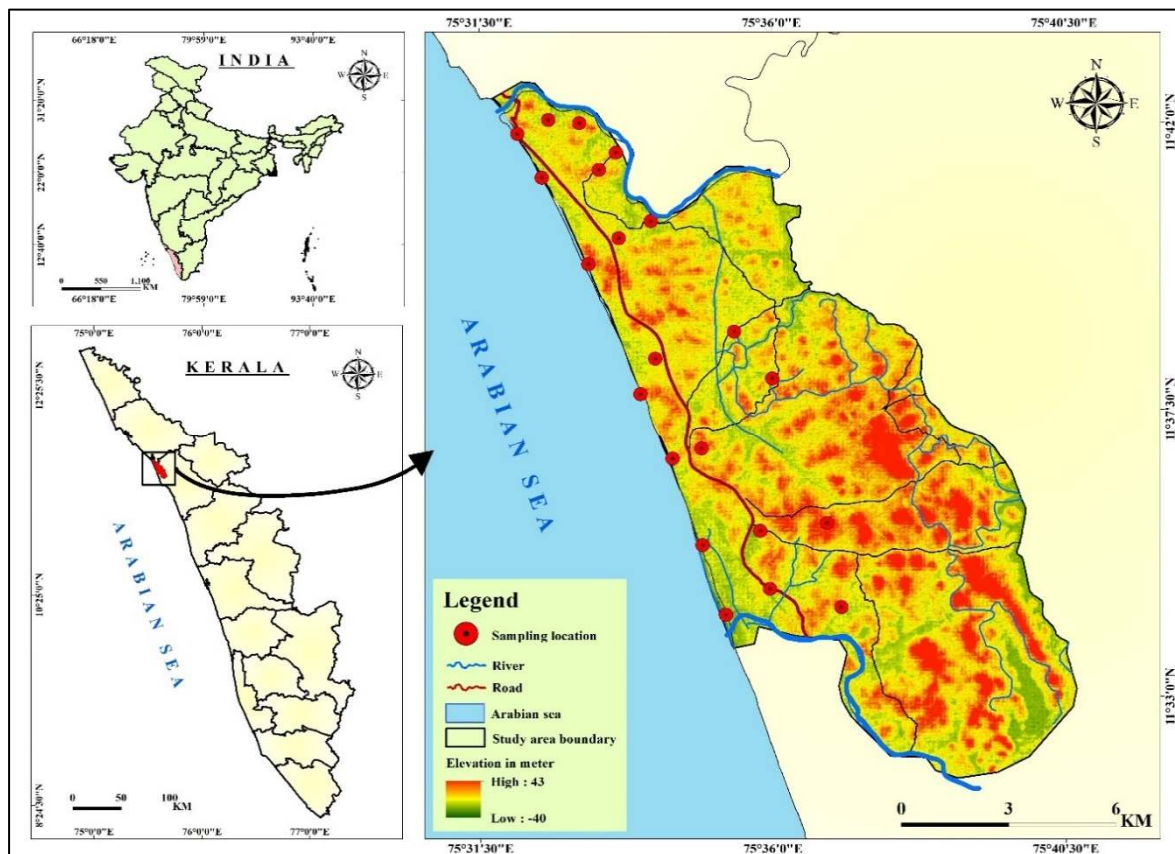


Figure 1. Study area with sampling points.

Detailed field investigations were carried out to choose representative groundwater and river water sampling locations within the research area. A comprehensive format for well inventory was established to gather

pertinent hydrogeological data, encompassing physical dimensions of wells, depth to water level, total well depth, well classification, and seasonal variability (Todd and Mays, 2005). Water samples

were obtained in 1-liter plastic containers, adhering to appropriate cleaning protocols as indicated by APHA (2017) guidelines.

The sampling approach entailed the collection of 21 samples of open well water during the pre-monsoon period within a proximity of 1-7 km from the coastline. These wells, mainly utilized for residential purposes, varied in depth from 2 to 13 m, with an average depth of 6.816 m. Furthermore, 14 samples of river water were acquired. A clustered yet networked technique was employed to ascertain the rates of saline water intrusion as the distance from both the river and sea increased (Freeze and Cherry, 1979).

A portable multi-analyzer kit was used for on-site analysis of pH, electrical conductivity (EC), salinity, and total dissolved solids (TDS). All groundwater quality parameters underwent laboratory analysis in accordance with the standards outlined by APHA (2017). This encompassed titration methodologies for total alkalinity and hardness, EDTA titrimetric technique for calcium, argentometric titration for chloride, and spectrophotometric procedures for nitrate, iron, sulfate, and phosphate. Sodium and potassium levels were determined by employing a flame photometer.

The data examination commenced with an evaluation of data precision utilizing the anion-cation balance methodology (Domenico and Schwartz, 1997), which is expressed as Equation 1:

$$CBE = \frac{\sum|Cl^-| - \sum|A^+|}{\sum|Cl^-| + \sum|A^+|} \times 100 \quad (1)$$

The Charge Balance Error (CBE) was computed, with the majority of samples falling within the acceptable $\pm 5\%$ threshold. Major ion concentrations were standardized from mg/L to meq/L to nullify the impact of charges. Seven unique ionic ratios, like Na/Cl, Mg/Cl, Ca/Mg, K/Cl, SO_4/Cl , Na/Ca, and Cl/HCO_3^- , were identified to delineate saline pollution in coastal groundwater, utilizing techniques from various research (Nadler et al., 1981; Rosenthal, 1988; El Moujabber et al., 2006; Lee, 2007; Klassen and Allen, 2017).

Base Exchange Indices (BEX) developed by Stuyfzand (1989) were also used to distinguish if an aquifer is undergoing salinization or freshening. According to Klassen and Allen (2017), the best index for a dolomite-free aquifer system (Stuyfzand, 1989) is BEX, given as Equation 2:

$$BEX = Na + K + Mg - 1.0716 Cl \text{ (meq/L)} \quad (2)$$

Thus, BEX values were calculated for all the samples. A negative BEX value represents salinization, and a positive BEX represents freshening, whereas a BEX with a value of zero represents no base exchange.

Secondary data obtained from various sources was acquired for the purpose of categorizing the study area. The topographic data concerning the study region was collected from the Survey of India (SOI)

toposheets. The software utilized in this research comprises Aqua for the interpretation of hydrochemical aspects, as well as ArcGIS 10.8.2, an open-source GIS tool, for geospatial analysis. Additionally, the Inverse Distance Weighted (IDW) technique from the Geostatistical Analyst extension in the ArcGIS 10.8.2 software was utilized to perform weighted interpolation of the attributed data, allowing for the estimation of spatial variability in ionic concentration throughout the study area.

This all-encompassing methodology of data collection, analysis, and interpretation establishes a robust basis for comprehending the hydrogeochemical processes and the potential intrusion of seawater in the coastal aquifer system under scrutiny.

Results and Discussion

Evaluation of water quality parameters

Table 1 illustrates the physicochemical analysis of water quality parameters. Table 2 provides a summary of the measured water quality parameters used in this study. Chloride concentrations range from 11.529 to 871.42 mg/L, with the highest levels observed in groundwater samples taken within a 3 km radius from the coastline and near the Mahe River channel. The presence of chloride ions serves as a critical parameter in identifying seawater intrusion, owing to its conservative behavior.

Elevated levels of chloride are a significant sign of seawater, constituting over 55% of the total dissolved solids in seawater (Nadler et al., 1981). Nevertheless, sources other than seawater, such as septic systems, animal manure, and sea spray, can contribute to heightened chloride concentrations in groundwater. A clear link ($r = 0.97$) has been established between chloride levels and electrical conductivity (EC) values (Figure 2), showing that chloride ions influence the electrical conductance of coastal groundwater. The EC ranges from 82 to 3,160 $\mu\text{S}/\text{cm}$, with an average of 691.81, and approximately 19% of all sampled water exhibits an EC exceeding 1,000 $\mu\text{S}/\text{cm}$. An EC value of 1,000 $\mu\text{S}/\text{cm}$ or higher signifies the intrusion of seawater (Gimenez and Morell, 1997; Kim et al., 2003; Kim et al., 2019).

The amounts of the major ions (Na^+ , Ca^{2+} , Mg^{2+} , K^+ , SO_4^{2-} , NO_3^- , HCO_3^-) and electrical conductivity (EC) plotted in relation to chloride can be observed in Figure 2 next to their respective coefficient of determination (R^2) for the least squares linear regression line depicted on each plot. The values of R^2 vary from 0.0001 to 0.9843, as illustrated in Figure 2. The strong linear coefficient of determination noted between chloride and the other major ions (Na^+ , Ca^{2+} , K^+ , SO_4^{2-}) could potentially be attributed to the mixing of freshwater with a single-brine chemical composition (Stoessell, 1997). Conversely, weak coefficient of determination values was observed for

nitrate, phosphate, and bicarbonate ion levels; hence, their origins may differ from that of chloride, suggesting a distinct source, such as a single brine

solution or seawater, contributing to the saline contamination. Ion exchange processes arise, as does the coastal aquifer matrix.

Table 1. Physico-chemical analysis of water quality parameters.

Parameters	pH at 25 °C	Color, Hazen	Turbidity, NTU	Total Dissolved Salts, mg/L	Total Hardness as CaCO ₃ , mg/L	Total Alkalinity as CaCO ₃	Chloride as Cl ⁻ , mg/L	Sulfate as SO ₄ , mg/L	Calcium as Ca, mg/L	Magnesium as Mg, mg/L	Iron as Fe, mg/L	Sodium, mg/L	Potassium, mg/L	Nitrate As N mg/L	Phosphate P mg/L	Salinity ppt	Electrical Conductivity (us/cm)
GW 1	7.47	1	1.5	561	320	293.76	53.802	22.24	83.2	27.22	bdl	44.35	6.9	1.5	0.04	0.13	790
GW 2	7.44	1	1.6	349	172	138.72	46.116	25.4	64	2.916	bdl	13.1	4.25	6.34	0.01	0.11	491
GW 3	7.98	1	1	372	248	179.52	42.273	17.92	83.2	9.72	bdl	14.95	2.85	11.1	0.01	0.11	524
GW 4	7.37	1	1.2	727	304	130.56	242.11	28.92	96	15.55	bdl	75.1	3.3	3.06	0.01	0.46	1024
GW 5	7.67	1	1.8	432	208	102	73.017	19.04	62.4	12.64	bdl	34.75	8.2	20.9	0.01	0.16	608
GW 6	7.78	1	2.2	589	276	122.4	84.546	34.08	99.2	6.804	0.2	53.35	1.5	8.9	0.01	0.18	830
GW 7	7.93	1	1.6	309	164	126.48	53.802	27.96	54.4	6.804	bdl	32.2	1.65	0.45	0.07	0.13	435
GW 8	7.1	15	13	272	96	40.8	84.546	13.36	30.4	4.86	1.74	33.5	4.4	0.38	0.02	0.18	383
GW 9	7.17	20	29	514	224	167.28	130.66	17.44	51.2	233.3	4.85	56.25	8.2	1.09	0.12	0.26	724
GW 10	6.27	bdl	0.7	92	24	8.16	23.058	7.2	6.4	1.944	bdl	15.11	2.23	2.9	0.05	0.07	129
GW 11	7.04	bdl	0.9	393	160	93.84	88.389	25.52	51.2	7.776	bdl	56.65	8.45	8.48	0.04	0.19	553
GW 12	6.36	5	4.8	59	20	16.32	15.372	2.48	4.8	1.944	0.98	6.65	1.45	0.33	0.02	0.06	83
GW 13	5.92	bdl	0.8	93	32	12.24	19.215	8.48	6.4	3.888	bdl	10.53	2.05	1.78	0.01	0.06	131
GW 14	7.7	bdl	0.8	1157	480	236.66	495.13	12.72	96	58.32	bdl	230.5	14.75	0.52	0.07	0.92	1630
GW 15	7.22	3.1	3.1	79	36	12.24	15.84	3.92	8	3.888	0.49	7.65	0.59	0.06	0.04	0.06	111
GW 16	6.62	1	1.6	88	24	16.32	38.43	4.08	4.8	2.916	bdl	13.85	1.81	0.89	0.04	0.1	124
GW 17	6.54	3	5.9	58	20	12.24	15.372	2.52	4.08	2.52	0.28	13.46	1.92	0.65	0.02	0.06	82
GW 18	6.7	1	1.4	160	92	48.96	11.529	14.28	22.4	8.748	0.2	9.17	5.29	2.22	0.09	0.05	226
GW 19	6.04	bdl	0.7	2244	480	12.24	871.42	171.6	104	53.46	bdl	371	10.25	0.4	0.03	1.59	3160
GW 20	7.76	1	2.1	1162	360	281.52	318.97	49.6	73.6	42.77	bdl	136.5	7.5	0.4	0.01	0.6	1637
GW 21	7.85	1	1	606	488	224.4	96.075	54.96	108.8	52.49	bdl	32.5	3.75	4.87	0.07	0.2	853

Note: bdl = below detection limit.

Table 2. Statistical summary of the parameter.

Parameters	Mean	Minimum	Maximum	Standard Deviation
CaCO ₃ (mg/L)	108.41	8.16	293.76	94.09
Cl ⁻ (mg/L)	134.27	11.53	871.42	206.51
SO ₄ (mg/L)	26.84	2.48	171.60	36.1
Ca (mg/L)	53.07	4.08	108.80	37.99
Mg (mg/L)	16.69	1.94	58.32	18.83
Fe (mg/L)	0.42	bdl	4.85	1.68
Na (mg/L)	60.05	6.65	371.00	88.38
K (mg/L)	4.82	0.59	14.75	3.65
N (mg/L)	3.68	0.06	11.10	5.11
P (mg/L)	0.04	0.01	0.07	0.03
EC (ms/cm)	699.81	82.00	3160.00	725.89

Note: bdl = below detection limit.

Ionic ratio analyses

Seawater intrusion is the main factor contributing to high salinity levels in many coastal aquifers. Ionic ratio analyses of water samples are presented in Table 3, while ionic ratios and respective value ranges are presented in Table 4. Figures 3a and 3b show spatial variations of major ions, and Figure 4 shows the spatial distribution of ionic ratios in the study area. Vengosh and Rosenthal (1994) found that the Na/Cl ratio of saline water connected to seawater intrusion is lower than that of fresh and seawater. The Na/Cl ratio of saltwater intrusion tends to be lower than the marine values (<0.86, molar ratio) due to the prevalence of Na and Cl ions in the chemical composition of saline groundwaters (Schoeller, 1956). Seawater intrusion is the main factor contributing to high salinity levels in many coastal aquifers. Vengosh and Rosenthal (1994) found that the Na/Cl ratio of saline water connected to

seawater intrusion is lower than that of fresh and seawater. The Na/Cl ratio of saltwater intrusion tends to be lower than the marine values (<0.86, molar ratio) due to the prevalence of Na and Cl ions in the chemical composition of saline groundwaters (Schoeller, 1956). The Na/Cl ratio within the research area falls within the range of 0.3 to 0.9, with around 85.7% of the groundwater samples demonstrating a lower ratio (<0.86), indicating the occurrence of seawater intrusion. The mechanisms behind these reduced ratios are elucidated by Mercado (1989) and Nadler et al. (1981): the replacement of Na⁺ by calcium (Ca²⁺) leads to Na⁺ depletion while Cl⁻ concentrations remain constant, resulting in a decrease in the Na/Cl ratio. Having an average value of 0.366, the SO₄/Cl ratio spans from 0.066 to 1.120, with 95% of the groundwater samples displaying ratios below that of seawater (<1), suggesting a rise in chloride ion concentrations.

Table 3. Ionic ratio analyses of water samples.

Parameters	Na/Cl	K/Cl	Ca/Na	SO ₄ /Cl	Ca/SO ₄	(Ca+Mg)/Cl
GW 1	0.8	0.1	1.9	0.4	3.7	2.1
GW 2	0.3	0.1	4.9	0.6	2.5	1.5
GW 3	0.4	0.1	5.6	0.4	4.6	2.2
GW 4	0.3	0	1.3	0.1	3.3	0.5
GW 5	0.5	0.1	1.8	0.3	3.3	1.0
GW 6	0.6	0	1.9	0.4	2.9	1.3
GW 7	0.6	0	1.7	0.5	1.9	1.1
GW 8	0.4	0.1	0.9	0.2	2.3	0.4
GW 9	0.4	0.1	0.9	0.1	2.9	0.6
GW 10	0.7	0.1	0.4	0.3	0.9	0.4
GW 11	0.6	0.1	0.9	0.3	2	0.7
GW 12	0.4	0.1	0.7	0.2	1.9	0.4
GW 13	0.6	0.1	0.6	0.4	0.8	0.5
GW 14	0.5	0	0.4	0	7.5	0.3
GW 15	0.5	0	1.0	0.2	2.0	0.8
GW 16	0.4	0.1	0.3	0.1	1.2	0.2
GW 17	0.9	0.1	0.3	0.2	1.6	0.4
GW 18	0.8	0.5	2.4	1.2	1.6	2.7
GW 19	0.4	0	0.3	0.2	0.6	0.2
GW 20	0.4	0	0.5	0.2	1.5	0.4
GW 21	0.3	0	3.3	0.6	2.0	1.7

Seawater intrusion, the main contributor to elevated salinity levels in numerous coastal aquifers, can be identified through alterations in ion ratios. When seawater infiltrates freshwater systems, heightened chloride (Cl⁻) levels diminish the SO₄²⁻/Cl⁻ ratio, functioning as a key indicator of intrusion. According to Vengosh and Rosenthal (1994), saline water impacted by seawater intrusion typically exhibits a lower Na⁺/Cl⁻ ratio compared to both freshwater and seawater. Schoeller (1956) highlighted that in saline groundwater environments where Na⁺ and Cl⁻ ions prevail, the Na⁺/Cl⁻ molar ratio generally falls below 0.86. Within the research area, Na⁺/Cl⁻ ratios vary from 0.3 to 0.9, with around 85.7% of samples registering values under 0.86, implying the presence of seawater intrusion. Nadler et al. (1981) and Mercado (1989)

expounded that this reduced ratio arises from calcium (Ca²⁺) displacing sodium (Na⁺), leading to Na⁺ depletion while Cl⁻ concentrations remain steady. With an average of 0.366, the ratio of SO₄ to Cl exhibits a range from 0.066 to 1.120, with a majority (95%) of the groundwater samples showcasing ratios below that of seawater (<1), suggesting a rise in chloride ion levels. The heightened concentrations of Cl⁻ ions lead to a decline in the SO₄/Cl ratio as seawater permeates freshwater; this decline serves as an indicator of seawater encroachment. The range of the K/Cl ratio in the study area varies from 0.001 to 0.5, with the average falling at 0.1. Around 66% of the samples analyzed showed K/Cl ratios below that of seawater (0.02). An observed trend indicates an escalation in chloride concentrations compared to potassium ions.

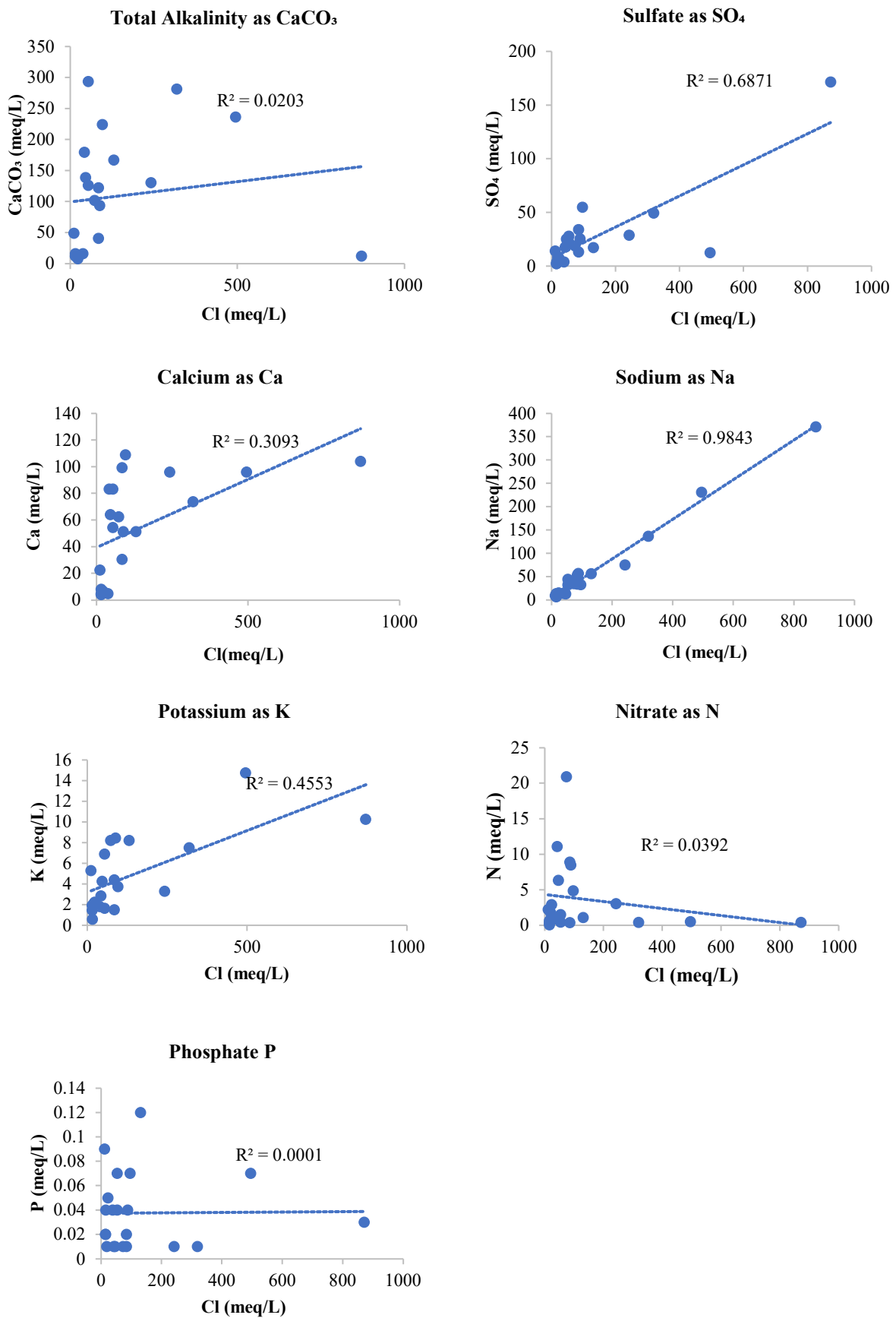


Figure 2. Bivariate plots of some major ions and EC with chloride ion.

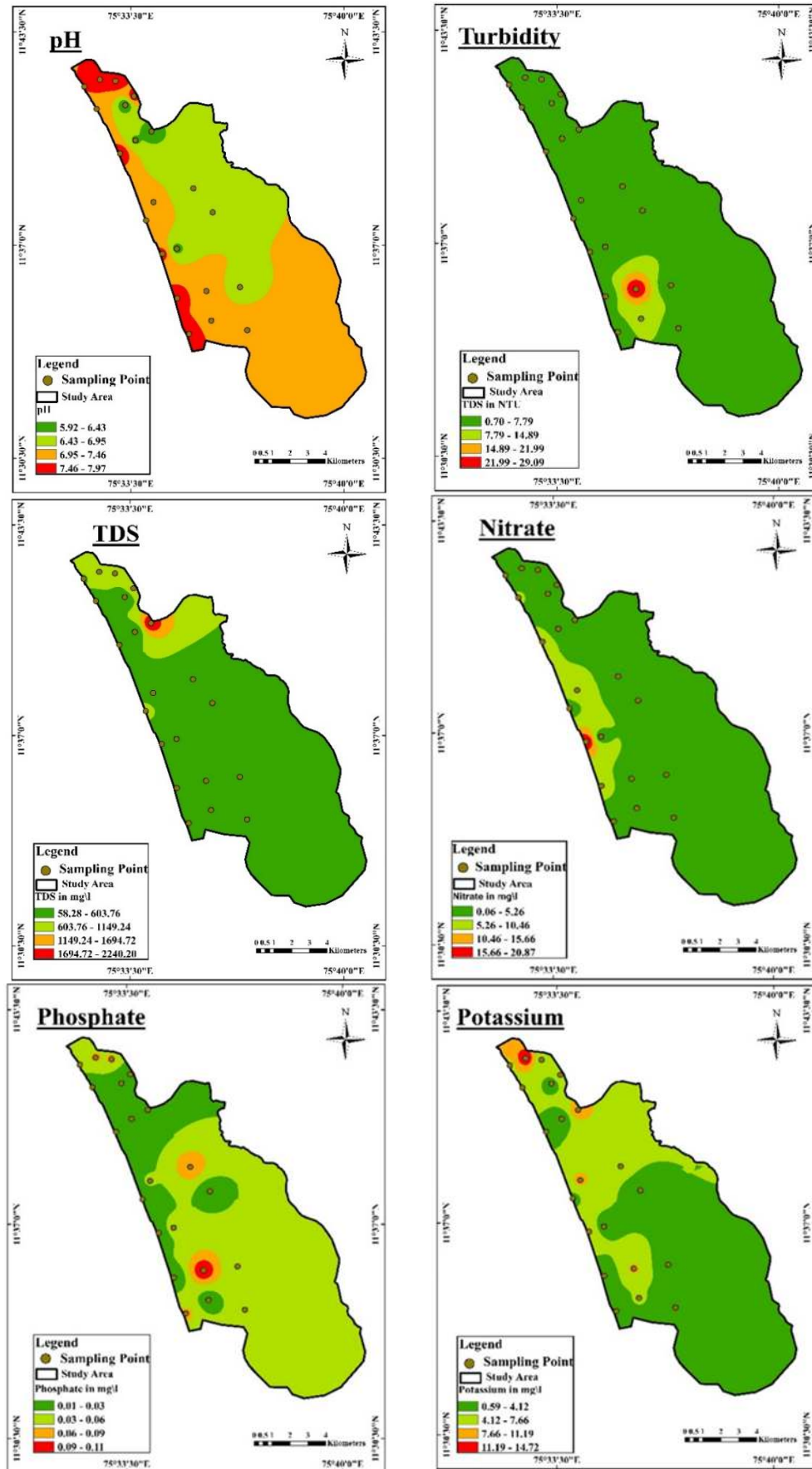


Figure 3a. Spatial variations of pH, turbidity, TDS, nitrate, phosphate, and potassium.

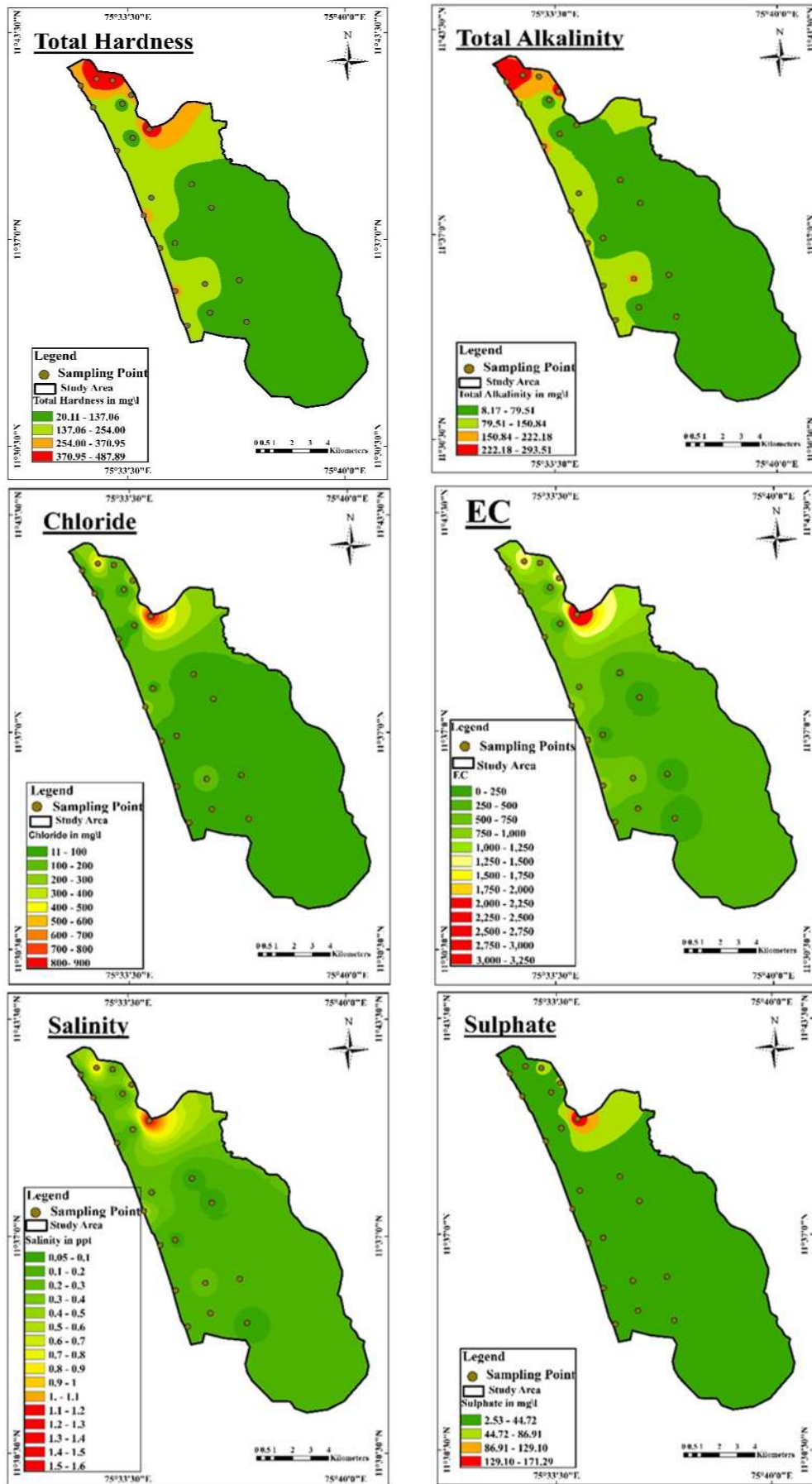


Figure 3b. Spatial variations of total hardness, total alkalinity, chloride, EC, salinity, and sulphate.

Table 4. Ionic ratios and respective value ranges.

Ionic Ratio	Values	Water Type
Na/Cl	<0.86	Saline water
	>0.86	Fresh water
K/Cl	<0.02	Saline water
	>0.02	Fresh water
Ca/Na	>1	Saline water
	<1	Fresh water
SO ₄ /Cl	>1	Saline water
	<1	Fresh water
Ca/SO ₄	>1	Saline water
	<1	Fresh water
(Ca+Mg)/Cl	>0.2	Saline water
	<0.2	Fresh water

The influx of seawater into coastal aquifers leads to the adsorption of K⁺ ions onto clay particles, consequently reducing the K/Cl ratios in the water (Vengosh and Rosenthal., 1994). The Ca/Mg ratio in the research site fluctuates between 1.6 and 21.9, with the highest ratio detected in the groundwater of the Mahe region, enclosed by hornblende biotite gneiss. Furthermore, human activities like agricultural runoff or industrial pollution may also impact the Ca/Mg ratio.

In the study area, the Ca/Na ratio spans from 0.3 to 5.6, with 47.6% of water samples exhibiting Ca/Na>1, an indication of seawater intrusion as per Giménez and Morell (1997). As seawater infiltrates fresh coastal water, the Na⁺ concentration decreases (aquifer matrix adsorption) (Domenico and Schartz 1997; Giménez and Morell, 1997), leading to a rise in calcium (predominant), resulting in a higher Ca/Na ratio compared to seawater. The Ca/SO₄ ratio in the study area ranges from 0.8 to 7.5, where higher values (>1) suggest seepage of seawater into freshwater aquifers, with approximately 81% of the samples displaying this phenomenon.

An advantageous parameter for discriminating between fresh and saline water, including seawater, is the (Ca+Mg)/Cl ratio. In freshwater, this ratio typically falls between 0.5 and 2, often below 0.2. The discrepancy arises from higher concentrations of calcium and magnesium ions in fresh water due to processes like rock weathering, whereas saline water demonstrates lower chloride ion concentrations owing to dissolved salt presence.

Groundwater quality and assessment

The water in the wells contains chemical constituents that may impact crop yield and reduce the fertility of the soil. Isolating the irrigation water chemistry is essential to managing long-term crop productivity. Hence, an attempt has been made in the study area to quantify the irrigation water chemistry based on BIS (1991) and WHO (2011) standards. The groundwater palatability based on TDS by WHO (1984) is listed in Table 5. Groundwater quality and assessment maps are presented in Figure 5.

Total Hardness (TH)

Total hardness is the sum of the calcium and magnesium concentrations, both expressed as calcium carbonate, in milligrams per liter (mg/L). The groundwater hardness is defined as the sum of divalent cations in solution but depends largely upon the concentrations of aqueous calcium and magnesium (Taylor and Howard, 1994). Hardness can be temporary or permanent. Bicarbonates of Ca and Mg cause temporary hardness. Calcium carbonate is removed by boiling the water. The presence of calcium, magnesium chlorides, and sulfates is responsible for permanent hardness and can be treated with an ion exchange process. Total hardness is determined by substituting the concentration of Ca²⁺ and Mg²⁺ in mg/L (Todd and May, 2005) as expressed by Equation 3:

$$TH = 2.497 Ca^{2+} + 4.115 Mg^{2+} \quad (3)$$

Where the concentrations are reported in meq/L. Total hardness for the groundwater samples varied between 18.187 and 487.662 meq/L with 28.5%, 9.52%, 14.28% and 81% of samples representing soft (0-60 mg/L), moderately hard (60-120 mg/L), hard (120-180 mg/L) and very hard (>180 mg/L) category. by Sawyer and McCarty (1967). The causes of high TH in the study area might be the dissolution of Ca²⁺ and Mg²⁺ ions from the aquifer matrix and or effluents released from bleaching, which might increase the hardness of the water.

Permeability index (PI)

The permeability of soil is affected by the long-term use of irrigation water and is influenced by sodium, calcium, magnesium, and bicarbonate contents in soil. Doneen (1964) has evolved a criterion for assessing the suitability of water for irrigation based on Permeability index (PI). The permeability index is given by the following formula (Equation 4).

$$PI = \frac{(Na^+ + \sqrt{HCO_3}) \times 100}{(Ca^{2+} + Mg^{2+} + Na^+)} \quad (4)$$

where all the ions are expressed in meq/L. The value of the permeability Index ranged from 24.501 meq/L to 87.041 meq/L with an average value of 54.771 meq/L. Permeability Index is classified under the following: class I (>75% permeability) is 19.04%, class II (25-75% permeability) is 76.19%, and class III (<25% permeability) is 4.761%.

Table 5. Groundwater palatability based on TDS by WHO (1984).

Water class	TDS (mg/L)
Excellent	<300
Good	300-600
Fair	600-900
Poor	900-1,200
Unacceptable	>1,200

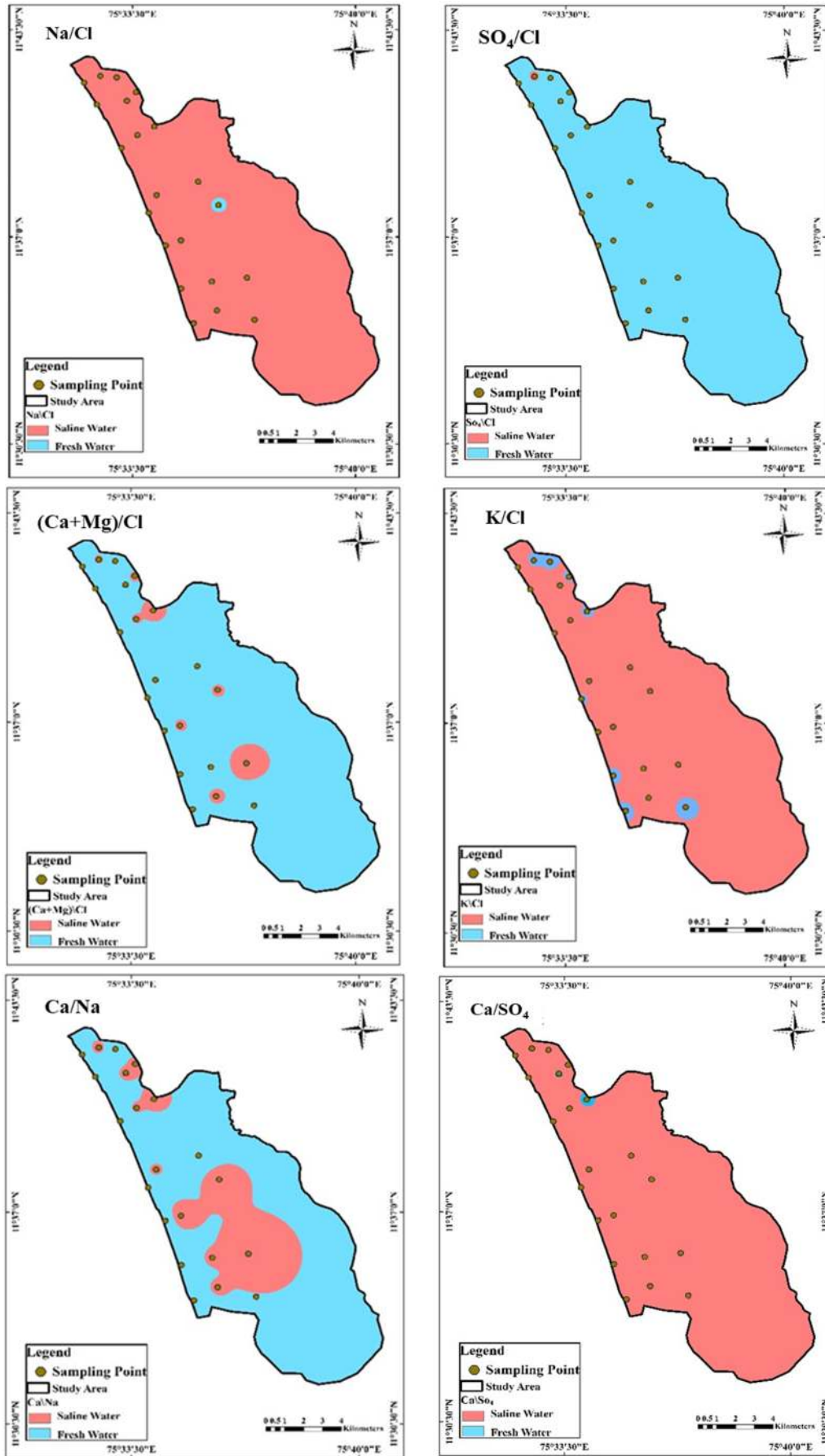


Figure 4. Spatial distribution of ionic ratios in the study area.

Magnesium Ratio / Magnesium Absorption Ratio (MAR)

One of the most important factors to take into account when analyzing the quality of water for irrigation is its magnesium content. An equilibrium is maintained in many waters by the natural process of rock-water interaction between calcium and magnesium. Such water has an adverse effect on crop yields when the concentration of magnesium greatly exceeds that of calcium because the soil becomes more saline and unsuitable for plants. The MAR is given by the following Equation 5.

$$\text{MAR} = (\text{Mg}^{2+} * 100) / (\text{Ca}^{2+} + \text{Mg}^{2+}) \quad (5)$$

The MAR values ranged from 4.358 meq/L to 37.792 meq/L, with a mean value of 22.949 meq/L. The MAR classifies irrigation water into two broad classes: water having $\text{MAR} < 50$ is considered suitable for irrigation, whereas water with $\text{MAR} > 50$ is considered unsuitable. The statistics that are currently available indicate that 100% of the water samples have MAR values less than 50% and fall into the appropriate category.

Kelly's Ratio (KR)

Kelly's Ratio, which differs the concentration of sodium ions from that of calcium and magnesium ions, was invented by Kelly (1940). Kelly's Ratio is given using the following Equation 6:

$$\text{KR} = \text{Na}^+ / (\text{Ca}^{2+} + \text{Mg}^{2+}) \quad (6)$$

Kelly's Ratio had a mean value of 0.9334 meq/L and ranged from 0.161 meq/L to 2.234 meq/L in the current study. Water with a KR value of less than one can be considered suitable for irrigation is 66.66% where as those with a value greater than one are considered unsuitable is 33.33%.

Magnesium Hazard (MH)

Most waters remain in equilibrium by a combination of calcium and magnesium. Paliwal (1972) developed an index of magnesium hazard, which is a ratio. The MR is given by the following Equation 7.

$$\text{MR} = \frac{\text{Mg}^{2+}}{\text{Ca}^{2+} + \text{Mg}^{2+}} \times 100 \quad (7)$$

In the study area, the magnesium hazard values fall in the range of 6.419 to 37.792%. In the study area. All the samples collected showed MH ratio of <50% (suitable for irrigation).

Potential Salinity (PS)

The suitability of water for irrigation is not dependent on soluble salts. Because the low solubility salts precipitate in the soil and accumulate with successive irrigation, the concentration of highly soluble salts increases the soil salinity by Doneen (1964). Potential salinity is defined as the chloride concentration plus half of the sulfate concentration (Equation 8).

$$\text{PS} = \text{Cl}^- + \sqrt{\text{SO}_4^{2-}} \quad (8)$$

All ionic concentrations are in meq/L. The potential salinity of the water samples ranges from 15.308 to 884.508 meq/L. It suggests that the potential salinity in all the groundwater samples of the studied area is nearly high (>10), thus making the water unsuitable for irrigation. High values of potential salinity in the area can be attributed to high chloride content since the industrial area might contribute to the effluents, which potentially increases the salinity value.

Sodium Percentage (SP)

Sodium concentration in groundwater is a very important parameter in determining the irrigation quality. The formula used for calculating the sodium percentage is as follows (Equation 9) where all the ionic concentrations are in meq/L.

$$\text{SP} = \frac{\text{Na}^+ + \text{K}^+}{\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+ + \text{K}^+} \times 100 \quad (9)$$

The determined value of sodium percentage lies between 18.381 and 70.771. In irrigation water, if the sodium concentration becomes high, sodium ions tend to replace the Mg^{2+} and Ca^{2+} ions by absorbed clay particles. Hence, water and air circulation is restricted during wet conditions, and such soils become hard in dry conditions. Chemical weathering of rock-forming minerals, dissolution-precipitation of secondary carbonates, and ion exchange between water and clay minerals are some of the general reactions responsible for the geochemical constitution of the groundwater. Dissolution of both primary silicate and carbonate minerals may lead to the increase of calcium, sodium, magnesium, and bicarbonate, which increases the pH value. The low sodium in some of the samples is due to the ion exchange with calcium and magnesium in clays, which is common in saline groundwater.

Sodium Adsorption Ratio (SAR)

The sodium adsorptive ratio, or SAR, is an essential illustration. It is an indicator of the soil's sodicity and provides important information about the adsorption of sodium by soils. The ratio between sodium and potassium to calcium and magnesium determines the quantity of water accessible to plants. High sodium concentrations in soil or water are harmful to plants. Dead tissue around the outside edges of leaves and leaf burn demonstrates a plant or tree's level of toxicity. The ratio of sodium to all the cations in the irrigation water decides how sodium affects the soil. The SAR was calculated using the following Equation 10.

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{\text{Ca}^{2+} + \text{Mg}^{2+}}{2}}} \quad (10)$$

In the present study, the SAR values ranged from 2.193 meq/L to 41.812 meq/L, with a mean value of 8.932 meq/L. For irrigation, SAR values less than 10.0 meq/L are ideal meq/L. For irrigation, SAR values less than 10.0 meq/L are ideal. All of the samples, with the exception of five, fall within the range of the SAR values, indicating low sodium (alkali) hazard and good

irrigation water. Rain and the dissolution of host rocks introduce sodium into the groundwater system. Plants that have a high soil sodium content experience stunted

growth and yellowing of leaves. High SAR values (>10) could cause sodium to replace adsorbed calcium or magnesium, thereby damaging the soil structure.

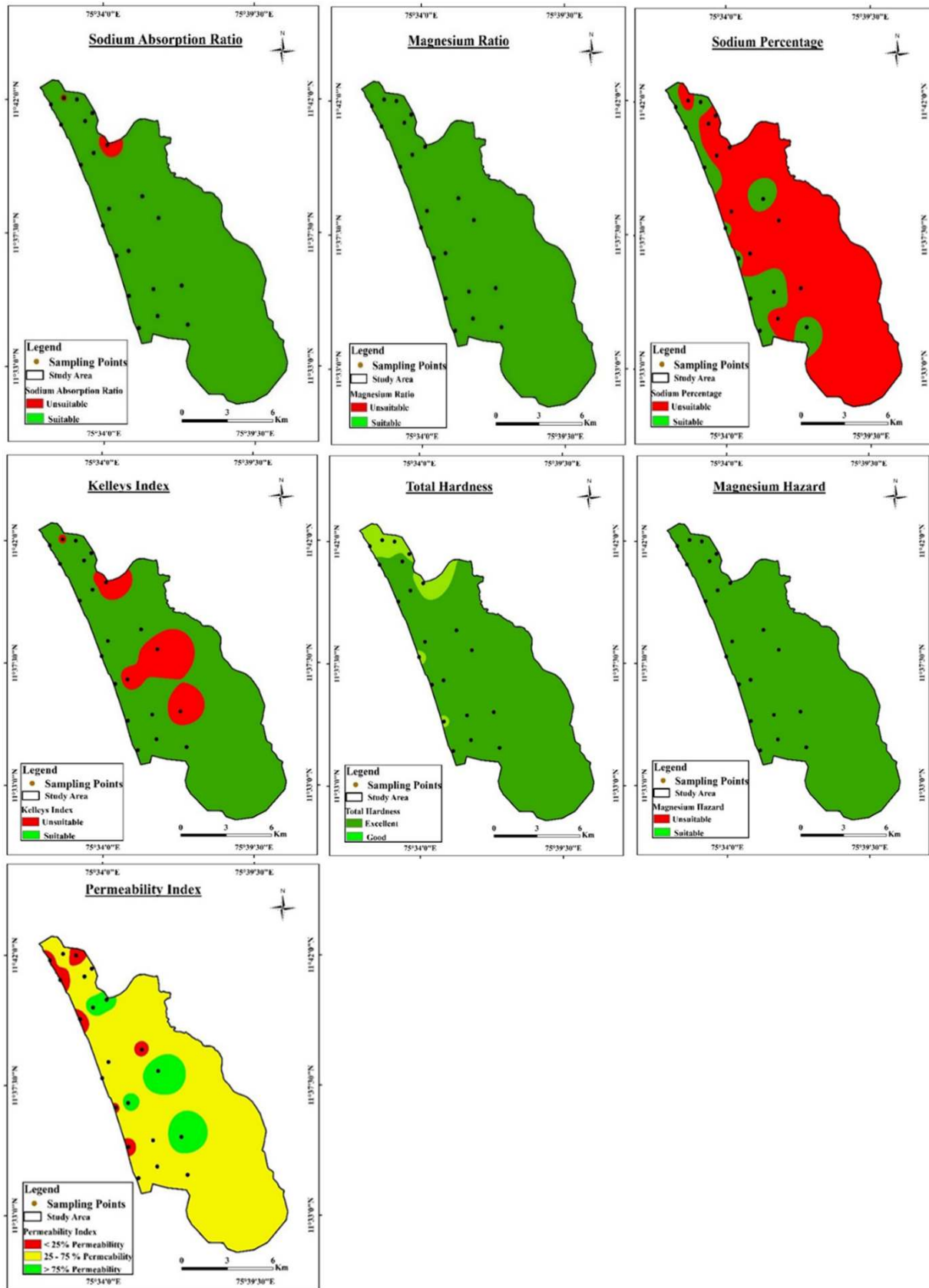


Figure 5. Groundwater quality and assessment maps.

Base exchange index

The computed BEX ranges between 20.8118 and 1.4274 in the study area, with most open wells close to the sea showing negative values (an indication of salinization). Approximately 85.71% of the samples analyzed had negative BEX values, indicating an increase of (Na+Mg+K) in the sampled groundwaters relative to chloride ion concentration (Stuyfzand, 1989; 1993; 2008). The spatial variation of BEX suggests that the salinization process affects most of the southern parts (close to the sea) of the study area.

Hill piper diagram

This diagram for disseminating hydrochemical facies was introduced by Hill (1940) and later improved by

Ghalit et al. (2017). The tri-linear graph consists of three major components: a ternary diagram on the left with the cations (magnesium, calcium, and sodium plus potassium), the one on the right with the anions (chloride, sulfate, and carbonate plus bicarbonate), and a diamond plot in the center, which is a matrix transformation of the two ternary diagrams. The diamond plot in the center reveals the type of water. Samples in the top quadrant are calcium sulfate waters, and samples in the left quadrant and the bottom quadrant are sodium bicarbonate waters. The trilinear piper plots of the water samples from the study area reveal the fact that pre-monsoon season samples from the coastal wells have Na-K-Cl-Mg type of water as the predominant facies followed by Na-K-HCO₃ (Figure 6).

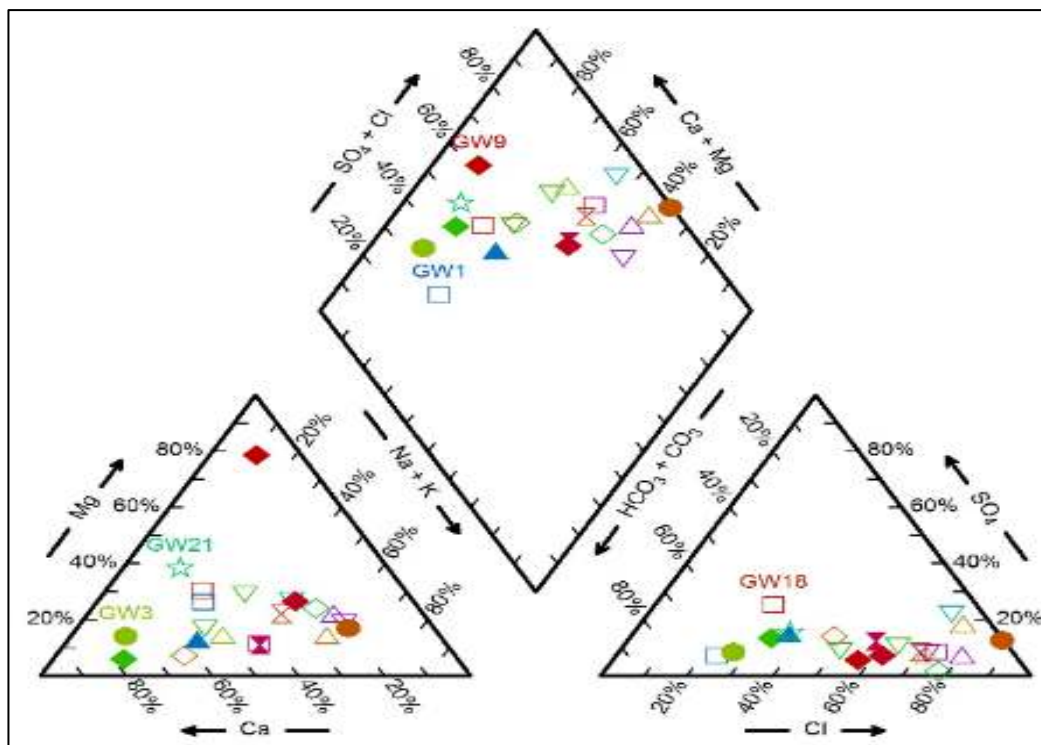


Figure 6. Hill piper trilinear diagram of groundwater.

Conclusion

The assessment of groundwater within the coastal region of the research site has been conducted concerning the potential occurrence of seawater intrusion. The investigation utilized distinct fundamental ionic indicators, including ionic ratios, bivariate plots, and BEX. Findings from the research suggest that the probable origin of salinity in the coastal vicinity is attributed to the mixing of freshwater and seawater, evident through elevated levels of chloride ions (≥ 8 meq/L) and EC ($> 1,000$ $\mu\text{S/cm}$). The bivariate plots of major ions (Na^+ , Ca^{2+} , K^+ , SO_4^{2-} versus Cl^-) displayed a notably high coefficient of determination (r^2), with values of 0.6871 for SO_4 , 0.0392 for Na, 0.3093 for Ca, and 0.4553 for

K^+ . These strong associations indicate a probable common source for the major ions and chloride content in the groundwater. Various analyses of ionic ratios revealed diverse degrees of seawater intrusion (salinization) impact on the groundwater in the study area. The distinct ionic ratios scrutinized exhibited varying degrees of influence from seawater intrusion (salinization) on the groundwater within the research site. The percentage of impact is delineated as follows: K/Cl (66%), Ca/Mg (100), Na/Cl (85.7%), Mg/Cl (100%) $>$ Ca/Na (47.6%), (Ca+Mg)/Cl (100%), Ca/SO₄ (81%), SO₄/Cl (95%). As per the BEX assessments, the groundwater quality indicated salinization in 18 (85.71%) out of the 21 samples, while the remaining samples displayed characteristics of freshwater. The spatial representation of the combined ionic ratios

suggests that groundwater in proximity to rivers and the sea is more vulnerable to salinization due to seawater intrusion. Furthermore, it has been discerned that the geological composition significantly influences the mechanism by which saltwater infiltrates coastal aquifers. Identifying areas susceptible to seawater intrusion is crucial for the effective management and provision of groundwater within the study area.

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