J. Indian Soc. Coastal Agric. Res. 41(2): 36-51 (2023) https://doi.org/10.54894/JISCAR.41.2.2023.131676

Assessment and Characterization of Groundwater Quality of Malabar Coast in Kerala, India

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Received: 26.12.2022 Accepted: 21.09.2023

A study was conducted to assess and characterize the groundwater quality of the coastal aquifer of the Vatakara-Koyilandy stretch in the Kozhikode district of Kerala. The trend in groundwater levels was analyzed using the Mann-Kendall test. To determine the chemical facies of the groundwater and understand the evolution of hydrochemical parameters, the Piper diagram was employed. The Gibbs diagram was used to describe the source of the dissolved ions in the groundwater. The suitability of groundwater for irrigation was evaluated using the United States Salinity Laboratory diagram. Geostatistical tools were utilized to examine the spatial variability of groundwater levels and salinity, and the ordinary kriging method was employed to create spatial variability maps. The study revealed that Na^+ was the predominant cation with maximum concentration varying from 455.6 mg L^{-1} to 1844 mg L^{-1} during pre-monsoon and post-monsoon seasons, respectively. The concentration of Cl^- in pre-monsoon and post-monsoon varied from 184 mg L^{-1} to 2417 mg L^{-1} and 99 mg L^{-1} to 714 mg L^{-1}, respectively. The presence of these ions indicated the mixing of seawater with groundwater as the primary source. The study also highlighted the high salinity levels of the groundwater, making it unsuitable for irrigation in most of the areas. Additionally, negative trends in groundwater levels were observed in confined and semi-confined aquifers, with wells near the coasts showing a significant decreasing trend. These findings emphasize the need for careful management and monitoring of the coastal aquifers to ensure sustainable water resources in the region.

(***Key words:*** *Aquifer characterisation, Geostatistics, Groundwater, Hydrochemical analysis, Seawater intrusion, Trend analysis*)

Large-scale groundwater extraction to meet the increasing water demand due to rapid urbanisation and expansion of agriculture is causing land subsidence and saltwater intrusion along the coast in several regions(Bhagat *et al.,* 2021; Boumaiza *et al.,* 2022; Hasan *et al.,* 2021). Deterioration in groundwater quality due to seawater intrusion in the coastal aquifer is a widespread environmental hazard (Albuquerque *et al.,* 2013; Alfarrah *et al.,* 2011; Subba Rao, 2006). Groundwater becomes unfit for human consumption and irrigation due to seawater-freshwater interactions (Prusty and Farooq, 2020; Soujanya Kamble *et al.,* 2020). Excessive pumping in coastal aquifers causes a decline of groundwater level and reversal of hydraulic gradient which results in the movement of seawater into the freshwater aquifer.

The migration of saline water into the fresh groundwater zone is known as seawater intrusion which is a serious concern in coastal regions. Seawater intrusion is most common among the various salinisation sources, followed by inland salinity of groundwater, oil and gas-field brine, halite dissolution, and domestic, agricultural, and industrial effluents (Alfarrah *et al.,*

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2011). When coastal aquifers are pumped at a faster rate, the groundwater level drops, allowing seawater to infiltrate the freshwater due to a reverse hydraulic gradient. Large-scale seawater intrusion has occurred in coastal places worldwide due to sea-level rise, extreme weather events, changing precipitation patterns, and groundwater depletion (Mohd Isaand Aris, 2012). If seawater intrusion is not controlled along the coast, then it will spread to the inland aquifer, causing water quality to deteriorate due to saltwater up-coning as well. Even less mixing of seawater with freshwater renders it unfit for human consumption, while slightly greater amounts make it unfit for irrigation (Paniconi *et al.,* 2001).

The deterioration in groundwater quality can be determined by analysing the concentration of the chemical components which is highly influenced by geological and human actions (Saravanan *et al.,* 2011; Wu *et al.,* 2017). There are several studies on hydro-geochemical analysis for determining the hydrochemical facies of the groundwater and identifying the evolution of hydrochemical parameters of groundwater sources (Ali and Ali, 2018; Prathap and Chakraborty, 2019; Sangadi *et al.,* 2022; Shiyan *et al.,* 2022). The functional sources of chemical constituents in the groundwater were studied (Lanjwani *et al.,* 2022; Ravish *et al.,* 2019; Sangadi *et al.,* 2022) by preparing the Gibbs diagram. Information on the suitability of the contaminated groundwater due to its salinity hazard was explored using the United States Salinity Laboratory (USSL) diagram in many studies (Sangadi *et al.,* 2022; Sathiamoorthy and Ganesan, 2018). Identifying the trends in long-term groundwater level and salinity data using the non-parametric Mann-Kendall test can give insight into the sustainability of the groundwater sources for irrigation water management (Das *et al.,* 2020; Gibrilla *et al.,* 2018; Sahoo *et al.,* 2021). Geostatistical methods are widely used for developing spatial prediction maps of groundwater level, contamination and its constituents (Arslan, 2012; Boudibi *et al.,* 2021; Lanjwani *et al.,* 2022).

Kerala has about 600 km long coastline. Decadal pre-monsoon and post-monsoon water level trends (1996-2005) suggest groundwater levels are declining at the rate of 0.1 m y^{-1} or more in 13% and 30% of monitoring wells, respectively (Ravi, 2005; Shaji *et al.,* 2009). The shallow aquifers that draw water from the coastal alluvium are mostly fresh, while a few isolated areas near lakes, tidal rivers, and backwater channels may be saline throughout the summer. Water in shallow wells near backwaters, lagoons, lakes, and tidal rivers is saline. During the summer, Kerala's rivers frequently experience saline water intrusion in their lower reaches. As the freshwater in these water bodies reduces, seawater intrudes upstream, in turn, the pumped wells adjacent to the river discharge saline water. The Kuttiady is one such river in the Kozhikode district of Kerala which is affected by this problem (Shaji, 2011).

Jesiya and Gopinath (2013) conducted a study to evaluate the groundwater quality of phreatic aquifers along urban clusters of Kozhikode coast. The analytical results showed the abundance of the ions in the following order $Na^{+} > Ca^{2+} > Mg^{2+} > K^{+} = HCO_3^{-} > Cl^{-} > SO_4^{2-}$. Na/Cl ratio indicates that 14% of the wells in the study area are affected by saline water Intrusion to some degree and 10% showing Na/Cl ratio greater than 1 may be indicative of anthropogenic contamination. Sukumaran and Raj (2020) studied the saline water intrusion to urban coastal area of Kozhikode district. The TDS value of groundwater samples which lies sides of Kuttiady river showed greater than 2000 mg L^{-1}. EC and TDS values of groundwater samples riverside beyond the permissible limits indicated the intrusion into the aquifer from the river. Salaj *et al.* (2018a) also reported the high salinity more than 800 mg L^{-1} found extending up to 2 km from the shoreline along the eroded tracts of Kozhikode coast. The present study was conducted to investigate the groundwater quality in the coastal region of the Malabar coast in Kozhikode district of Kerala, India and characterisation of groundwater in this region for effectively managing the coastal aquifer.

MATERIALS AND METHODS

Study area description

The Vatakara-Koyilandy coastline stretch is part of Kerala's Kozhikode coast, which is also known as the Malabar coast. The shore is 25 kilometres long and is located 20 kilometres north of Kozhikode, Kerala. It is located between 75° 73′ to 75° 62′ East longitudes and 11° 42′ to 11° 56′ North latitudes, with a total area of 270 km^2 (Fig.1). The west of the research area is bounded by the Arabian Sea. The study area has a humid subtropical

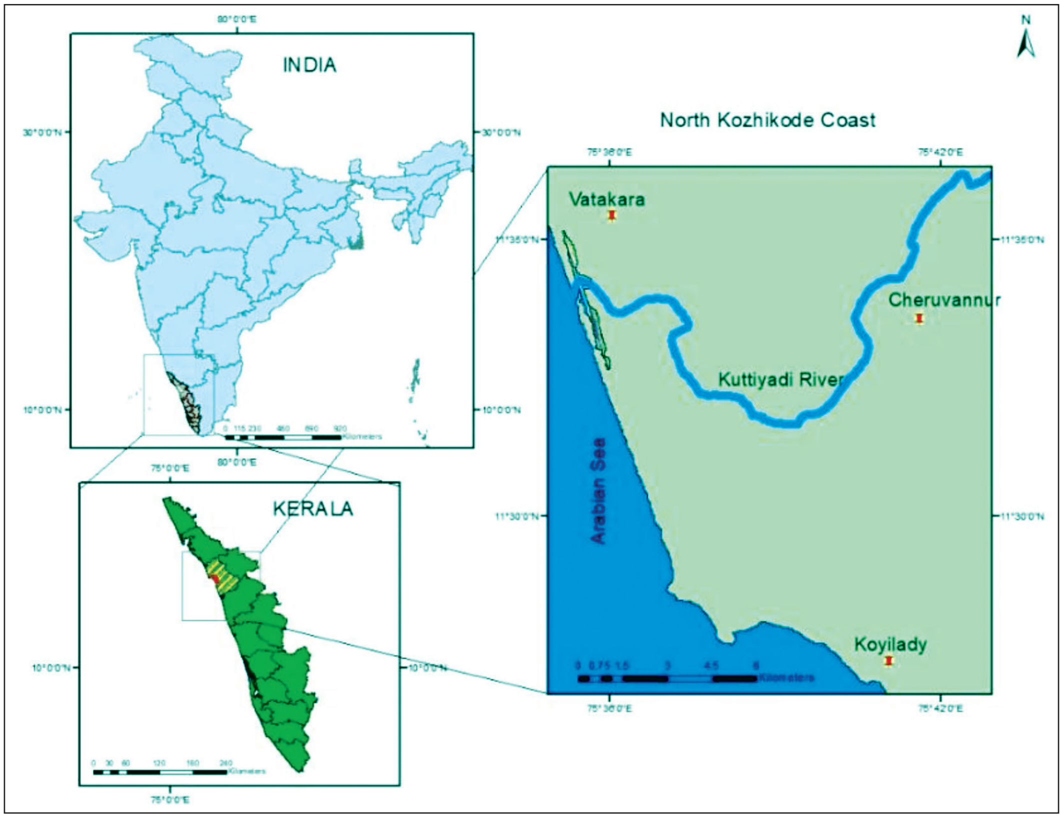

Fig.1. *Study area location map*

climate with an average temperature of 27°C. The average annual rainfall in the area is 2700 mm. Of this 65% is received during the North-east monsoon and 25% is received during the South-west monsoon. The rest of the rainfall occurs in other months.

The soil types in the region are coastal alluvial soil in coastal plain and in low-lying areas. Riverine alluvial soils are found along river banks. At some places red loam soil and brown hydromorphic soil are also found (KSPCB, 2019; Nair, 1987; Nazimuddin, 1993). The alluvium deposits are underlain by laterite and sedimentary rocks, mostly charnockites with mafic granulite enclaves. The coastal zone is covered by excessively drained to moderately drained sandy deposits, and the alluvium deposits are covered by excessively drained to moderately drained sandy deposits (CGWB, 2013; KSPCB, 2019; Salaj *et al.,* 2018b). Groundwater in weathered crystalline is present under unconfined conditions and semi-confined in deep crystalline formations. Groundwater table depth ranges from 0.73 m to 16.11 m below ground level (CGWB, 2013). The well logs of representative wells suggest aquifer consists of three layers namely; the top unconfined layer, an aquitard and a semi-confined aquifer at the bottom (Fig. 2). The soil conditions are ideal for growing coconuts, spices, and plantation crops, and are average for other crops. Coconut, spices, paddy and plantation crops are the most important crops cultivated in the study area.

The Kuttiyadi River which flows through this region originates from the Banasura peak in the Naripatta hills in Wayanad and flows for 74 km until joining the Arabian Sea near Kottackal. The river drains a total area of 583 km^2. The river flows through evergreen forests in the upper catchment and densely populated midlands and plains with rubber, coconut, and rice fields. Kuttiyadi irrigation project (Peruvannamuzhi dam) in the upstream catchment provides the drinking water needs of Kozhikode Corporation and surrounding villages. Hence maintaining the Kuttiyadi River's water quality at suitable levels is essential. Seawater intrusion is a major problem that affects the quality of water in the

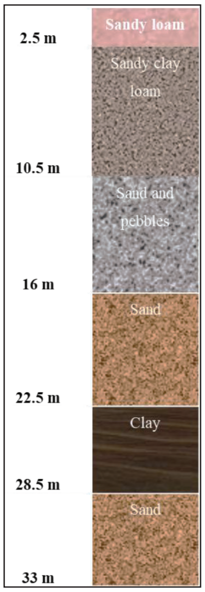

Fig. 2. *Well log of the exploratory well in the study area*

Kuttiady river and adjoining aquifers. During low flows the tidal water causes seawater intrusion into the river up to 24 km upstream (Sukumaran and Raj, 2020). With a decrease in groundwater recharge and an increase in water demand throughout the summer, the severity of seawater intrusion has increased over the years. The salinization of groundwater systems is adversely affecting the water supply for agriculture and domestic sectors (Sukumaran and Raj, 2020).

Data collection

Water samples from the pumped wells and river were collected from different locations monthly from 2020 June to 2021 May. The sampling in the river was done starting from the river mouth to 22 km along the river. The interval between the sampling points was 1.0 km up to 3.0 km in length and 2-5 km afterwards. Groundwater wells located 100 m and 200 m away from the river were selected for water sampling. The water quality was analysed in the water quality laboratory of CWRDM, Kozhikode as per standard methods specified by the American Public Health Association (APHA, 2017; Jesiya and Gopinath, 2013). Water quality parameters analysed were Sodium (Na^+), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Potassium (K^+), Chloride (Cl^-), Sulphate (SO_4^{2-}), Bicarbonate (HCO_3^-), total dissolved salts (TDS), electrical conductivity (EC) and pH.

Data on groundwater level and salinity were also collected from the State Groundwater Department, State Public Health Department and the Central Groundwater Board. Data from 10 observation wells in the unconfined aquifer and 9 piezometers in the semi-confined aquifer observed between 2005 and 2020 were used to study the spatial variation of groundwater salinity and water levels of pre-and post-monsoon periods were used in the analysis.

Data analysis

The statistical analysis was performed on water quality parameters to determine the minimum, maximum, mean and standard deviation. Mann-Kendall Test was used to detect the trend in the annual rainfall series.

Mann-Kendall test

The trend in the annual rainfall series was detected by applying the non-parametric Mann-Kendall test (Das *et al.,* 2020; Kendall, 1975; Mann, 1945; Motevalli *et al.,* 2018; Shaji *et al.,* 2009). The magnitude of the slope was estimated using the Sen slope estimator (Sen, 1968). The test was conducted with the null hypothesis (H_0) that there is no trend in the series and the alternative hypothesis that there was a trend in the series.

The Mann-Kendal-statistic S is given as:

$$S = \sum_{i=1}^{n=1} \sum_{j=i+1}^{n} \left(Sign\left(x_j - x_i\right)\right) \qquad \text{... 1}$$

where,

$$Sign\left(x_j - x_i\right) = \begin{cases} 1\; if x_j - x_i > 0 \\ 0\; if x_j - x_i = 0 \\ -1\; if x_j - x_i < 0 \end{cases}$$

The variance of S denoted by (σ_s^2) was computed from Eq. 2.

$$\sigma_s^2 = \frac{n(n-1)(2n+5) - \sum_{j=1}^{q} t_j\left(t_j - 1\right)\left(2t_j + 5\right)}{18} \qquad \text{... 2}$$

where, n is the number of data points, q is the number of tied groups in the data set and t_j is the number of data points in jth tied group.

Then S and σ_s^2 were used to compute the test statistics Z_s as:

$$Z_s = \begin{cases} \frac{S-1}{6} if S > 0 \\ 0 \qquad if S = 0 \\ \frac{S+1}{6} if S < 0 \end{cases} \qquad \text{... 3}$$

An increasing trend is indicated by a positive value of S and a decreasing trend is indicated by a negative value. The null hypothesis H_0 that there is no trend in the data is either accepted or rejected if the computed Z_S statistic is less than or more than the critical value of Z-statistics obtained from the normal distribution table at a 5% significance level.

The nonparametric Sen's method was used to estimate the slope. This involves computing slopes for all the pairs of time points and then using the median of these slopes as an estimate of the overall slope. The equation to estimate slope is given by Eq. 4.

$$Q_i = \frac{x_j - x_k}{j - k} \quad \ldots 4$$

where, j > k. If there are n values x_ji series, we get as many as $N = ((n+1)/2)$ slope estimate Q_i. Sen's estimator of slope is simply given by the median of these N values of Q_i's.

$Q = Q_{([(N+1)/2)]}$ if N is odd

$Q = (Q_{[N/2]} + Q_{[(N+2)/2]})/2$ if N is even.

Q_{med} was computed by a two-sided test at 100 (1-α) % confidence interval. An increasing trend in time series is indicated by a positive value and a decreasing trend by a negative value.

Hydrochemical analysis

Data on the concentration of major ions such as HCO_3^-, Cl^-, Ca^{2+}, Mg^{2+}, Na^+, etc. K^+ was used for hydrochemical analysis using the Piper diagram. The trilinear Piper diagram proposed by (Ali and Ali, 2018; Piper, 1944, Sangadi *et al.,* 2022, Shin *et al.,* 2020,) was applied to plot the concentration of major cations and anions to determine the chemical facies of the groundwater to identify the evolution of hydrochemical parameters of groundwater sources.

The Trilinear Piper diagram was constructed with the help of Geochemical Analyst software version 2015.1.14.

Mechanism governing the groundwater chemistry

Gibb's diagram is a tool for understanding the various mechanisms and processes involved in groundwater chemistry (Gibbs, 1970; Sangadi *et al.,* 2022). The source of the dissolved ions in the groundwater can be understood by the Gibbs diagram which is a plot of $(Na^+)/(Na^+ + Ca^{2+})$ vs TDS and $Cl^-/(Cl^- + HCO_3^-)$ vs TDS. Gibbs diagram was prepared with the help of GRAPHER software.

Irrigation water quality

The United States Salinity Laboratory diagram (USSL diagram) for the suitability of water for agricultural uses was used to determine the suitability of groundwater for irrigation. Sodium percentage determines the ratio of sodium to the total cations *viz.*, sodium, potassium, calcium and magnesium. The diagram was prepared using GRAPHER software.

Sodium adsorption ratio (SAR) was estimated using the following formula.

$$SAR = \frac{Na^+}{\frac{\sqrt{Ca^{2+} + Mg^{2+}}}{2}} \quad \ldots 5$$

where, the ionic concentrations are expressed in meq L^{-1}.

Spatial variation of groundwater level and salinity

Geostatistical tools were used to describe the spatial variability of groundwater levels and salinity using ArcGIS 10.7.1. The spatial structure is quantified by using a semivariogram. In this study, the salinity and water level data in observation wells and piezometers measured in the year 2005 and 2020 were used for developing the spatial interpolation map and log-normal transformation was applied to the data. Ordinary kriging was used to plot the spatial variability map of groundwater salinity and levels. After fitting the best theoretical model for each parameter, the spatial prediction maps were prepared using ordinary kriging for electrical conductivity and groundwater level for the unconfined and semi-confined aquifers.

Ordinary kriging

Kriging involves both mathematical and statistical methods (Isaaks and Srivastava, 1989).This interpolation is based on the semi-variogram which is defined as half the average squared difference between the attribute values at all points separated by a lag distance h (Eq.6).

$$\gamma(h,\alpha) = \frac{1}{2N(h,\alpha)} \sum_{i=1}^{N(h)} [z(x_i + h) - z(x_i)]^2 \quad \ldots 6$$

where, $\gamma(h,\alpha)$: semivariance as a function of both the magnitude of the lag distance or separation vector (h) and its direction (α), $N(h,\alpha)$: number of observation pairs separated by h and direction α used in each summation, $Z(x_i)$: random variable at location x_i.

The kriging equation is given by Eq. 7.

$$Z^*(x_0) = \sum_{i=1}^{n} \lambda_i . Z(x_i) with \sum_{i=1}^{n} \lambda_i = 1 \quad \ldots 7$$

where, $Z^*(x_0)$: random variable at the location, x_0, $Z(x_i)$: measured value at a location x_i, λ_i: weighting factor assigned to $Z(x_i)$ and n: number of observations.

RESULTS AND DISCUSSION

Statistical summary of water quality pre-monsoon and post monsoon seasons

The range of the electrical conductivity in the study area varied between 4.30 dS m^{-1} to 0.76 dS m^{-1} during pre-monsoon and 1.96 dS m^{-1} to 0.66 dS m^{-1} in post-monsoon. The TDS in pre-monsoon season varied from 2.79 kg m^{-3} to 0.51 kg m^{-3} and in post-monsoon and in post-monsoon it varied from 1.28 kg m^{-3} and 0.36 kg m^{-3} (Table 1). Data showed Na^+ was the predominant cation with a maximum concentration of 1844 mg L^{-1} and 455.6 mg L^{-1} during pre-monsoon and post-monsoon; respectively. Other cations with higher concentrations were K^+, Mg^{2+} and Ca^{2+} with an average concentration of 440.45 mg L^{-1}, 324.68 mg L^{-1} and 226.89 mg L^{-1} in pre-monsoon and 196.89 mg L^{-1}, 139.09 mg L^{-1} and 139.09 mg L^{-1} in post-monsoon respectively.

Table 1. *Statistical data for the analysed groundwater samples*

	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-	TDS	EC	pH
Pre-monsoon										
Minimum	58.61	29	119	54.32	74	45	184	0.51	0.76	6.8
Maximum	492.6	786.3	1844	1023	196.6	1146	2417	2.79	4.30	8.6
Mean	226.89	324.68	697.50	440.45	129.59	239.79	755.76	1.41	2.11	8.1
STDV	133.26	250.08	473.54	344.66	36.961	363.44	620.56	0.71	1.10	0.6
Post-monsoon										
Minimum	41	22	74.3	39.8	53.8	30.2	99	0.36	0.66	6.9
Maximum	251	314	455.6	428	128	425	714	1.28	1.96	8.1
Mean	107.45	139.09	312.89	196.89	75.88	110.73	327.96	0.75	1.12	7.6
STDV	59.42	91.42	138.19	142.12	19.38	136.42	211.92	0.26	0.44	0.5

Ca^{2+}: Calcium (mg L^{-1}), Mg^{2+}: Magnesium (mg L^{-1}), Na^+: Sodium (mg L^{-1}), K^+: Potassium (mg L^{-1}), HCO_3^-: Bicarbonate (mg L^{-1}), SO_4^{2-}: Sulphate (mg L^{-1}), Cl^-: Chloride (mg L^{-1}), TDS: Total Dissolved Salts (kg m^{-3}), EC: Electrical conductivity (dS m^{-1})

The chloride concentration in pre-monsoon varied from 184 mg L^{-1} to 2417 mg L^{-1} and in post-monsoon it varied from 99 mg L^{-1} to 714 mg L^{-1}. Other anions were SO_4^{2-} and HCO_3^- with an average concentration of 239.79 mg L^{-1} and 129.59 mg L^{-1} in pre-monsoon and 110.73 mg L^{-1} and 75 mg L^{-1} in post-monsoon; respectively. The EC, TDS and concentration of all the anions and cations were found to be decreasing from pre-monsoon to post-monsoon.

Trends in groundwater level, and quality

The results of trend analysis for pre-monsoon groundwater levels in both confined and semi-confined aquifers using the Mann-Kendall test and Sen's slope estimates are given in Tables 2 to 5. All the monitoring wells in both confined and semi-confined aquifers showed negative trends whereas eight wells resulted in a significantly negative trend (Table 2 and Table 3). A significant decreasing trend was observed in wells near the coasts. There was a significant rise in the groundwater salinity in both unconfined and semi-confined aquifers (Table 4 and Table 5). The Mann-Kendall test reveals that the study area is affected by the decline in groundwater level and seawater intrusion during pre-monsoon. The groundwater decline is creating a reverse hydraulic gradient which results in the movement of seawater into the freshwater aquifer (Motevalli *et al.,* 2018). Due to this, the groundwater in parts of the study is becoming unsuitable for drinking as well as irrigation purposes.

Since the test was conducted with a 95% confidence level, the p-value <0.05 was considered to be significant. All the monitoring wells in both confined and semiconfined aquifers in the region showed negative trends whereas eight wells resulted in a significantly negative trend. A significant decreasing trend was observed in wells near the coasts. The salinity was also found to have an increasing trend in both the aquifers. In the unconfined aquifer,wells namely KKDOW019, KPH16, KPH95, KPH96, KPH31 and QKKD060 were found to have a significant falling trend in groundwater levels in the last 15 years. The Z statistic was found to be more than 1.96. Among them, KPH96 showed a strongly falling trend with the highest Sen's slope, 0.22 and a p-value of 0.007. Similarly, in the semi-confined aquifer, W23765,KPH15, KPH65, and L01176 exhibited a significant falling trend in groundwater level. This clearly shows that the groundwater level is declining in both aquifers (Shaji *et al.,* 2009).

Trend analysis on groundwater salinity shows that all the wells have a rising trend with few of them having a significantly rising trend (Das *et al.,* 2020, Sahoo *et al.,* 2021). Wells namely KPH16 and KPH96 had a significantly rising trend in salinity in the unconfined aquifer. Sen's slope varies from 0.005 to 0.01. Similarly, in the semiconfined aquifer, KPH15 and L00994 were found to have significant negative trends.

Table 2. *The trend in groundwater level in the unconfined aquifer*

Pre-monsoon				
Well ID	Z	Sen's slope	p-value	Trend
KKDOW019	-2.3	-0.05	0.02	Fall
KKDOW174	-1.57	-0.008	0.11	Fall
KKDOW176	-1.89	-0.031	0.06	Fall
KPH16	-2.57	-0.036	0.01	Fall
KPH95	-2.07	-0.22	0.03	Fall
KPH96	-2.70	-0.023	0.007	Fall
KPH31	-2.41	-0.014	0.010	Fall
QKKD059	-1.93	-0.045	0.052	Fall
QKKD060	-2.21	-0.023	0.027	Fall

Table 3. *The trend in groundwater level in the semi-confined aquifer*

Pre-monsoon				
Well ID	Z	Sen's slope	p-value	Trend
KPH15	-2.52	-0.046	0.01	Fall
KPH19	-1.31	-0.017	0.19	Fall
KPH65	-2.92	-0.029	0.003	Fall
L00994	-1.35	-0.02	0.17	Fall

Table 4. *The trend in groundwater salinity in unconfined aquifer*

Pre-monsoon				
Well ID	Z	Sens slope	p-value	Trend
KPH16	1.94	0.01	0.05	Rise
KPH95	0.9	0.006	0.36	Rise
KPH96	1.31	0.005	0.19	Rise
KPH31	2.03	0.011	0.04	Rise

Table 5. *The trend in groundwater salinity in the semi-confined aquifer*

Pre-monsoon				
Well	Z	Sens slope	p-value	Trend
KPH15	1.98	0.015	0.04	Rise
KPH19	1.22	0.003	0.22	Rise
KPH65	1.67	0.09	0.09	Rise
L00994	2.17	0.01	0.02	Rise

The Z statistics were 1.98 and 2.17 and the p-value was 0.04 and 0.02 respectively. The groundwater table is gradually decreasing to below sea level due to the over-pumping of freshwater sources thereby causingthe rising of saltwater at the up-coning zone and sub-surface movement of seawater from the sea (CGWB, 2013; Salaj *et al.,* 2018b).

There is a significant risein the groundwater salinity in both unconfined and semi-confined aquifers. The Mann-Kendall test reveals that the coastal aquifer in Vadakara, Kozhikode North is being affected by the decline in groundwater and seawater intrusion (Salaj *et al.,* 2018). The groundwater decline causes the seawater to intrude into the groundwater over the years (Motevalli *et al.,* 2018; Prusty and Farooq, 2020; Salaj *et al.,* 2018b), which makes the groundwater unsuitable for drinking as well as irrigation (Salaj *et al.,* 2018b).

Hydrochemical facies

The results of the Piper diagram for the pre-monsoon season in the year 2020 are presented in Fig. 3. On the cationic triangle, the samples fall within the limits for Na^+, Ca^+ and K^+. In 2020, the most dominant cations were Na^+ and K^+ and the dominant anions were SO_4^- and Cl^-. Hydrogeochemical facies were Na-Cl followed by Ca-Mg-Cl which indicates the influence of seawater intrusion or upconing into the coastal aquifer (Alfarrah *et al.,* 2011; Shin *et al.,* 2020). Furthermore, the dominant cations and anions were from seawater indicating the mixing of seawater with the groundwater (Slama and Sebei, 2020).

Groundwater chemistry

The Gibbs plot I of the ratios of anions vs TDS (Fig. 4) showed a higher concentration of Cl^- proportion in most of the samples, indicating that Cl^- ions might

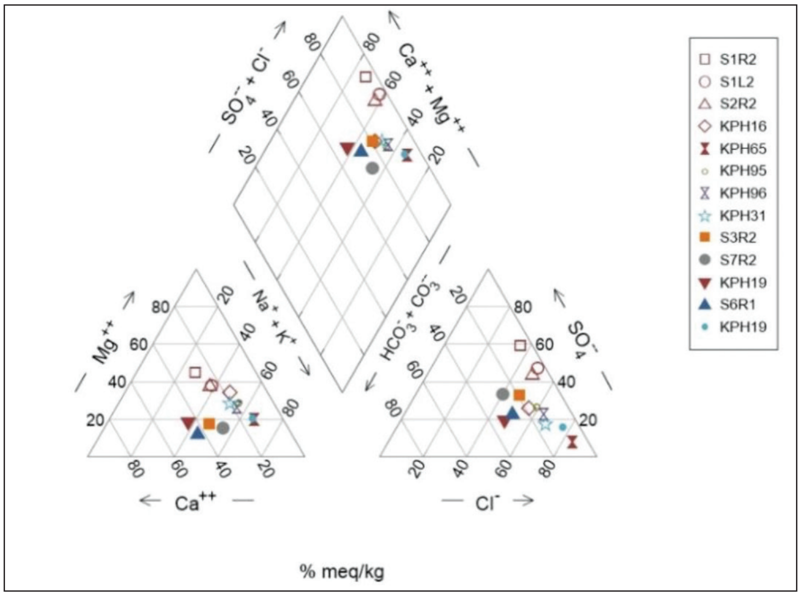

Fig. 3. *Concentration of major cations and anions on Piper diagram*

have been generated by a variety of sources. The Gibbs plot I also revealed the higher concentration of Na^+ proportion and its distribution in larger part indicated that the Na^+ ions are produced from a similar source or through the same geochemical process. In both the plots, all the samples showed evaporation crystallization dominance and no sample showed rock and precipitation dominance. This reveals that evaporation augments the concentration of Na^+ and Cl^- ions in the aquifer with increasing TDS (Rao *et al.,* 2017). The Na^+ and Cl^- ions present in the aquifer of the study area were generated from seawater and the salinity in the groundwater in some areas may be due to the evaporation dominance of the ions (Alfarrah *et al.,* 2011; Lanjwani *et al.,* 2022; Sangadi *et al.,* 2022). From the spatial distribution diagrams and the statistical summary of the water sampling and analysis, the aquifer is characterised by saline nature due to seawater intrusion.

Groundwater quality for irrigation

The USSL diagram includes the four classes of salinity hazards based on the electrical conductivity of the water. The USSL diagram (Fig. 5) illustrates that most of the groundwater samples fall in the category of C3S2 (high salinity with medium sodium) followed by C4S2 (very high salinity with medium sodium). The electrical conductivity ranges from 1.87 to 4.2 dS m^{-1} and SAR values range from 12 to 18. The values of SAR specified that 55% of the samples contained a low to medium sodium adsorption ratio. The gradual accumulation of Na^+ levels in the soil might have occurred as a result of irrigating with water having high SAR values. It may have a negative impact on filtration as well as percolation rates thus resulting in inadequate aeration and soil crusting (Slama and Sebei, 2020).

Groundwater with low salinity (EC< 0.5 dS m^{-1}) is suitable for agriculture provided there will not be any development of salinity (Lanjwani *et al.,* 2022). In this study, there were no groundwater samples in this category. Groundwater with medium salinity (EC 0.5-1 dS m^{-1}) and high salinity (EC 1-2.25 dS m^{-1}) can be used for irrigation with leaching, proper crop selection and other reclamation techniques (Lanjwani *et al.,* 2022). The result revealed that there was an occurrence of medium alkalinity and high to very high salinity hazards in the aquifer. About 35% of the samples were designated marginally suitable for agriculture and 65% of the samples were classified as unsuitable for agriculture due to the high salinity and little danger of exchangeable sodium (Lanjwani *et al.,* 2022; Qishlaqi *et al.,* 2017).

Spatial variability map of groundwater level

The area under groundwater elevations less than 2 m, 2-4 m, and greater than 4 m was determined

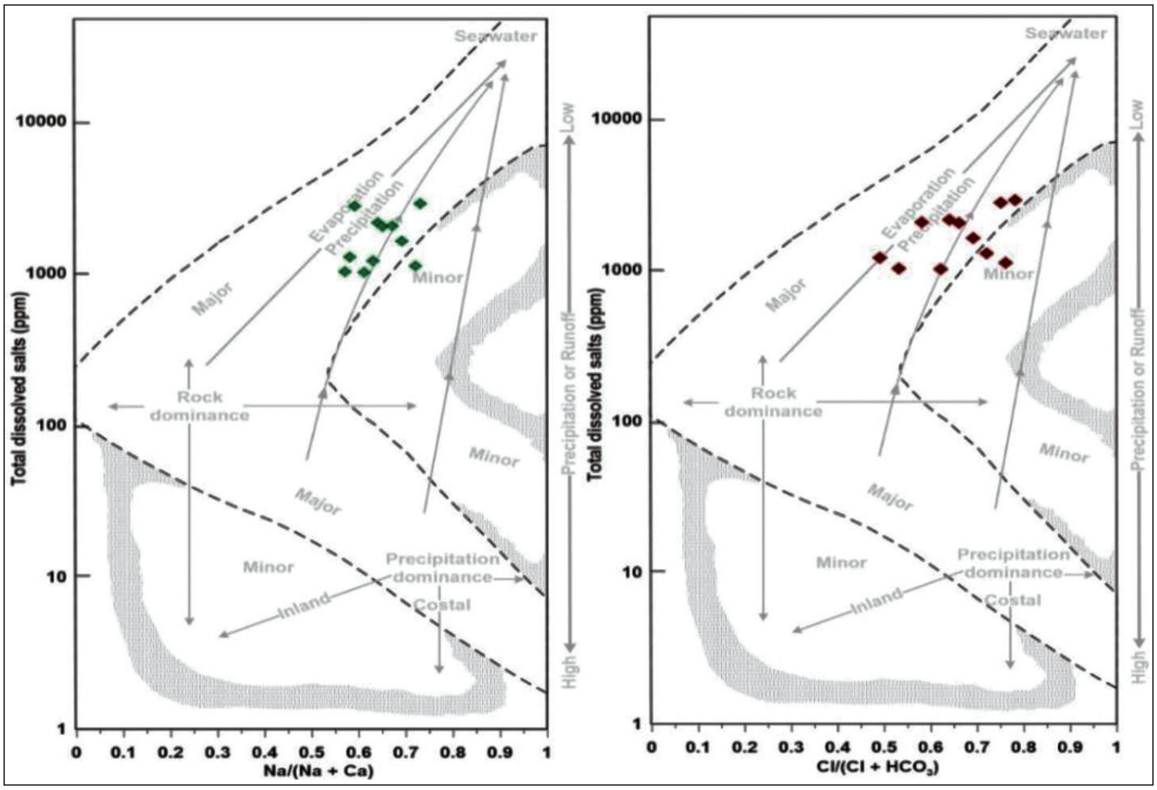

Fig. 4. Gibbs plot of ratios of anions and cations vs TDS

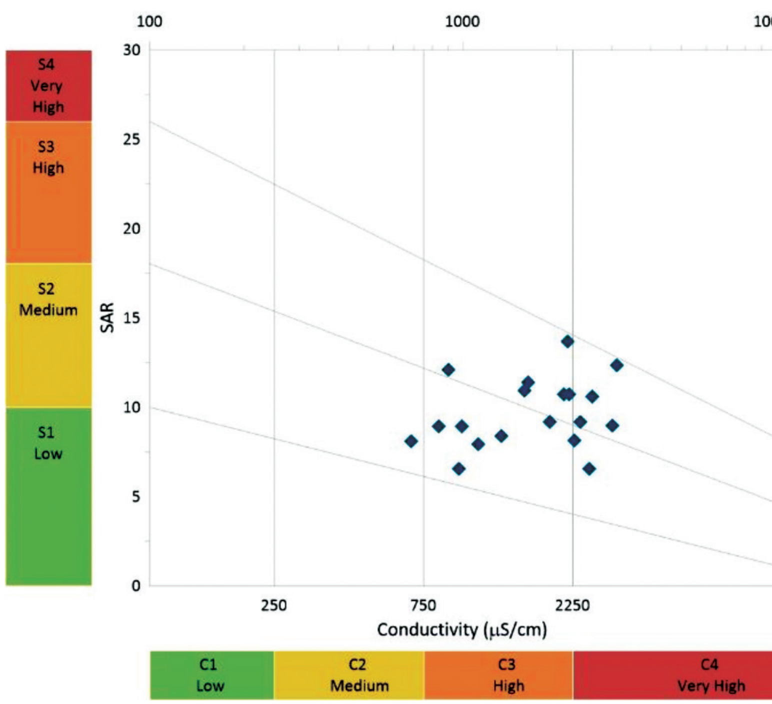

Fig. 5. USSL diagram

from the spatial variability maps of groundwater elevation in pre-monsoon and post-monsoon for the year 2020 for both unconfined and semi-confined aquifers. The results are presented in Fig. 6 and Table 6. In an unconfined aquifer, the area under water table elevation of less than 2 m was 27.1% and in post monsoon 28.4 % m. Area under 2-4 m was 21.3% in pre-monsoon and 46.3% in post-monsoon. In pre-monsoon season, 51.6% area was under the water table depth greater than 4 m. There are also areas with water table elevation below 0 m. This will create a reverse hydraulic gradient and thereby seawater intrusion into the coastal aquifer (Salaj *et al.,* 2018a).

In the semi-confined aquifer (Fig. 7 and Table 6), the water table elevation under less than 2 m in pre-monsoon was 32.5% of the total area and post-monsoon it was 52.3 %. Area under water table elevation of 2-4 m in pre-monsoon was 41.6 % which decreased to 29.9% in post-monsoon.

Area under water table elevation of more than 4 m in pre- and post- monsoon were 25.9% and 17.8 %; respectively. The improvement in groundwater level in the aquifer during post-monsoon may be due to the recharge in the unconfined aquifer and vertical leakage through the semiconfined aquifer during monsoon (Mini, 2012).

Spatial variability map of groundwater salinity

Irrigation water quality classification based on the Central Pollution Control Board of India (CPCB, 2018) was used for the categorisation of the suitability of

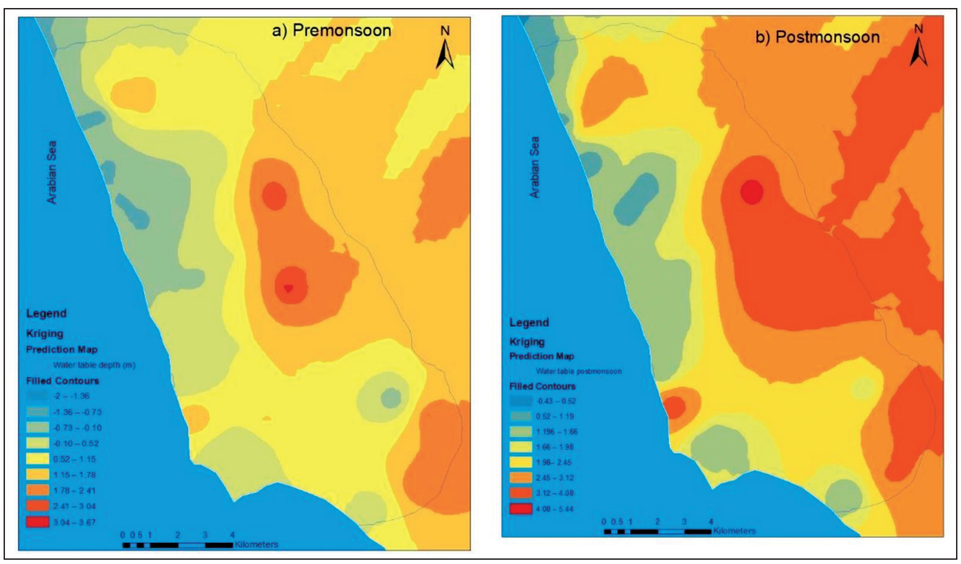

Fig. 6. *Spatial variability map of groundwater level in unconfined aquifer*

Table 6. *The area under various water table elevation*

Water table elevation (m)	Area (%)			
	Unconfined aquifer		Semi-confined aquifer	
	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon
< 2	27.1	28.4	32.5	52.3
2.0 - 4.0	21.3	46.3	41.6	29.9
>4.0	51.6	25.3	25.9	17.8

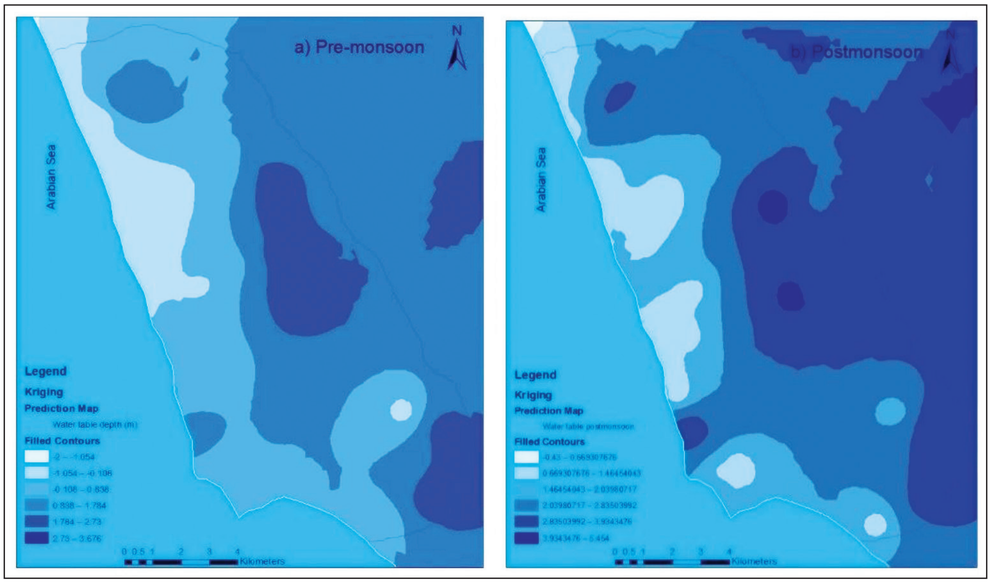

Fig. 7. Spatial variability map of groundwater level in semi-confined aquifer

groundwater for irrigation. The electrical conductivity in the aquifer varied from 0.2 dS m^{-1} to 4.3 dS m^{-1}. In the unconfined aquifer (Fig. 8 and Table 7), most of the area lies in the EC range of 0.75-2.25 dS m^{-1} (Pre-monsoon: 31.7%, post-monsoon: 44.5%). The area in pre-monsoon season under EC of more than 4 dS m^{-1} was 25.2 %, which is unfit for irrigation. As of now most of the area lies under the moderately safe to unsafe category which in future may increase due to increasing groundwater pumping (Salaj *et al.,* 2018a).

In the semi-confined aquifer (Fig. 9 and Table 7), 20.1% area was under the safe and moderately safe category which is almost the same in post-monsoon. The area under the moderately unsafe category was 33%. The area under the moderately safe category increased from 21.7% in pre-monsoon to 45.5% in post-monsoon. About 24.0% area was categorised as unfit for irrigation in pre-monsoon and there was no area present in this category during post-monsoon. During monsoon, recharge occurs in the unconfined aquifer and vertical

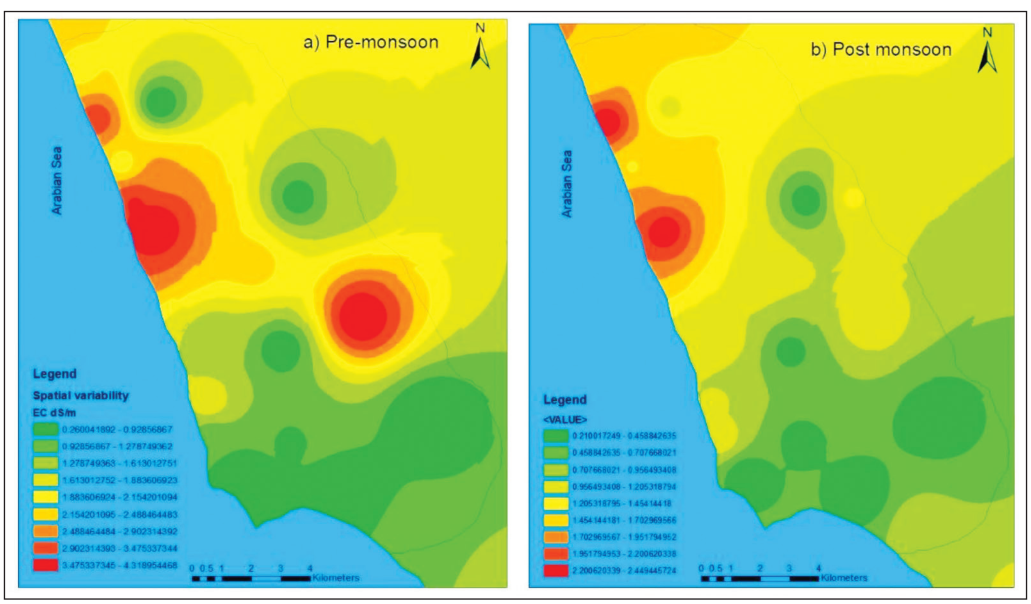

Fig. 8. Spatial variability map of salinity in unconfined aquifer

leakage through the semiconfined aquifer diminishes the reverse hydraulic gradient in the aquifer thus reducing the salinity (Mini, 2012).

The characterization of the coastal aquifer of Kozhikode district in Kerala was done based on physical and chemical parameters, hydrogeochemical analysis, trend analysis and spatial variations in groundwater levels and salinity. The aquifer consists of three layers; the top unconfined layer, and the bottom semi-confined layer which are separated by an aquitard. It was concluded that the dominant cations and anions were from seawater due to the mixing of seawater with the groundwater. The groundwater in the affected area has medium alkalinity and high to very high salinity and is not suitable for irrigation. Most of the area in the unconfined aquifer in pre- and post- monsoon lies in the EC range of 0.75-2.25 dS m^{-1}. The area in pre-monsoon season under EC of more than 4 dS m^{-1} was 25.2% and is unfit for irrigation. As of now most of the area lies under the moderately safe to unsafe category which in future may increase as the groundwater table is declining. In semi-confined aquifer, about 20.1% area in pre- and post- monsoon was under the safe and moderately safe category whereas the groundwater in about 24.0% area was unfit for irrigation in pre-monsoon. Further studies should be conducted to investigate the impact of urbanisation on increasing groundwater abstraction, the influence of Kuttiady river on groundwater salinity during pre-monsoon and post-monsoon, the extent of seawater intrusion in the study area and the effect of various aquifer parameters on these issues, with a focus on demarcating vulnerable zones for the development of effective management strategies to mitigate the problem.

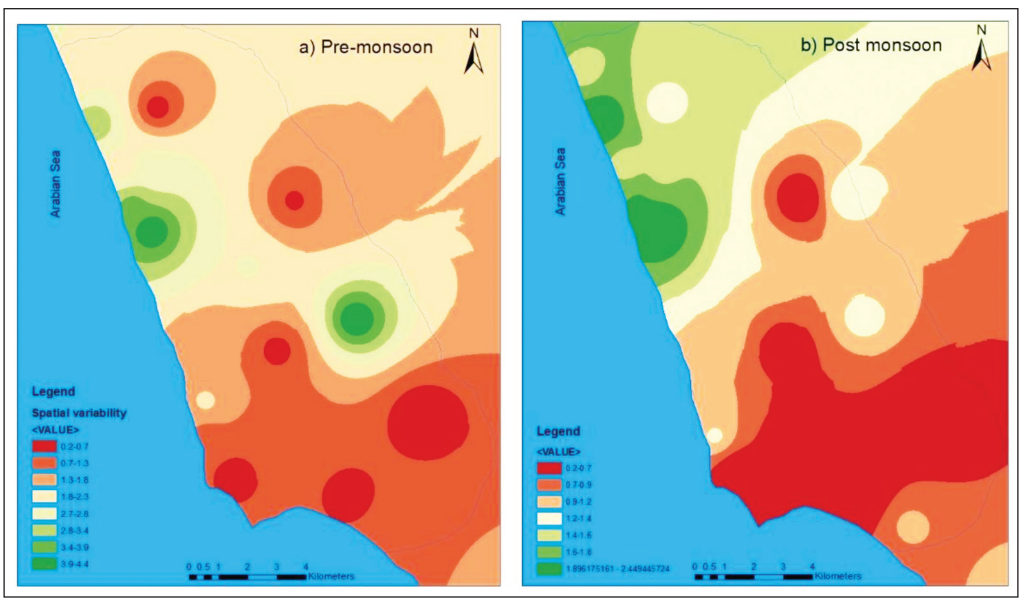

Fig. 9. *Spatial variability map of salinity in semi-confined aquifer*

Table 7. *Percentage area under various EC classes*

Water table elevation (m)	Area (%)			
	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon
< 2	27.1	28.4	32.5	52.3
2.0 - 4.0	21.3	46.3	41.6	29.9
>4.0	51.6	25.3	25.9	17.8

CONFLICTS OF INTEREST

The authors have no competing interests.

REFERENCES

Albuquerque, M.T.D., Sanz, G., Oliveira, S.F., Martínez-Alegría, R. and Antunes, I.M.H.R. (2013). Spatio-temporal groundwater vulnerability assessment - A coupled remote sensing and GIS approach for historical land cover reconstruction. *Water Resources Management* **27**(13): 4509-4526.

Alfarrah, N., Martens, K.and Walraevens, K. (2011). Hydrochemistry of the upper miocene-pliocene-quaternary aquifer complex of Jifarah Plain, NW-Libya. *Geologica Belgica* **14**(3-4): 159-174.

Ali, S.A. and Ali,U. (2018). Hydrochemical characteristics and spatial analysis of groundwater quality in parts of Bundelkhand Massif, India. *Applied Water Science* **8**(39):1-15.

APHA. (2017). *Standard Methods for the Examination of Water and Wastewater,* Twenty third edition, American Public Health Association, Washington DC, USA.

Arslan, H. (2012). Spatial and temporal mapping of groundwater salinity using ordinary kriging and indicator kriging: The case of Bafra Plain, Turkey. *Agricultural Water Management* **113**: 57-63.

Bhagat, C., Puri, M., Mohapatra, P.K. and Kumar, M. (2021). Imprints of seawater intrusion on groundwater quality and evolution in the coastal districts of South Gujarat, India. *Case Studies in Chemical and Environmental Engineering* **3**: 1-8.

Boudibi, S., Sakaa, B. and Benguega, Z. (2021). Spatial variability and risk assessment of groundwater pollutionin El-Outaya Region, Algeria. *Journal of African Earth Sciences* **176**: 1-12.

Boumaiza, L., Walter, J., Chesnaux, R., Zahi, F., Huneau, F., Garel, É., Stotler, R.L., Bordeleau, G., Johannesson, K.H., Vystavna, Y., Drias, T., Re, V., Knöller, K. and Stumpp, C. (2022). Combined effects of seawater intrusion and nitrate contamination on groundwater in coastal agricultural areas: A case from the plain of the El-Nil river (North-Eastern Algeria). *Science of The Total Environment* **851**: 158153. https://doi.org/10.1016/j.scitotenv.2022.158153.

CGWB. (2005). *Annual Report 2005-06*, Central Groundwater Board, Ministry of Water Resources, Faridabad, Haryana, India. 204 p.

Ravi, A. (2013). *Groundwater Information Booklet of Kozhikode District, Kerala State.* Central Groundwater Board, Kerala Region, Kedaram, Kesavadasapuram, Thiruvananthapuram, Kerala, India. 29 p.

Das, J., Rahman, A.T.M.S., Mandal, T. and Saha, P. (2020). Challenges of sustainable groundwater management for large scale irrigation under changing climate in lower Ganga riverbasin in India. *Groundwater for Sustainable Development* **11**: 1-11.

Gibbs, R.J. (1970). Mechanisms controlling world water chemistry. *Science* **170**(3962): 1088-1090.

Gibrilla, A., Anornu, G. and Adomako, D. (2018). Trend analysis and ARIMA modelling of recent groundwater levels in the White Volta river basin of Ghana. *Groundwater for Sustainable Development* **6**:150-163.

Hasan, K., Paul, S., Tareq, J.C. and Antipova, A. (2021). Analysis of groundwater table variability and trend using ordinary kriging: The case study of Sylhet, Bangladesh. *Applied Water Science* **11**: 1-12.

Isaaks, E.H. and Srivastava, R.M. (1989). *An Introduction to Applied Geostatistics,* Oxford University Press, New York, USA. 561 p.

Jesiya, N.P and Gopinath G. (2023). Evaluation of groundwater quality of phreatic aquifers along urban clusters of Kozhikode Coast, Kerala, India. International Conference on *Advances in Water Resources Development and* Management (AWRDM-2013), Punjab University, Chandigarh and National Institute of Hydrology (NIH), Roorkee, October 23-27 2013, Centre of Advanced Study, Department of Geology, Punjab University, Chandigarh, India.

Kendall, M.G. (1975). *Rank Correlation Methods,* Fourth edition, Charles Griffin, London, UK.

KSPCB. (2019). *Report on Restoration of Polluted River Stretches Draft Action Plan of River Kuttiyadi*

(Priority V). Kozhikode District Level Technical Committee, Kozhikode, Kerala, India. 50 p.

Lanjwani, M.F., Khuhawar, M.Y., Lanjwani, A.H., Khuahwar, T.M.J., Samtio, M.S., Rind, I.K., Soomro, W.A., Khokhar, L.A. and Channa, F.A. (2022). Spatial variability and risk assessment of metals in groundwater of District Kamber-Shahdadkot, Sindh, Pakistan. *Groundwater for Sustainable Development* **14**: 1-15.

Mann, H.B. (1945). Nonparametric tests against trend. *Econometrica* **13**(3): 245-259.

Mini, P.K. (2012). Modelling seawater intrusion for management of coastal aquifer. *Unpublished PhD Thesis,* ICAR-Indian Agricultural Research Institute, New Delhi, India.

Mohd Isa, N. and Aris, A.Z. (2012). Extent and severity of groundwater contamination based on hydrochemistry mechanism of sandy tropical coastal aquifer. *The Science of the Total Environment* **438**: 414-425.

Motevalli, A., Moradi, H.R. and Javadi, S. (2018). A comprehensive evaluation of groundwater vulnerability to saltwater up-coning and seawater intrusion in a coastal aquifer (case study: Ghaemshahr-juybar Aquifer). *Journal of Hydrology* **557**: 753-773.

Nair, M.M. (1987). Coastal geomorphology of Kerala. *Journal of The Geological Society of India.* **29**: 450-458.

Nazimuddin, M. (1993). Coastal hydrogeology of Kozhikode, Kerala. *Unpublished Ph. D. Thesis,* Cochin University of Science and Technology, Kochi, Kerala. 216 p.

Paniconi, C., Khlaifi, I., Lecca, G., Giacomelli, A. and Tarhouni, J. (2001). A modelling study of seawater intrusion in the Korba coastal plain, Tunisia. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere* **26**(4): 345-351.

Piper, A.M. (1944). A graphic procedure in the geochemical interpretation of water-analyses. *Transactions American Geophysical Union* **25**(6): 914-923.

Prathap, A. and Chakraborty, S. (2019). Hydrochemical characterization and suitability analysis of groundwater for domestic and irrigation uses in open cast coal mining areas of Charhiand Kuju, Jharkhand, India. *Groundwater for Sustainable Development* **9**:100244. https://doi.org/10.1016/j.gsd.2019.100244.

Prusty, P. and Farooq, S.H. (2020). Seawater intrusion in the coastal aquifers of India - A review. *Hydro Research* **3**: 61-74. https://doi.org/10.1016/j.hydres.2020.06.001.

Qishlaqi, A., Kordian, S. and Parsaie, A. (2017). Hydrochemical evaluation of river water quality - A case study. *Applied Water Science* **7**(5): 2337-2342.

Rao, N.S., Vidyasagar, G., Surya Rao, P. and Bhanumurthy, P. (2017). Chemistry and quality of groundwater in a coastal region of Andhra Pradesh, India. *Applied Water Science* **7**(1): 285-294.

Ravish, S., Setia, B. and Deswal, S. (2019). Hydro-chemical analysis of pre-monsoon groundwater of north-eastern Haryana. *Groundwater for Sustainable Development* **8**: 630-643.

Sahoo, S., Swain, S., Goswami, A., Sharma, R. and Pateriya, B. (2021). Assessment of trends and multi-decadal changes in groundwater level in parts of the Malwa region, Punjab, India. *Groundwater for Sustainable Development* **14**: 100644. https://doi.org/10.1016/j.gsd.2021.100644.

Salaj, S.S., Ramesh, D., Suresh Babu, D.S. and Kaliraj, S. (2018a). Assessment of coastal change impact on seawater intrusion vulnerability in Kozhikode coastal stretch, South India using geospatial technique. *Journal of Coastal Sciences* **5**(1): 27-41.

Salaj, S.S., Ramesh, D., Suresh Babu, D.S. and Kaliraj, S. (2018b). Impacts of urbanization on groundwater vulnerability along the Kozhikode coastal stretch, Southwestern India using GIS based modified DRASTIC-U model. *Journal of Coastal Sciences* **5**(1): 1-27.

Sangadi, P., Kuppan, C. and Ravinathan, P. (2022). Effect of hydro-geochemical processes and saltwater intrusion on groundwater quality and irrigational suitability assessed by geo-statistical techniques in coastal region of eastern

Andhra Pradesh, India. *Marine Pollution Bulletin* **175**: 113390. https://doi.org/10.1016/j.marpolbul.2022.113390.

Saravanan, R., Balamurugan, R., Karthikeyan, M.S., Rajkumar, R., Anuthaman, N.G. and Navaneetha Gopalakrishnan, A. (2011). Groundwater modelling and demarcation of groundwater protection zones for Tirupur basin - A case study. *Journal of Hydro-Environment Research* **5**(3): 197-212.

Sathiamoorthy, M. and Ganesan, M. (2018). Hydrogeochemical characterization of surface and groundwater quality and assessing its suitability of drinking and irrigational purposes in Veeranam Tank area, Cuddalore District, Tamil Nadu, India. **23**(3): 1477-1493.

Sen, P.K. (1968). Estimates of the regression coefficient based on Kendall's Tau. *Journal of the American Statistical Association* **63**(324): 1379-1389. https://doi.org/10.1080/01621459.1968.10480934.

Shaji, E. (2011). Groundwater quality of Kerala-Are we on the brink?, In: Applied Disaster Research, Vol. 1, Proceedings *First Disaster, Risk and Vulnerablity Conference*, A.P. Pradeepkumar, F.-J. Behr, E.V. Ramasamy (eds.), March 12-14, 2021, School of Environmental Sciences, Mahatma Gandhi University, Kottayam, Kerala, India. pp 188-191.

Shaji, E., Nayagam S.P., Kunhambu, V. and Thambi, D.S. (2009). Change in groundwater scenario in Kerala. *Journal of Geological Society of India* **67-85**.

Shin, K., Koh, D.C., Jung, H. and Lee, J. (2020). The hydrogeochemical characteristics of groundwater subjected to seawater intrusion in the Archipelago, Korea. *Water (Switzerland)* **12**(6): 1-17.

Shiyan, L.N., Machekhina, K.I. and Frantcuzskaia, E.O. (2022). Groundwater sources in the west Siberian region: Chemical composition, analysis, and water treatment technologies. *Cleaner Engineering and Technology* **7**: 100441. https://doi.org/10.1016/j.clet.2022.100441.

Slama, T. and Sebei, A. (2020). Spatial and temporal analysis of shallow groundwater quality using GIS, Grombalia aquifer, Northern Tunisia. *Journal of African Earth Sciences* **170**:103915. https://doi.org/10.1016/j.jafrearsci.2020.103915.

Soujanya Kamble, B., Saxena, P.R., Kurakalva, R.M. and Shankar, K. (2020). Evaluation of seasonal and temporal variations of groundwater quality around Jawaharnagar municipal solid waste dumpsite of Hyderabad city, India. *SN Applied Sciences* **2**: 498. https://doi.org/10.1007/s42452-020-2199-0.

Subba Rao, N. (2006). Seasonal variation of groundwater quality in a part of Guntur District, Andhra Pradesh, India. *Environmental Geology* **49**(3): 413-429.

Sukumaran, D. and Raj, J.P.(2020). Saline water intrusion in urban coastal area: A case study of Kuttiyadiriver, Kerala, India. *American Journal of Water Resources* **8**(3): 128-133. https://doi.org/10.12691/ajwr-8-3-3.

Wu, J., Wang, L., Wang, S., Tian, R., Xue, C., Feng, W. and Li, Y. (2017). Spatiotemporal variation of groundwater quality in an arid area experiencing long-term paper wastewater irrigation, northwest China. *Environmental Earth Sciences* **76**(13): 460. https://doi.org/10.1007/s12665-017-6787-2.