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Seasonal Salinity Dynamics in Coastal Phreatic Aquifers of Kollam District, Kerala, India

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Abstract

This study evaluates the spatial and seasonal dynamics of seawater ingress in the coastal phreatic aquifer systems of Kollam District, Kerala, using an integrated hydrochemical and index-based approach. A total of 21 groundwater samples were collected during the pre- and post-monsoon seasons of 2022 and analysed for major ions and physicochemical parameters. The Groundwater Quality Index for Seawater Mixing (GQI_{SWI}) was employed to identify salinization levels by integrating hydrochemical facies and chloride-derived mixing ratios. The Hill–Piper diagrams of the analysed water samples from the study area showed a shift, with samples transitioning from Na-Cl dominated facies during the pre-monsoon to Ca–HCO_3 type in the post-monsoon, indicating freshening of groundwater due to monsoon recharge. Similarly, the USSL diagram displayed a shift in several post-monsoon samples toward lower salinity zones, reflecting the dilution effect of rainfall. An inverse relation between depth to the water table and electrical conductivity was observed across coastal transects, with higher electrical conductivity observed in the shallow coastal zones and a decrease in conductivity with increasing depth towards the east. Despite the overall improvement in water quality during the post-monsoon season, a few localized zones continued to exhibit elevated salinity levels—likely attributable to limited aquifer thickness, proximity to the coastline/saline water bodies. The study demonstrates that monsoonal recharge plays a vital role in reversing salinity levels and provides a replicable framework for seawater ingress assessment and aquifer vulnerability mapping in coastal regions.

Keywords: Kollam District, Seawater Ingress, Seasonal Salinity Dynamics, Coastal Phreatic Aquifer System, Hydrochemical Facies, Ground Water Quality Index

Introduction

Coastal aquifers around the world are increasingly under threat from seawater intrusion, a process driven by a combination of anthropogenic and natural factors. Excessive groundwater abstraction, unregulated urbanization, and climate change-induced sea-level rise are among the most prominent drivers (Bear *et al*., 1999; Werner *et al*., 2013; Singh *et al*., 2021; Abd-Elaty *et al*., 2021; Aju *et al*., 2024; Anisha *et al*., 2025.). The mixing of saline water into freshwater aquifers compromises groundwater quality, reducing its suitability for drinking, agriculture, and industrial uses. This not only endangers human health but also disrupts agricultural productivity and the functioning of coastal ecosystems (Barlow and Reichard, 2010; Ferguson and Gleeson, 2012). In India, coastal aquifers are particularly vulnerable due to their high dependence on groundwater for domestic and agricultural requirements (Bhattacharya, 2020). This is particularly relevant in the coastal stretches of Kerala, where population density is high and surface water availability is seasonally variable; however, the region's high rainfall recharge acts as a natural safeguard against large-scale seawater ingress. The State's lateritic and alluvial aquifer systems are shallow and discontinuous in nature, making them more susceptible to salinization through seawater ingress in response to pumping stress (CGWB, 2023a; Saleena *et al*., 2025). Studies have reported elevated chloride concentrations and electrical conductivity values in observation wells along parts of Kerala's coast, including regions such as Kollam, Alappuzha, Ernakulam, and Kozhikode, which are indicative of localized or seasonal seawater ingress (Nagarajan *et al*., 2018; Suraj *et al*., 2019; Renu *et al*., 2024; Anisha *et al*., 2025). However, it is pertinent to note that localized increase in salinity observed during the pre-monsoon season tends to reverse during the monsoon, primarily due to substantial rainfall recharge. The high volume of precipitation during monsoon period enhances groundwater replenishment and dilution, mitigating salinity buildup in coastal aquifers. In addition to hydrogeological factors, land use changes, including sand

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mining, conversion of wetlands and paddy fields into urban settlements, have further impaired the natural recharge potential of the aquifers. Further the projected sea-level rise due to climate change is expected to exacerbate these challenges, placing increased stress on freshwater resources in these densely populated coastal belts (Werner *et al*., 2013; IPCC, 2021). Effective management strategies, including artificial recharge, regulation of groundwater extraction, and continuous monitoring using hydrochemical and geophysical methods, are essential to understand and curb the progression of seawater intrusion and safeguard the sustainability of coastal aquifers.

Study Area

The study was conducted in the coastal tracts of Kollam District, Kerala, India, covering an area of approximately 210 km² between Poothakulam in the south and Alappad in the north, bounded by the geographic coordinates 8°46′42″N to 9°07′39″N and 76°27′59″E to 76°43′24″E (Fig.1). The study area falls within a tropical humid climatic zone and receives an average annual rainfall of approximately 2428 mm. The rainfall heat map of the study area (Fig. 2), derived from station-wise rainfall data from IMD observatory stations in and around the study area for 2013–2022, clearly shows that June to September are the wettest months in Kollam, indicating peak southwest monsoon rainfall. Moderate rainfall in October–November reflects the northeast monsoon, while January to March remain dry. These patterns align with Kerala's monsoonal climate, where over 70% of rainfall occurs during the southwest monsoon (Kumar *et al*., 2009; IMD, 2023).

Physiographically, the region comprises alluvial lowlands (in the west adjoining coast) and lateritic midlands (in the eastern fringe of the study area) with elevation ranging from sea level to about 72 meters above mean sea level. The coastal tracts feature geomorphic elements such as sandy beaches, bars, beach ridges, lagoons, and tidal flats formed by active marine and fluvial processes (Raveendran *et al*., 2023; Kunjupillai, 2025). Inland, the terrain rises into undulating lateritic uplands consisting of plateaus and pediplains. Land use is dominated by agriculture, which occupies nearly 78% of the area, followed by water bodies (16%) and built-up land (6%) (KSLUB, 2014). The principal crops in the study area consist of coconut, banana, a variety of vegetables, and to a lesser extent, some paddy. The region also hosts the Chavara mineral separation plant operated by IREL (India) Ltd., an area noted for its rich placer deposits of ilmenite, rutile, zircon, and monazite, concentrated along the Chavara–Alappad Belt (Raju, 2021; IBM, 2022). In the study area, coastal alluvial soils—originating from marine and estuarine deposits—predominate in the western zone with sandy to loamy textures, while the eastern parts are characterized by lateritic soils formed through prolonged weathering processes. The coastal alluvium typically exhibits high permeability, low fertility, and low cation exchange capacity due to minimal clay and organic matter content (Sureshkumar *et al*., 2023; Rajasekharan *et al*., 2023; Joseph and Gandhi, 2025b). Along the inland margins and floodplain areas of west-flowing rivers like the Kallada, Ithikkara, Ayirur, Achankovil, and Pallikkal, fluvially deposited alluvium contributes to the development of fertile soils that sustain agricultural activities. These rivers drain into water bodies like Ashtamudi Lake, Paravur Lake, and Edava-Nadayara Kayal, and their interaction with coastal lakes plays a significant

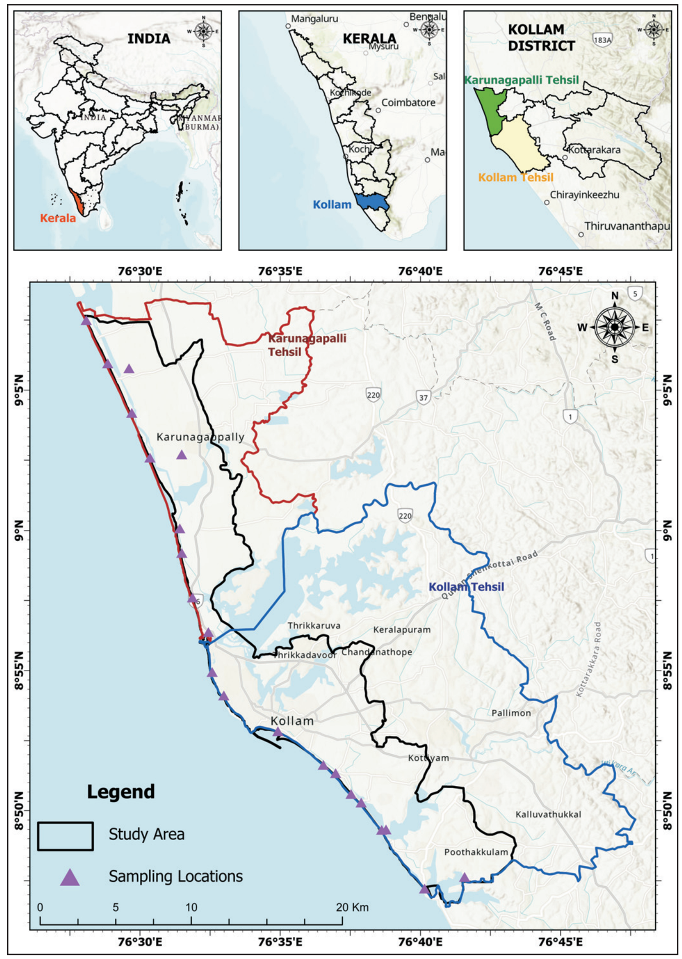

Fig.1. Location map of the study area showing sampling sites.

role in shaping the hydrogeology, ground water quality and agricultural potential of the region (Hussain *et al*., 2020; Joseph and Gandhi, 2025a).

This study attempts to add to existing research by filling the gap in site-specific and seasonal assessments of seawater ingress in coastal aquifers. It uses pre- and post-monsoon sampling, hydrochemical analysis, and an integrated index-based approach to map spatial and temporal changes in salinity. By evaluating irrigation suitability and developing GIS-based vulnerability maps, this study aims to provide a scalable framework for predictive modelling and policy development that can be applied to other coastal areas.

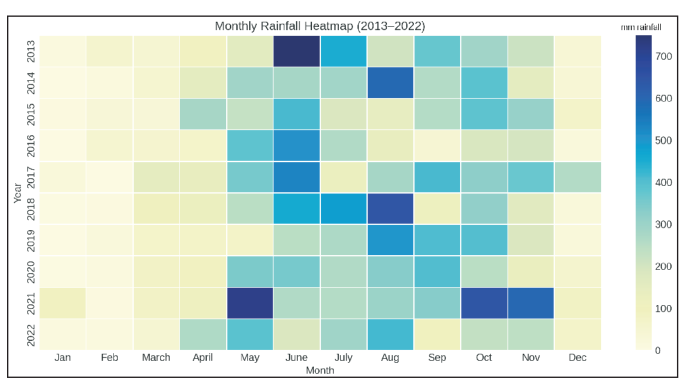

Fig.2. Rainfall heatmap of the study area

Geological Setting

The coastal regions of Kollam District, Kerala, are underlain by a laterally and vertically heterogeneous sequence of unconsolidated, semi-consolidated, and consolidated geological formations, forming a complex, multi-tiered aquifer system (CGWB, 1992; GSI, 1995; CGWB, 2023b). This system includes shallow phreatic aquifers developed within Quaternary alluvium and lateritic crusts, as well as deeper confined aquifers within Tertiary sedimentary formations. The alluvial aquifer system is prominently developed in the central and northern parts of the district, extending up to 10 kilometers inland from the coast. Composed primarily of sand, silt, and clay, the alluvium attains a maximum thickness of approximately 38 meters south of Kollurvila (central part of study area), although it thins significantly toward the southern coastal areas. Groundwater occurs under unconfined (phreatic) conditions in alluvial aquifers with water level depths ranging between less than 1 meter and 6 meters below ground level. These aquifers are extensively utilized through dug wells and shallow filter-point tube wells, yielding between 5 and 35 m^3/day. Transmissivity values typically range from 100 to 500 m^2/day, and specific yield is estimated between 10% and 12%, reflecting moderate groundwater storage potential in the shallow zone (CGWB, 1992; Shaji *et al*., 2009; Sindhu *et al*., 2012; Sanjeev Kumar *et al*., 2013; CGWB, 2023b). Lateritic aquifers, developed through intense weathering of Tertiary sedimentary rocks are prevalent across the midland and coastal uplands, especially in the eastern part of the study area. These laterites overlie older sediments and are geologically older than the overlying alluvium. Groundwater in these lateritic aquifers primarily exists under phreatic conditions, with the formation ranging in thickness from 3 to 28 meters. The depth to the water level in the laterite aquifers of the study area generally ranges from 5 to 10 meters below ground level. These aquifers generally yield between 1 and 10 m^3/day, with transmissivity values ranging from 10 to 100 m^2/day. Due to high surface permeability, recharge in laterites predominantly occurs through direct infiltration of rainfall (CGWB, 1992; Sanjeev Kumar *et al*., 2013; CGWB, 2023b; Ribinu *et al*., 2023.). Deeper sedimentary aquifers are encountered within the Tertiary sequence, specifically the Warkalli and Vaikom formations. Although the current study primarily focuses on shallow phreatic aquifer system and the associated risks of seawater ingress, a brief overview of these deeper aquifers provides a holistic understanding of the hydrogeological framework. The Warkalli formation (Youngest Tertiary Formation), comprising sandstones and carbonaceous clay beds, has a thickness ranging from 12 to 46 meters and is predominantly found in the western part of the district. The Quilon Formation, underlying Warkalli and composed mainly of fossiliferous limestone and marl, often exceeds 100 meters in thickness and is extensively developed north of Kollam. The Quilon formation is considered to be a poor aquifer compared to Vaikom and Warkali beds. Beneath the Quilon Formation, the Vaikom Formation, composed of argillaceous and arenaceous strata, is widely distributed across the coastal tract. It reaches thicknesses exceeding 200 meters in the Chavara region, where it often hosts confined aquifers with significant potential for groundwater development (CGWB, 1992; CGWB, 2023b). In contrast, the Alleppey formation—oldest component of the regional Tertiary sequence—is not encountered in Kollam District and remains confined to Alappuzha District, where its groundwater is typically saline and considered unsuitable for potable or agricultural purposes (Shaji *et al*., 2009; Nair *et al*., 2010; Krishnakumar and Prijilal, 2015; CGWB, 2023b). The hydrogeological framework of Kollam District highlights a diverse and multi-layered aquifer system, wherein shallow alluvial and lateritic aquifers serve as primary sources for domestic and agricultural needs, while deeper confined aquifers offer viable alternatives for large-scale water supply. The generalized lithostratigraphic succession of formations in Kollam District is presented in Table 1 (GSI, 1995).

Materials and Methods

During the pre-monsoon and post-monsoon seasons of 2022, a total of 21 water samples were collected from dug wells across the coastal tract of Kollam District, Kerala, to assess the extent of seawater ingress. The sampling locations were chosen to represent hydrogeochemical variability across the shallow phreatic aquifer system. The samples were analysed for key physicochemical parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+), major anions (Cl^-, HCO_3^-, SO_4^{2-}, NO_3^-, F^-). The analysis was conducted in the Chemical Laboratory of Central Ground Water Board (CGWB), Kerala Region, Trivandrum, equipped with relevant instruments including pH meter (potentiometric method for pH), EC meter with conductivity cell (potentiometric method for EC, from which TDS was derived), flame photometer (flame emission photometry for Na^+ and K^+), titration setup (EDTA titrimetric for Ca^{2+} and total hardness; volumetric analysis for HCO_3^-; argentometric for Cl^-),

Table 1: Generalized stratigraphy of Kollam district (GSI, 1995)

Era	Age	Formation	Lithology
QUATERNARY	Recent	Alluvium	Sand and clays along the coast, flood plain deposits of back water area, river alluvium and valley fill deposits
TERTIARY	Sub-recent	Laterites	Laterites and lateritic clays derived from Tertiary sediments and crystalline rocks.
	Eocene to Lower Miocene	Warkalli beds Quilon beds Vaikom Aleppey beds	Sandstone and carbonaceous clay with thin bands of lignite. Limestone and Clay Sandstone clay and thin bands of lignite Carbonaceous clay with minor lenses of sand
UNDATED		Intrusives	Dolerite, Gabbro, Pegmatites and Quartz veins.
PRECAMBRIAN	Archaean	Migmatite Group Charnockite Group	Granite gneiss, Hornblende biotite gneiss, Biotite gneiss and Garnet biotite gneiss. Charnockite, charnockite gneiss, cordierite gneiss and Pyroxene granulites
		Khondalite Group	Garnet sillimanite gneisses and calc-granulites

UV-VIS spectrophotometer and ion chromatograph (ultraviolet spectrophotometric screening for NO_3^-), spectrophotometer with nephelo turbidimeter (turbidimetric for SO_4^{2+}; Mg^{2+} computed from total hardness and Ca^{2+} data), and fluoride spectrophotometer with ion meter (SPADNS method and ion-selective electrode for F^-). Standard laboratory procedures outlined in APHA (2017) were strictly followed to ensure analytical accuracy and comparability. A comprehensive index-based approach, along with classical hydrogeological, hydrogeochemical, and geostatistical tools such as the Hill-Piper diagram, USSL diagram, correlation matrix, and hydrogeological sections depicting the relationship between water level and electrical conductivity, was employed to evaluate the salinization status of groundwater and determine the extent of seawater ingress. The index-based approach follows a framework that proposes a combined groundwater quality index specific to seawater mixing, known as GQI_{SWI} (Tomaszkiewicz *et al*., 2014). The methodology integrates two critical hydrochemical indicators: $GQI_{Piper(mix)}$, derived from Piper diagram domains, and GQI_{fsea}, based on chloride-derived seawater mixing fractions (Appello and Postma, 2005). The first index, $GQI_{Piper(mix)}$, numerically quantifies the hydrochemical facies of a water sample using its ionic composition. It is calculated based on the proportion of divalent cations ($Ca^{2+} + Mg^{2+}$) and bicarbonate ions (HCO_3^-) relative to the total cation and anion content, respectively. Samples dominated by Ca-HCO_3 type waters (indicative of freshwater) yield values near 100, while those resembling Na-Cl type water (seawater facies) approach 0. This transformation, proposed by Tomaszkiewicz *et al*. (2014), enhances the traditional Piper diagram's applicability by enabling spatial interpolation and indexing within a GIS environment.

$$GQI_{Piper(mix)} = \left[\frac{(Ca^{2+} + Mg^{2+})}{\text{Total Cations}} + \frac{HCO_3^-}{\text{Total Anions}}\right] \times 50 \quad ....1$$

(All values in meq/L)

The second index, GQI_{fsea}, estimates the proportion of seawater in a sample using the conservative behaviour of chloride ions during mixing. In fact, the fraction of seawater (f_{sea}) in a water sample can be approximated from the concentrations of Cl^- (mCl) (in meq/L) as expressed as the equation given below (Appello and Postma, 2005; Prusty and Farooq, 2020):

$$f_{sea} = \frac{[\text{mCL(sample) - mCl(freshwater)}]}{[\text{mCL(seawater) - mCl(seawater)}]} \quad ....2$$

where mCl(freshwater) is the representative chloride concentration in local freshwater (taken as 0.35 meq/L), and mCl(seawater) is the reference value for seawater (566 meq/L) (Appello and Postma, 2005; Prusty and Farooq, 2020). The index GQI_{fsea} is then calculated as:

$$GQI_{fsea} = (1 - f_{sea}) \times 100 \quad ....3$$

Higher GQI_{fsea} values denote fresher water conditions. However, chloride-based indices alone may overlook complex hydrogeochemical interactions such as cation exchange, dolomitization, or sulphate reduction that often accompany saline water mixing in aquifers (Singhal and Gupta, 2010; Tomaszkiewicz *et al*., 2014). To overcome the individual limitations of both indices, a combined index—GQI_{SWI} Groundwater Quality Index for Seawater Mixing)—was developed, calculated as the arithmetic mean of $GQI_{Piper(mix)}$ and GQI_{fsea} (Pulido-Leboeuf., 2004; Tomaszkiewicz *et al*., 2014; Moorthy *et al*., 2024). This integration leverages the hydrochemical facies classification and chloride-based mixing estimates to generate a robust indicator of seawater mixing. The GQI_{SWI} ranges from 0 to 100, with values approaching 100 representing freshwater and values near 0 indicating severe seawater contamination. According to validated global datasets, freshwater typically has GQI_{SWI} values above 75, mixed water ranges between 50–75, and saline water typically falls below 50 (Tomaszkiewicz *et al*., 2014; Aladejana *et al*., 2021; Moorthy *et al*., 2024).

$$GQI_{SWI} = (GQI_{Piper(mix)} + GQI_{fsea}) / 2 \quad ....4$$

This index allows researchers and water managers to classify groundwater samples based on dominant hydrochemical signatures, facilitating assessment of seawater mixing and freshwater quality in coastal aquifers. By employing this integrated framework in the Kollam coastal region, a more comprehensive understanding of the spatial and seasonal dynamics of seawater ingress is achieved. The methodology also provides a scalable approach for developing vulnerability maps under GIS platforms, which is especially valuable for coastal aquifers experiencing dynamic salinity ingress due to over-extraction and sea-level rise.

Results and Discussion

Descriptive Statistics

The comparative analysis of pre-monsoon and post-monsoon groundwater quality data from Kollam District reveals a clear seasonal dilution effect due to monsoonal recharge. Key parameters such as Electrical Conductivity (EC), Total Hardness (TH), and major ions like Na^+, Cl^-, and SO_4^{2+} show significant reductions in their mean values post-monsoon—indicating a decrease in salinity and overall ionic concentration. For instance, mean EC drops from 2789.3 µS/cm in the pre-monsoon to 1460.5 µS/cm post-monsoon, while chloride reduces from 910.7 mg/L to 381.1 mg/L. This pattern underscores the role of high rainfall recharge in flushing out accumulated salts and reversing seawater mixing trends (Laluraj and Girish Gopinath, 2006; Roman-Stork and Subrahmanyam, 2020; Pitchaimani *et al*., 2024b; Gireesh and Sreedevi, 2024). The narrowing of standard deviations in the post-monsoon dataset further suggests a homogenizing effect of rainfall on water quality. A summary of the ranges of selected hydrochemical parameters for the pre- and post-monsoon seasons is presented in Table 2.

Relationship between Electrical Conductivity and Depth to Water Level

Three cross-sectional profiles (A–A′, B–B′, and C–C′) depict variations in Depth to Water Level (DTWL) and Electrical Conductivity (EC) across coastal transects within the study area, as shown in Figure 3. A clear inverse relationship is observed in all sections: as DTWL increases landward, EC values consistently decrease. This trend is particularly distinct in the C–C′ transect, where EC drops from above 4000 µS/cm near the coast to below 1000 µS/cm further inland, while DTWL increases simultaneously. Such a pattern indicates localized seawater mixing, where shallow water tables near the coast mix with saline water, resulting in higher EC values. As one moves inland and the water table deepens, the influence of saline ingress diminishes, leading to lower EC values

Table 2: Descriptive statistics of selected hydrochemical parameters (Pre- and Post-Monsoon)

Parameter	Pre-Monsoon				Post-monsoon			
	Mean	Std.dev.	Minimum	Maximum	Mean	Std.dev.	Minimum	Maximum
pH	8	0.8	6.6	10.5	7.9	0.3	7	8.3
EC (µS/cm)	2789.3	8141.3	105	38000	1460.5	3719.6	100	17200
TH (mg/L)	412.6	946.6	15.7	4500	269.8	454.8	13	2185
Ca (mg/L)	72.3	64.1	4.3	320	61.7	44.3	3	190
Mg (mg/L)	56.5	194	1.3	899	28.2	89.5	1.3	416
Na (mg/L)	359.8	1145.8	8.7	5300	227	691.5	9	3140
K (mg/L)	18.1	40.4	0.9	191	12.9	25.9	0.5	124
HCO_3 (mg/L)	156.1	100.6	5.2	363.4	141.2	89.3	5.2	388
SO_4 (mg/L)	139.1	450.9	6.1	2100	68.5	163.4	2.6	759
Cl (mg/L)	910.7	3384	9.1	15620	381.1	1239.5	6.4	5650
NO_3 (mg/L)	20.6	46.1	0.4	198.4	14.8	20.8	0	83
F (mg/L)	0.1	0.1	0	0.6	0.1	0.1	0	0.4

and better groundwater quality. These sections of the study area indicate that the ingress is localized, primarily confined to areas near the sea or saline water bodies. Additionally, in the northern part of the study area, groundwater salinity is attributed to the removal of aquifer materials, with activities such as sand mining contributing to the localized salinity of the aquifer.

Seasonal Variation in Ionic Correlation Patterns

The correlation matrices for groundwater parameters during the pre-monsoon and post-monsoon seasons in Kollam District reveal notable seasonal shifts in ionic relationships, reflecting the influence of seawater intrusion and rainfall recharge on groundwater chemistry (Fig.4). In the pre-monsoon matrix, when seawater ingress is more prevalent, Electrical Conductivity (EC) exhibits near-perfect positive correlations with Total Hardness (TH) (r = 0.997***), Mg^{2+} (r = 0.998***), Na^+ (r = 0.998***), and Cl^- (r = 0.998***), indicating strong ionic linkage due to evaporative concentration and active seawater mixing. Similarly, Na^+ and Cl^- display very strong mutual correlation (r = 0.998***), underscoring the dominance of sodium-chloride facies characteristic of marine influence. The weak correlations of pH and NO_3^- with major cations and EC suggest that these parameters are influenced by localized geochemical or anthropogenic processes, rather than marine mixing. HCO_3^- shows moderate correlation with Ca^{2+} (r = 0.443*) and weak correlation with TH (r = 0.161), indicative of limited carbonate weathering contributions during this period (Vandenbohede and Lebbe, 2012; Senthil Kumar *et al*., 2014; Halder *et al*., 2021).

In contrast, the post-monsoon matrix shows distinct changes in inter-ionic relationships following monsoon recharge, when dilution occurs and reversal of seawater ingress happens. While EC maintains strong correlations with Na^+ (r = 1.000***) and Cl^- (r = 1.000***), correlations with TH (r = 0.993***) and Mg^{2+} (r = 0.989***) show slight weakening compared to pre-monsoon values, suggesting partial freshening of the aquifer system. Notably, HCO_3^- displays strengthened associations with Ca^{2+} (r = 0.670***) and TH (r = 0.309), indicating enhanced freshwater recharge influence. NO_3^- and F^- continue to exhibit negative or weak correlations with other ions, suggesting leaching from point sources rather than geogenic origins. The subtle reduction in correlation strengths for certain ion pairs—particularly EC-Mg and EC-TH—reinforces the effect of monsoonal dilution in moderating the conservative mixing patterns typical of saline water mixing (Tomaszkiewicz *et al*., 2014; Roman-Stork *et al*., 2020; Jena *et al*., 2024; Fernandes *et al*., 2025).

Overall, the comparison confirms that pre-monsoon water chemistry is more strongly influenced by concentration processes

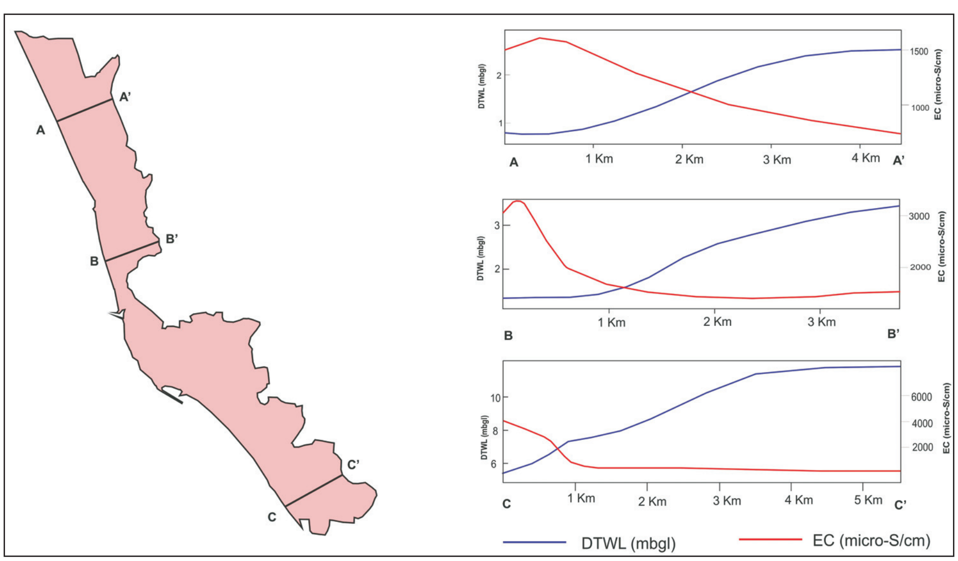

Fig.3. Cross-sectional profiles showing the variation of Depth to Water Level (DTWL) and Electrical Conductivity (EC) in the study area.

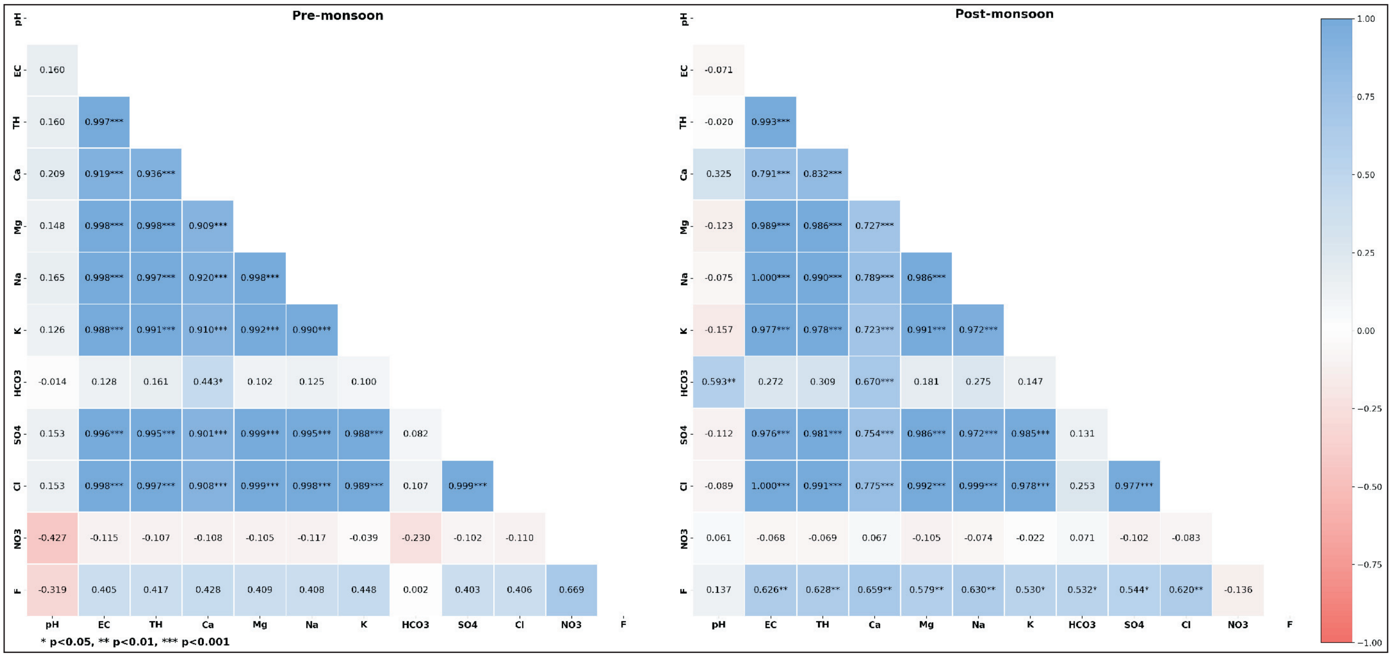

Fig.4. Correlation heatmap of major ion parameters during pre- and post-monsoon seasons

and marine ingress, while post-monsoon recharge moderates ionic interactions through dilution and promotes partial freshening of the aquifer system. These seasonal correlation patterns are consistent with earlier findings on groundwater salinity dynamics in coastal Kerala (Vandenbohede and Lebbe, 2012; Saleena Vahid *et al*.,2025).

Piper Diagram Analysis

Hydrochemical facies identified using Piper plots (Piper, 1944; Fig. 5) reveal dominance of Ca-HCO_3 type water with seasonal shifts. The paired Piper diagrams illustrate the hydrochemical evolution of groundwater in Kollam District during pre- and post-monsoon seasons, revealing a distinct seasonal transition in water facies and mixing processes. In the pre-monsoon diagram, many of groundwater samples fall within the mixing and conservative mixing zones, marked by elevated Na^+ and Cl^- concentrations, suggesting the influence of seawater mixing processes. This is typical of coastal regions during the dry season, when reduced recharge and higher abstraction draw saline water into freshwater aquifers. In contrast, the post-monsoon Piper plot shows a clear shift of groundwater samples toward the freshening and slight freshening zones, indicating improved water quality due to monsoonal dilution. Increased recharge during the southwest monsoon introduces large volumes of low-salinity water into the aquifer, flushing out accumulated salts and reversing salinization trends. The movement of samples toward Ca–HCO_3 facies also reflects a transition toward more meteoric or recharged groundwater signatures, consistent with studies on monsoon-induced hydrochemical shifts (Kelly, 2006; Vandenbohede and Lebbe, 2012; Khan *et al*., 2021; Balamurali and Sivanandan, 2023.).

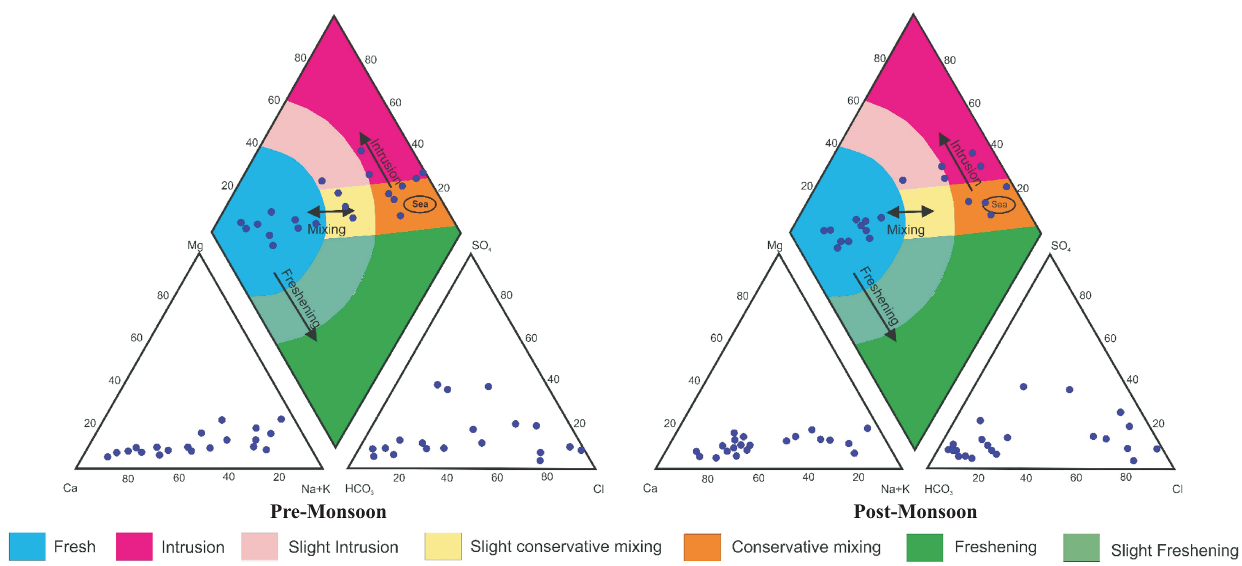

Fig.5. Pre-monsoon and post-monsoon Piper diagrams showing hydrochemical facies classification and seawater mixing patterns (Piper, 1944; Kelly, 2006)

USSL Diagram and Irrigation Suitability

The USSL diagram (Fig. 6) provides a hydrochemical classification of irrigation water based on its salinity hazard (measured as electrical conductivity) and sodium hazard (expressed through Sodium Adsorption Ratio, SAR) (U.S. Salinity Laboratory Staff, 1954). Groundwater samples collected during the pre- and post-monsoon seasons from the coastal aquifers of Kollam District were plotted on the USSL diagram to evaluate their suitability for agricultural use. During the pre-monsoon season, most of the samples were clustered in the C2–S1 zone, indicating moderate salinity and low sodium hazard. Water falling in these categories can generally be used for irrigation on well-drained soils with salt-tolerant crops, although prolonged use may lead to soil salinization if proper management is not practiced. A few pre-monsoon samples, however, extended into the C4–S4 and C4–S3 zones, representing very high salinity and high sodium hazard. Such water is generally unsuitable for irrigation unless advanced soil and water management techniques are employed, including gypsum application, improved drainage, and restricted cropping choices. During the post-monsoon season, most of the samples remain in the C2-S1 zone. However, it is important to note that the EC values of these samples decrease due to the dilution effect from monsoon rains. The pre-monsoon samples, which were classified in the C4-S4 category, retained their C4-S4 status but shifted left on the plot due to a reduction in EC, resulting from the dilution effect. This shift indicates the impact of monsoonal recharge, which reduces ionic concentrations and improves water quality overall. The observed seasonal migration of sample points on the USSL plot supports the hypothesis that salinity increases during the dry season and is reversed by monsoonal flushing. This effect has been widely documented in coastal regions of Kerala (Pitchamani *et al.*, 2024b; Joseph and Gandhi, 2025a).

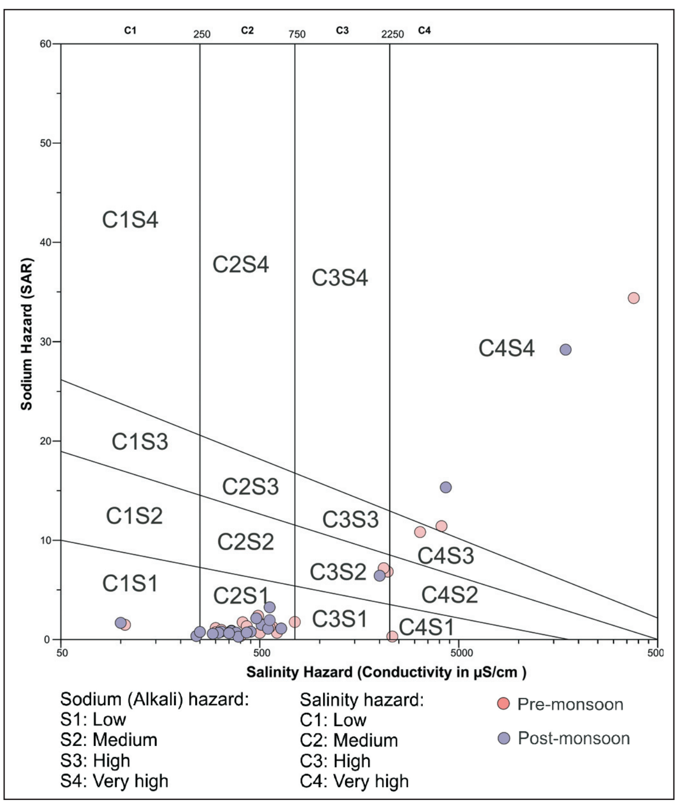

Fig.6. USSL diagram showing irrigation suitability of groundwater in the study area.

This seasonal improvement in irrigation water quality is consistent with the broader findings of the study, which suggest that despite localized seawater ingress in shallow coastal aquifers, the high recharge from the southwest monsoon acts as a natural remedial mechanism. However, the presence of some samples in critical zones even after the monsoon indicates localized vulnerabilities, likely driven by excessive pumping, lithological controls, removal of aquifer material, or proximity to tidal water bodies. This spatial variability highlights the need for targeted groundwater management strategies in areas where salinity risk persists.

GQI_{SWI}-Based Seawater Ingress Mapping

The comparison of pre-and post-monsoon groundwater data from 21 sampling locations in Kollam District reveals notable seasonal shifts in both water quality index and hydrochemical facies (Fig. 7). The Groundwater Quality Index for Seawater Mixing (GQI_{SWI}) shows an overall improvement post-monsoon, with several locations exhibiting a significant increase. For instance, one location improved from a GQI_{SWI} of 15.98 (indicating poor quality) during pre-monsoon to 41.59 post-monsoon, reflecting the dilution effect of intense rainfall recharge typical of the southwest monsoon in Kerala. The validity of the GQISWI method is supported by its successful application in the Kadaladi coastal aquifer study, where it effectively identified seawater intrusion zones by integrating hydrochemical parameters from Piper diagrams and seawater fraction analysis (Pitchaimani *et al*., 2024a). Further, its usage in the coastal aquifers of Mayiladuthurai, Karaikal, and Nagapattinam districts was found effective, with GQISWI values ranging from 52.05–76.15 during pre-monsoon and 52.49–71.91 during post-monsoon (Moorthy *et al*., 2024). Hydrochemical facies transformation is also evident: pre-monsoon samples are largely dominated by Na-Cl-type water (Piper Domain II), indicative of salinity and localized seawater ingress, whereas post-monsoon data show a shift toward $Ca\text{-}HCO_3$ -type facies (Piper Domain I), representing fresher conditions. This transition reinforces the role of seasonal rainfall in flushing salts and restoring aquifer quality, consistent with prior monsoonal studies on Indian coastal hydrogeochemistry (Bhattacharya, 2020; Halder *et al*., 2021; Girish and Sreedevi, 2024). A comparison of GQI_{SWI} ranges and the corresponding dominant hydrochemical facies observed during the pre- and post-monsoon seasons is provided in Table 3.

Table 3: Comparison of GQI_{SWI} Range and Dominant Facies during pre- and post-monsoon seasons

Parameter	Pre-Monsoon	Post-Monsoon
GQI_{SWI} Range	15.98 - 93.84	41.59 - 93.44
GQI_{SWI} (mean ± Std. Dev)	72.72 ± 17.14	76.79 ± 14.11
Dominant Facies and Piper Domain	Mixed Water and Saline Water facies (Domain-II; Na-Cl Type): 57% of samples	Fresh Water Facies (Domain-I; $Ca\text{-}HCO_3$): 43 % of samples
	Mixed Water, Saline Water (Na-Cl Type): 38 % of samples	Facies (Domain-I; $Ca\text{-}HCO_3$): 62 % of samples

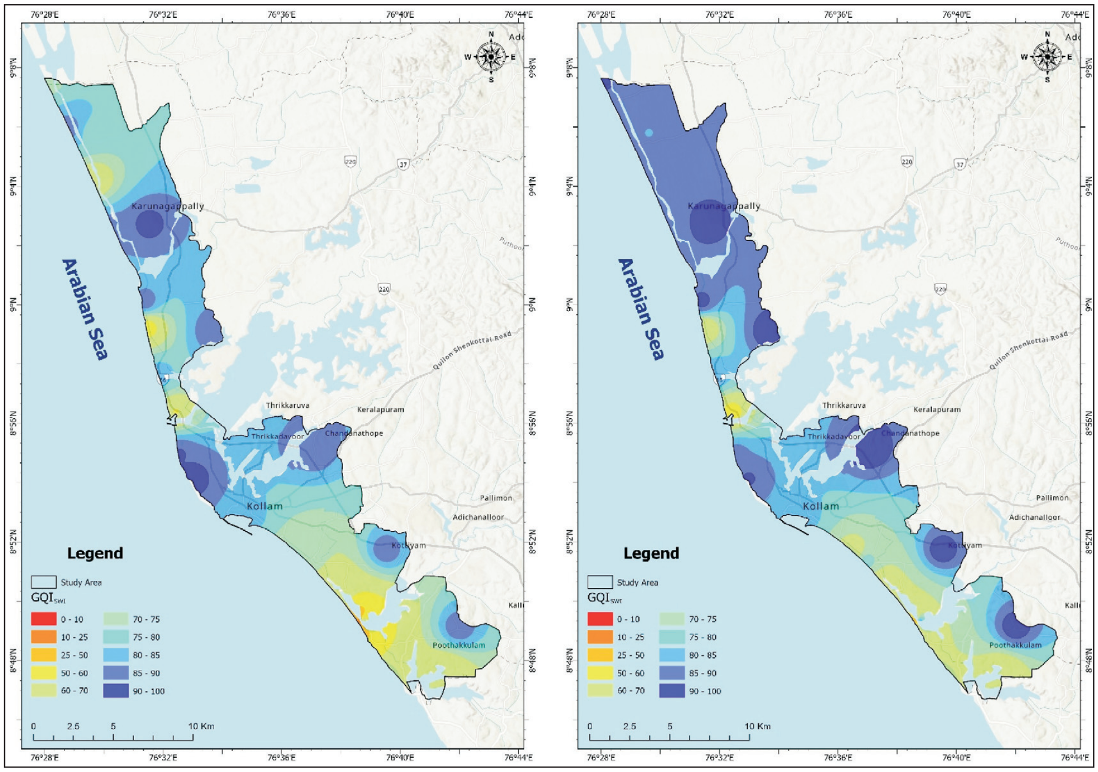

Fig.7. GQI_{SWI} based seawater sea water mixing maps for pre-and post-Monsoon seasons in the study area

Conclusions

This study investigated the extent and seasonal variability of seawater mixing in the coastal aquifers of Kollam District, Kerala, using a comprehensive hydrochemical and index-based approach. Groundwater samples collected during the pre- and post-monsoon seasons of 2022 were analyzed for physicochemical parameters and major ions to trace seasonal salinity evolution and aquifer vulnerability. Two complementary indices—$GQI_{Piper(mix)}$ and GQI_{fsea}—were integrated into a composite Groundwater Quality Index for Seawater Mixing (GQI_{SWI}), offering a quantitative framework to assess the degree of saline intrusion. In addition, traditional tools such as Piper plots and USSL diagrams were employed to classify water types and evaluate irrigation suitability. Results revealed a clear seasonal shift in groundwater quality, with few pre-monsoon samples showing elevated salinity and dominance of Na-Cl facies, indicative of localised seawater ingress. Post-monsoon samples, in contrast, displayed significant freshening of aquifer conditions, supported by a shift toward Ca–HCO_3 facies and a general decline in electrical conductivity and major ion concentrations. These findings underscore the influential role of the southwest monsoon in diluting salinity levels and reversing dry-season saline encroachments. USSL plots further confirmed the irrigation suitability of most samples in both the pre- and post-monsoon seasons, with a temporal improvement in irrigation suitability observed after the monsoon. Localized high-salinity zones were observed even after the monsoon, particularly in isolated patches along the southern and central coastal parts of the study area. This persistence is likely attributed to a combination of limited aquifer thickness, coastal proximity, removal of aquifer material and sustained groundwater abstraction in these regions. In conclusion, while no widespread seawater ingress was detected in the study area, the presence of seasonally dynamic and spatially restricted poor-quality zones emphasizes the need for continuous monitoring and aquifer-specific management strategies. The integration of GQI_{SWI} with hydrochemical and spatial analyses offers a replicable framework for vulnerability mapping and resource planning in similar coastal aquifer systems. Efforts to regulate groundwater abstraction, enhance recharge, and conserve coastal buffer zones are crucial to mitigating long-term salinization risks in the Kollam coastal belt and beyond. This study provides valuable insights into seawater ingress in coastal aquifers, offering a detailed analysis of seasonal variations. However, the study was conducted over a single year, which may not capture long-term trends influenced by inter-annual climate variability or progressive sea-level rise. Additionally, while the GQI_{SWI} index is effective, it could be complemented by isotope or geophysical data for more robust validation. Future research should prioritize multi-year monitoring with expanded sample networks, incorporating additional data from stable isotopes, geophysical surveys, and numerical modelling to enhance the understanding of seawater ingress mechanisms.

Authors' Contributions

VVK: Conceptualization, Investigation and Writing Original Draft. **RUR:** Data Curation, Visualization, Reviewing and Editing. **SK and MS:** Formal analysis and reviewing. **GPM:** Map Preparation and Data Analysis.

Conflict of Interests

The authors do not have any conflict of interest in terms of financial or personal relationship with a third party whose interests could positively or negatively influenced by the article's content research. The ideology addressed in this paper, solely belongs to the authors only and not necessarily of their organizations.

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Data Availability Statement

Derived data supporting the findings of this study will be made available by the corresponding author on request.

References

Abd-Elaty, I., Zelenakova, M., Krajníková, K. and Abd-Elhamid, H. (2021). Analytical solution of saltwater intrusion in coastal aquifers considering climate changes and different boundary conditions. Water, v. 13, pp. 995.

Aju, C.D., Achu, A.L., Mohammed, M.P., Raicy, M.C., Gopinath, G. and Reghunath, R. (2024). Groundwater quality prediction and risk assessment in Kerala, India: a machine-learning approach. Jour. Environ. Manag., v. 370, pp. 122616.

Aladejana, J., Kalin, R., Sentenac, P. and Hassan, I. (2021). Groundwater quality index as a hydrochemical tool for monitoring saltwater intrusion into coastal freshwater aquifer of eastern Dahomey Basin, southwestern Nigeria. Groundwat. Sustain. Dev., v. 13, pp. 100568.

Anisha, K., Joji, V.S., Vijesh, V.K. and Anitha Shyam, T.S. (2025). Incidence of brackishness in ground water from bore wells drilled in deeper aquifers in parts of Kozhikode District, Kerala, southern India. Jour. Geosci. Res., v. 10(1), pp. 1–12.

Appelo, C.A.J. and Postma, D. (2005). Geochemical reactions in seawater intrusion. *In*: Geochemistry, groundwater and pollution, 2nd edn, CRC Press, London, 634p.

APHA (2017). Standard Methods for the Examination of Water and Wastewater, 23rd Edition. American Public Health Association, Washington, D.C.

Balamurali Krishna, V. and Sivanandan Achari, S. (2023). Groundwater chemistry and entropy weighted water quality index of tsunami affected and ecologically sensitive coastal region of India. Heliyon, v. 9(10), pp. e20431.

Barlow, P.M. and Reichard, E.G. (2010). Saltwater intrusion in coastal regions of North America. Hydrogeol. Jour., v. 18(1), pp. 247–260.

Bear, J., Jacob, C.E., Cheng, A.H.D., Sorek, S., Ouazar, D. and Herrera, I. (1999). Seawater intrusion in coastal aquifers: Concepts, methods and practices. Theory and Applications of Transport in Porous Media, Kluwer Academic Publishers, Dordrecht, 625p.

Bhattacharya, R. (2020). Seawater intrusion in the coastal aquifers of India - A review. Hydro Res., v. 3, pp. 61–74.

CGWB (1992). SIDA Assisted Coastal Kerala Ground Water Project (1983–88). Unpublished Technical Report, Central Ground Water Board, Kerala Region, Thiruvananthapuram.

CGWB (2023a). Ground Water Quality in Shallow Aquifer of India. Ministry of Jal Shakti, Government of India, New Delhi.

CGWB (2023b). Ground water exploration in Kerala as on 31.03.2022. Unpublished Technical Report, Central Ground Water Board, Kerala Region, Ministry of Jal Shakti, Government of India, Thiruvananthapuram.

Ferguson, G. and Gleeson, T. (2012). Vulnerability of coastal aquifers to groundwater use and climate change. Nat. Clim. Change, v. 2(5), pp. 342–345.

Fernandes, L.L., Kessarkar, P.M., Narvekar, J. and Ray, D. (2025). Seasonal nutrient loadings in four monsoonal micro/meso tidal tropical estuaries, west coast of India. Mar. Environ. Res., v. 203, pp. 106845.

Girish, S. and Sreedevi, P.A. (2024). Multivariate insight into seasonal hydrogeochemical variations in coastal aquifers of Kerala, South India. Environ. Sci. Pollut. Res. (Advance online publication, 2025).

GSI (1995). Geological and Mineralogical Map of Kerala. Geol. Surv. India, Calcutta.

Halder, S., Mandal, R. and Mukhopadhyay, D. (2021). Seasonal groundwater quality assessment of coastal aquifers using multivariate analysis and hydrochemical modeling. Environ. Earth Sci., v. 80(15), pp. 602.

Hussain, S.M., Anbalagan, S., Kumar, K.S., Neelavannan, K., Pradhap, D., Radhakrishnan, K., Godson, P.S. and Krishnakumar, S. (2020). A baseline study on elemental concentration and potential ecological risk status of the surface sediments of Ashtamudi Lake, southwest coast of India. Mar. Pollut. Bull., v. 158, pp. 111410.

IMD (2023). Station wise Rainfall Data for Kerala (Kollam District) (2013–2022). India Meteorological Department, https://mausam. imd.gov.in/ thiruvananthapuram/

IBM (2022). Indian Minerals Yearbook 2022 (Part-III: Mineral Reviews) – Ilmenite and Rutile (Advance Release). 61st ed. Government of India, Ministry of Mines, Nagpur.

IPCC (2021). Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *In*: V. Masson-Delmotte *et al*. (*Eds.*), Cambridge University Press, Cambridge, 2391p.

Jena, M.R., Tripathy, J.K., Sahoo, D. and Sahu, P. (2024). Geochemical evaluation of groundwater quality in the coastal aquifers of Kujang Block, Jagatsinghpur District, eastern Odisha, India. Water Air Soil Pollut., v. 235, pp. 71.

Joseph, A.M. and Gandhi, M.S. (2025a). Spatial Distribution Analysis of Seasonal Variation in Salinity Stratification at Vembanad Estuary, Kerala, India. Jour. Geosci. Res., v. 10(1), pp. 36–43.

Joseph, A. and Gandhi, M.S. (2025b). Seasonal impact of river influx on the textural characteristics of Vembanad Lake sediments, Kerala, India. Jour. Sediment. Environ., pp. 1–21.

Kelly, D.J. (2006). Development of seawater intrusion protection regulations. *In*: Intrusion in Sedimentary Aquifers, Section 6, pp. 135–146.

Khan, A.F., Srinivasamoorthy, K., Prakash, R. and Rabina, C. (2021). Hydrochemical and statistical techniques to decode groundwater geochemical interactions and saline water intrusion along the coastal regions of Tamil Nadu and Puducherry, India. Environ. Geochem. Health, v. 43, pp. 1051–1067.

Krishnakumar, A. and Prijilal, K.G. (2015). Groundwater chemistry of Neyyar and Karamana basins, Kerala with special reference to salinity intrusion problems in the coastal urban environment. *Proc.* National Seminar Recent and Emerging Advances in Chemical Sciences (REACS – 2015), Trivandrum, pp. 45–50.

KSLUB (2014). Natural resources data bank - Kollam District. Kerala State Land Use Board, Thiruvananthapuram.

Kumar, R., Sankar, S. and Reason, C. (2009). An investigation into the conditions leading to monsoon onset over Kerala. Theor. Appl. Climatol., v. 95, pp. 69–82.

Kunjupillai, S. (2025). Geomorphic setting and geologic features of Kerala and their link to eco-hydrology of the region. *In*: S.G.T. Vincent, T.C. Jennerjahn, S. Kunjupillai and S. Chattopadhyay (*Eds.*), Ecohydrology from catchment to coast: Ecohydrology of Kerala, Elsevier, pp. 7–23.

Laluraj, C.M. and Girish Gopinath (2006). Assessment on seasonal variation of groundwater quality of phreatic aquifers – a river basin system. Environ. Monit. Assess., v. 117(1–3), pp. 45–47.

Moorthy, P., Rajesh, K. and Srinivas, K. (2024). Application of GQISWI and hydrogeochemical modeling for groundwater quality assessment in coastal Tamil Nadu districts. Environ. Sci. Pollut. Res., v. 31(18), pp. 21529–21547.

Nagarajan, R., Kumar, A., Hussain, S.M., Jonathan, M.P., Ramkumar, M., Eswaramoorthi, S.G., Agus, S. and Chua, B. (2018). Geochemical characterization of beach sediments of Miri, NW Borneo, SE Asia: Implications on provenance, weathering intensity, and assessment of coastal environmental status. *In*: Coastal Zone Management: Global Perspectives, Regional Processes, Local Issues, Elsevier, pp. 279–330.

Nair, K., Padmalal, D., Kumaran, N., Sreeja, R., Limaye, R. and Srinivas, R. (2010). Late Quaternary evolution of Ashtamudi–Sasthamkotta lake systems of Kerala, southwest India. Jour. Asian Earth Sci., v. 37, pp. 361–372.

Piper, A.M. (1944). A graphic procedure in the geochemical interpretation of water analyses. Eos Trans. Am. Geophys. Union, v. 25(6), pp. 914–928.

Pitchaimani, R., Kumar, S. and Narayanasamy, R. (2024a). Assessment of coastal aquifer vulnerability to seawater intrusion: Insights from Kadaladi region using the GALDIT model. Groundwat. Sustain. Dev., v. 25, pp. 101166.

Pitchaimani, V., Stephen, R.J., Shyamala, G., Manjula, G., Hemalatha, B., Dinesh, M., Ezhil, S. and Ravindran, G. (2024b). Multivariate statistical and hydrogeochemical analysis of seasonal groundwater quality variations in coastal villages of Trivandrum district, south India. Discov. Sustain., v. 5, pp. 1–20.

Prusty, P. and Farooq, S.H. (2020). Seawater intrusion in the coastal aquifers of India – a review. Hydro Res., v. 3, pp. 61–74.

Pulido-Leboeuf, P. (2004). Seawatter intrusion and associated processes in a small coastal complex aquifer (Castell de Ferro, Spain). Appl. Geochem., v. 19(10), pp. 1517–1527.

Rajasekharan, M., Suresh, G., Kumar, P.S. and Vishnu, R. (2023). Soil fertility and nutrient management in coastal agro-ecosystems of Kerala. Jour. Trop. Agric., v. 61(2), pp. 145–158.

Raju, R.D. (2021). Indian Placer Deposits. Cambridge Scholars Publishing, 312p.

Raveendran, A., Vasanthakumari, P., Simpson, L.T., Reju, R.G. and Pillai, R.R. (2023). Analysing the Shoreline Dynamics Along the Southern Coastal Region of Kerala: A Case Study of Kollam District in Kerala. Geo-Eye, pp. 1–15.

Renu, S., Pramada, S.K. and Yadav, B. (2024). Seawater intrusion susceptibility and modeling: a case study of Kerala, India. Acta Geophysica, v. 73, pp. 1476.

Ribinu, S.K., Prakash, P., Khan, A.F., Bhaskar, N.P. and Arunkumar, K.S. (2023). Hydrogeochemical characteristics of groundwater in Thoothapuzha River Basin, Kerala, South India. Tot. Environ. Res. Themes, v. 5, pp. 100021.

Roman-Stork, H.L., Subrahmanyam, B. and Murty, V.S.N. (2020). The role of salinity in the southeastern Arabian Sea in determining monsoon onset and strength. Jour. Geophys. Res.: Oceans, v. 125(1), pp. e2019JC015592.

Saleena Vahid, N., Binoj Kumar, R.B., Shaji, E. and Noble, J. (2025). Hydrochemical characteristics and groundwater assessment of a multi-aquifer system in Alappuzha area, South India. Jour. Geointer., v. 4(1), pp. 104–124.

Sanjeev Kumar, K.S., Radhakrishnan, E.V. and Jayappa, K.S. (2013). Disposition of aquifer system, geo-electric characteristics and gamma-log anomaly in the Kuttanad alluvium of Kerala. Jour. Geol. Soc. India, v. 81(2), pp. 183–190.

Senthilkumar, S., Balasubramanian, B., Gowtham, B. and Lawrence, S. (2014). Geochemical signatures of groundwater in the coastal aquifers of Thiruvallur district, south India. Appl. Water Sci., v. 4(3), pp. 213–224.

Shaji, E., Vinayachandran, N. and Thambi, D. (2009). Hydrogeochemical characteristics of groundwater in coastal phreatic aquifers of Alleppey district, Kerala. Jour. Geol. Soc. India, v. 74, pp. 585–590.

Sindhu, G., Ashith, M., Jairaj, P.G. and Reghunath, R. (2012). Modelling of coastal aquifers of Trivandrum. Proced. Eng., v. 38, pp. 3434–3448.

Singh, S., Gautam, P., Kumar, P., Biswas, A. and Sarkar, T. (2021). Delineating the characteristics of saline water intrusion in the coastal aquifers of Tamil Nadu, India by analysing the Dar-Zarrouk parameters. Contrib. Geophys. Geod., v. 51(2), pp. 141–163.

Singhal, B. and Gupta, R.P. (2010). Applied Hydrogeology of Fractured Rocks. Springer, 408p.

Sureshkumar, P., Geetha, P. and Bhindu, P.S. (2023). Chemistry and fertility—Management of humid tropical soils of Kerala as influenced by topography and climate. Ind. Jour. Fertilis., v. 14(3), pp. 30–44.

Suraj, P.R., Krishnakumar, K.N., Induja, K.N. and Anish, A.U. (2019). Hydrogeochemical characterisation of groundwater in coastal aquifers of Kollam district, southern Kerala, India. Poll. Res., v. 38 (Nov. Suppl. Issue), pp. S18–S22.

Tomaszkiewicz, M., Abou Najm, M. and El-Fadel, M. (2014). Development of a groundwater quality index for seawater intrusion in coastal aquifers. Environ. Model. Softw., v. 57, pp. 13–26.

U.S. Salinity Laboratory Staff (1954). Diagnosis and Improvement of Saline and Alkali Soils. USDA Agriculture Handbook No. 60, Washington, D.C., USA, 160p.

Vandenbohede, A. and Lebbe, L. (2012). Groundwater chemistry patterns in the phreatic aquifer of the central Belgian coastal plain. Appl. Geochem., v. 27, pp. 22–36.

Werner, A.D., Bakker, M., Post, V.E.A., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., Simmons, C.T. and Barry, D.A. (2013). Seawater intrusion processes, investigation, and management: Recent advances and future challenges. Adv. Water Resour., v. 51, pp. 3–26.