Research Article

Geochemical variations due to salinization in groundwater along the southeast coast of India

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Abstract

In recent years, the extraction of groundwater (GW) in coastal aquifers has rendered the fragile aquifers more saline due to the sea water intrusion. Groundwater from the coastal aquifers of the Pudhucherry region were sampled to study the process of salinization. An integrated approach was adopted to identify the salinization process, by coordinating the results of borehole geophysics, rainfall pattern, water level variation, hydrochemical characters and multivariate statistical analysis. A total of 136 groundwater samples were collected during two different seasons, southwest monsoon (SWM) and northeast monsoon (NEM). The major cations and anions were analyzed adopting standard procedures. Resistivity and litholog indicate that the southeastern (SE) part of the study region has lower resistivity than in north. Based on electrical conductivity (EC) and total dissolved solids (TDS) values, most of the samples are potable, except for few samples from southeastern region. The study results indicated that higher values of Na, EC, K, SO_4, Mg and Cl were observed during NEM, indicating leaching of salt into the aquifer and ion exchange process. The predominant hydrochemical facies of groundwater was Na-Cl and Ca–Mg–Cl type reflecting the saline water and the mixing process of saltwater and fresh groundwater, respectively. Though more number of samples with higher EC was noted in NEM, the results of PCA and correlation analysis indicate the predominance of leaching of salts and intense agricultural activities. The process of sea water intrusion was observed to be dominant during SWM.

1 Introduction

Aquifers along the coastal area are important sources of water, and it is usually affected by the diverse landuse practices and geochemical contaminants. Eight percentage of global population live along the coastal region and utilize the local aquifers for their needs [1–5]. The groundwater extraction from the coastal aquifers [6–8], leads to reduction in available fresh water (FW) and thus causes the lowering of water table resulting in the decrease in groundwater quality.

Various factors such as seawater intrusion, rock–water interaction, excess usage of groundwater, sea level rise, temperature variance, hydrogeological history of the area,

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salt panning, inadequate removal of manure and use of biochemical foods govern the salinization of groundwater [9–11]. Globally, a complex interplay of the abovementioned facts along with seawater intrusion into these coastal aquifers leads to geochemical hazard in groundwater along the coastal aquifers.

The amount of groundwater extracted from the coastal aquifers, hydrogeological conditions, the well design, fresh water sources (ponds, rivers or reservoirs) play a major role in the management of the sustainable utilization. Subsequently, the landuse pattern along the shore line determined the quantum of groundwater extracted from the aquifers which results in seawater intrusion, and in fact, this is also facilitated by sea level rise. [4]. The reduction of fresh water flow to the sea has increased the inland surface backwater flow enhancing the infiltration of brackish water into the adjacent flood plains. One of the most important techniques to determine the saline water intrusion is to enhance the monitoring of the groundwater geochemistry [12–18]. Groundwater with higher TDS are generally more saline in nature [19], and saline groundwater along the coast also have reported higher amount of trace metals apart from major cation and anions [14, 20].

The seawater intrusion (SWI) in the coastal region not only renders the quality of groundwater non-potable but also affects the vegetation, soil conditions and the sustainability of groundwater [21]. The mixing of seawater and freshwater in coastal aquifers leads to the lateral migration of sea water into the aquifer affecting the groundwater chemistry. The chief geochemical process observed in the coastal sedimentary aquifers with clay is ion exchange [22]. The mixing of seawater-freshwater and the ion exchange process are inferred from the ion ratios [23–25]. Further, the geochemical nature of the groundwater and the status of the sea water intrusion have been studied in the sedimentary coastal aquifers by using hydrochemical facies evolution diagram [22, 24, 26, 27]. In numerous coastal aquifers [11, 28–32], the hydrochemical facies evolution diagram had proved to be promising in identifying the spatiotemporal variation in seawater intrusion [33–35]. The lithology also plays a vital role in seawater intrusion as the flow of water in the aquifer is governed by the aquifer properties such as porosity and permeability [36].

The spatial variation of major ions in groundwater of the coastal aquifers and the changes in the geochemical processes can be established by integration the geochemical parameters in the GIS platform [37]. Apart from GIS techniques, other softwares like WATCLAST and CHIDAM are also used to plot, assess and categorize the groundwater [38, 39] and to identify the process of mineral weathering, evaporation and its suitability. Modeling softwares like PHREEQC determine the saturation states of minerals and predict their variation with an increase in evaporation and salinity [40]. AquaChem software determines that groundwater type and facilitates the plotting of standard diagrams like Wilcox plot and Piper facies. The statistical softwares plays a key role in determining the hidden process and identify the relationship between ions, thereby the source and process governing the geochemistry of groundwater [41].

Groundwater is unsuitable for irrigation in the coastal area due to the higher concentration of sodium ion. The earlier researchers had identified that this high concentration in the coastal groundwater is attributed to insufficient flushing into the sea and the fine-grained composition of aquifer sediments [42]. Enhancement of rainfall recharge and sustenance of the fresh surface water bodies like rivers, lakes and reservoirs control the salinity and help to derive a proper management strategy over a long period of time. The coastal saline groundwater is reported to have greater concentration of major ions and bromide [43]. The groundwater of arid coastal regions are hypersaline [44], and their spatial distributions show high nitrate, chloride, H_2S and ammonium [45].

The current study area is located at Pondicherry, southeast coastal India, and it is densely populated with more industrial, urban and rural population. Groundwater-dependent agriculture is one of the major landuse patterns and is one of the most prominent tourist centers in southeast India, with greater density of population. The domestic and the agricultural needs of the coastal regions are mainly supported by the groundwater resources in this region. Hence, the groundwater reserve become a prime water resource and is consequently exploited. In this scenario, the groundwater–seawater interface varies frequently and the salinity is observed to increase toward inland in the recent years. Studies have tried to demarcate the seawater intrusion through modeling techniques [46, 47]. Hydrogeochemical parameters to determine the seawater intrusion [46], and delineation of the areal extent of seawater intrusion by preparing a vulnerability map by [47] were also attempted by the earlier researchers. The studies on geochemical processes for limited area and limited samples were attempted [48, 49] and inferred that the geochemical weathering and ion exchange are the predominant factors. Apart from these studies, geophysical studies using borehole data, to determine the lithological variations [48]; studies on the geomorphology of the region [50]; saturation index of groundwater [51]; assessment of rainfall recharge using stable isotopes [52]; microbial contamination [53]; budgeting of groundwater with respect to water level variations [54] and dissolved organic carbon in groundwater [55–60] were also attempted by earlier researchers. The current study integrates the geophysical techniques such as resistivity and lithology, the temporal change of water level and rainfall along with the

hydrogeochemical investigation of groundwater samples to assess the salinity in this coastal aquifer. Thus, the study aims to assess the salinization in the coastal groundwater of the regions using integrated techniques.

2 Study area

The present study area is located in the southern part of Tamil Nadu, within latitudes of 11°45′ and 12°03′ and longitude of 79°37′ and 79°53′, representing the survey of India, toposheet maps of No.58 M/9, M/13 and 57 P/12 and P/16, with a geographical extent of 293 km^2, divided into
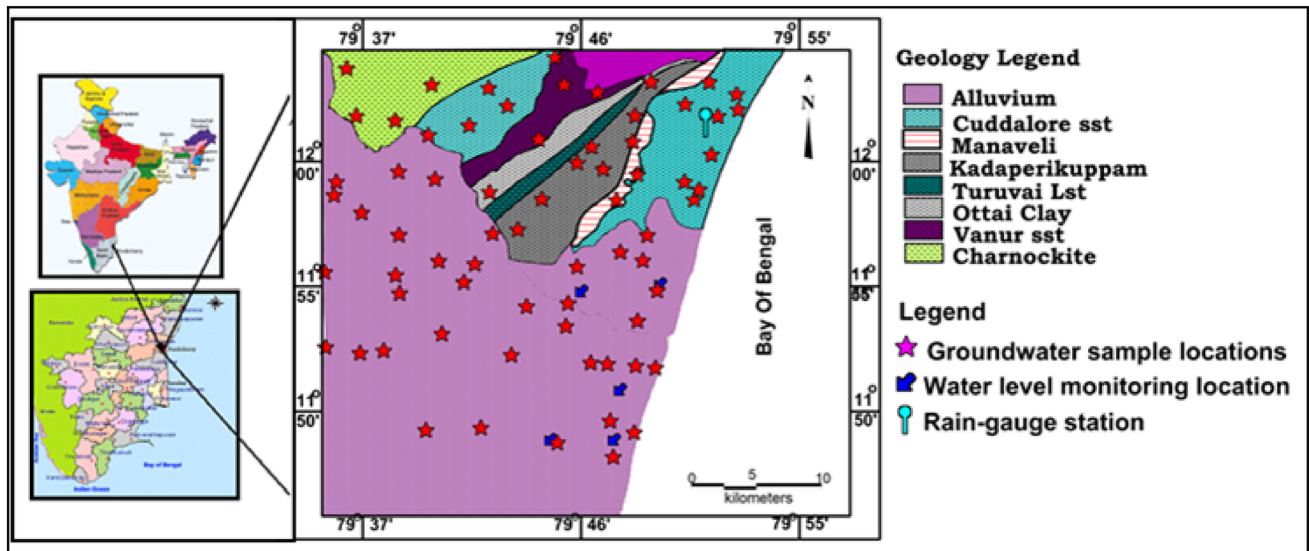

Fig. 1 The geology map of the study area showing the location of the samples collected

Table 1 Stratigraphic succession for the study region [88]

Era	Period	Formation	Typical lithology
Quaternary	Recent	Alluvium Laterite	Sands, clays, silts, Kankar, Laterite gravels
		Upper Cuddalore Formation	Sandstones with minor clays and siltstones with thin seams of lignite are pebbly and gravelly and coarse grained
Tertiary	Mio-Pliocene	Lower Cuddalore Formation	Dirty white, light gray sandstone, marcasite siltstones rich with thin clay lignite seams
Unconformity			
Tertiary		Manaveli Formation	Yellow and yellowish brown, calcareous gray siltstone and claystone and shale with limestone bands
	Paleocene	Kadaperikuppam formation	White to dirty white yellowish sandy rough fossiliferous calcareous; calcareous sandstone and clay
Unconformity			
Mesozoic	Upper Cretaceous	Turuvai limestone	Extremely limestone fossiliferous, conglomerate in areas, calcareous Sandstone and clays
		Ottai claystone	Claystones, silts with thin bands of sandy limestone and fine-grained calcareous sandstone, grayish to grayish green
		Vanur sandstone	Hard coarse grained quartzite sandstone, rarely feldspathic or calcareous with small clays
	Lower Cretaceous	Ramanathapuram formation (unexposed)	Silty black carbonaceous clay and fine to medium grained sands with lignite bands and medium to coarse grained sandstones
Unconformity			
Archaean		Eastern Ghats Complex	Charnockite and hornblende gneiss biotite

7 municipalities (Fig. 1) and 179 villages. The River Gingee and Pennaiyar's deltaic channel are the major source of drainage of the study area. The area encompasses sedimentary deposits, with geological age from Cretaceous to Quaternary (Table 1). The sedimentary formation of Cretaceous covers in the northwestern, northern part of Gingee River in the study area. However, the Tertiary comprises the Paleocene of Kadaperikuppam and Manaveli Formations and Mio-Pliocene Cuddalore Formation. The recent formation is characterized by Quaternary laterites and alluvium. Usually, the study area is a peneplain with a mean altitude of around 15 m above mean sea level (amsl). Geomorphologically, the area is covered with three features such as alluvial plain, uplands and coastal plain.

The hot and humid climate persists in the study area with a temperature fluctuation between 22 and 33 degrees Celsius. The area receives an average annual precipitation of 1281 mm. Northeast monsoon contributes to a major part of rainfall received in the study area (63%); likewise, southwest monsoon contributes to 29% of total rainfall [61]. The depth to water level ranges from 1.5 to 27 m below groundwater level (mbgl). The transmissivity range for the oldest Cretaceous aquifers is from 92 to 1925 m^2/day, and the storage coefficient is between 2.94×10^{-5} and 1.37×10^{-4} [62, 63]. Similarly, for the Tertiary aquifers transmissivity was assessed as 2000 m^2/day and the storage coefficient ranges between 9.58×10^{-5} to 8.99×10^{-4}. For the recent alluvium aquifers, the transmissivity ranges between 275.4 m^2/day and 770 m^2/per day.

3 Materials and methods

The rainfall data and depth of water level were collected from CGWB [61]. Resistivity and litholog used for the study were collected from borewell companies [49]. A total number of 68 groundwater samples were collected from the study area (Fig. 1) during NEM (November) of 2016 and SWM (July) of 2017 to compare the seasonal variation in groundwater chemistry of the region. The samples were collected from the production wells after purging the well for 15 min.

The collected samples were filtrated with 0.45 micron fiber membrane filters and measured for physical parameters like pH, EC and TDS by using a Thermo Orion ion electrode. The samples were acidified by adding few drops of HNO_3 acid for the cation analysis. Subsequently, the collected samples were brought to the laboratory and refrigerated in a temperature of 4 degrees Celsius until analysis. The samples were analyzed for the major cations like Ca, Mg, Na, K and anions like Cl, HCO_3, NO_3, SO_4 and PO_4. The cations like Ca and Mg were determined by titration method, and K and Na^+ were analyzed using a flame photometer. Similarly, the anions (PO_4, NO_3 and SO_4) were analyzed using the spectrophotometer. The titration method was adopted to measure bicarbonate (HCO_3) and Cl. The detail analytical instrumentation and its detection limits are provided in Table 2. The standard procedure of American Public Health Association was followed for the analysis of major ions [64]. The spatial distribution maps were prepared in GIS interface by using MAP Info software.

4 Results and discussion

4.1 Resistivity and lithology elucidation

The subsurface distribution of resistivity and lithology of eight different locations, namely Ariyankuppam, Chinverampattinam, Keezh Parikalpattu, Muthalyarpet, Nallavadu, Pillaiyarkuppam, Reddiyarpallayam, Thavalakuppam, are plotted as given in Fig. 2 by using the software Rockworks (version 14). The deeper aquifer has lowest resistivity in the northern part; however, the resistivity value has an

Table 2 Analytical instruments and its detection limits for the groundwater samples

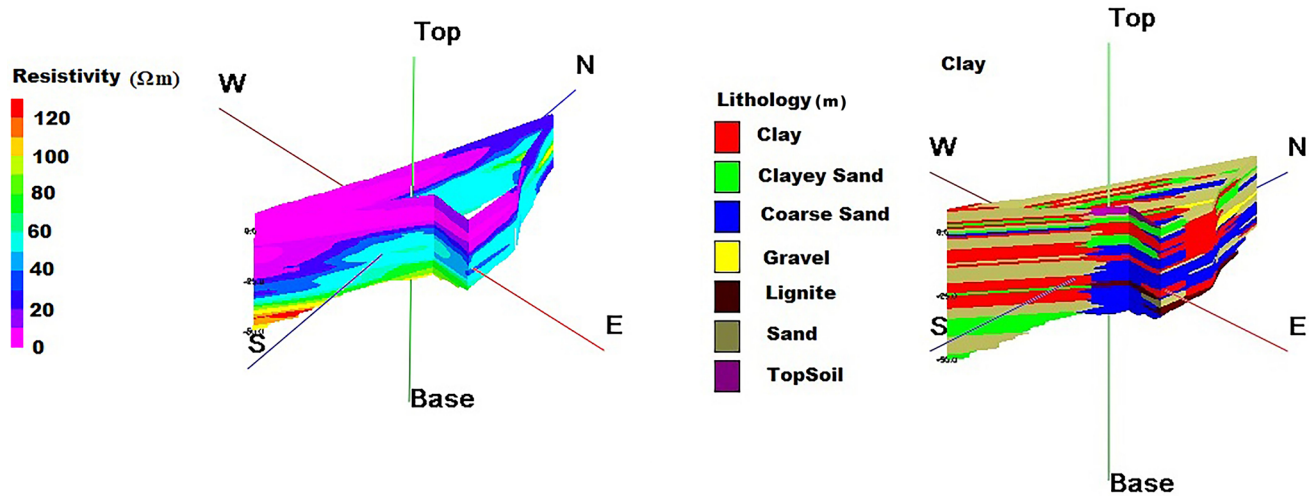| Parameters	Instruments and its model	Detection limit
pH	Ion electrode/Thermo Orion five-star meter	0–20
EC		0–3000 mS
TDS		0–20,000 ppm
Ca	Volumetric methods/titration using burette, flasks	±0.05 mL
Mg		
Cl		
HCO_3		
SO_4	Spectrophotometer/HACH (DR 6000)	0–70 mg/L
PO_4		0–25 mg/L
NO_3		0–10 mg/L
H_4SiO_4		0–10 mg/L
Na and K	Flame photometer/Elico CL 378	1–100 ppm

Fig. 2 3D variation of Resistivity (Ωm) and lithology (m) of the Study region

increasing trend toward southwestern part of the area. Subsequently, the subsurface distribution of lithological units shows that there is a disseminated patch of clay and lignite layer (Fig. 2). The presence of thick clay layers in the shallow depth along southwestern region lowers resistivity; however, the presence of clayey sand and sand influence the resistivity in depth. Low resistivity values in sand and clayey sand layer at greater depth near southwestern part indicate influence of saline intrusion. However, the presence of sand and coarse sand in the northern and northeastern part of the study area has relatively higher resistivity values indicating the present of fresh water.

4.2 Rainfall and water level

Groundwater level information for five bore wells Mangalam, Kattukuppam, Pondicherry, Viliyanur and Reddichavadi for the period of 2016–17 was considered to understand the status of water level fluctuation in this area. The shallowest water level as 1.4mbgl is recorded at Kattukuppam during 2016, and the deepest water level of 19.0 mbgl was observed at Mangalam in 2016. While comparing the depth of five monitoring wells, the average water level data of both the year 2016 and 2017 (Fig. 3) are recorded as 19 and 17 mbgl. The shallowest water level during 2016 might be referring to the surplus rainfall occurred during the NEM of 2016 (Fig. 4). In the year 2017, the water level was relatively deeper in almost all the stations due to inadequate rainfall (Fig. 4). Thus, rainfall variation is considered as the major cause of water level fluctuation in the area apart from the groundwater exploitation.
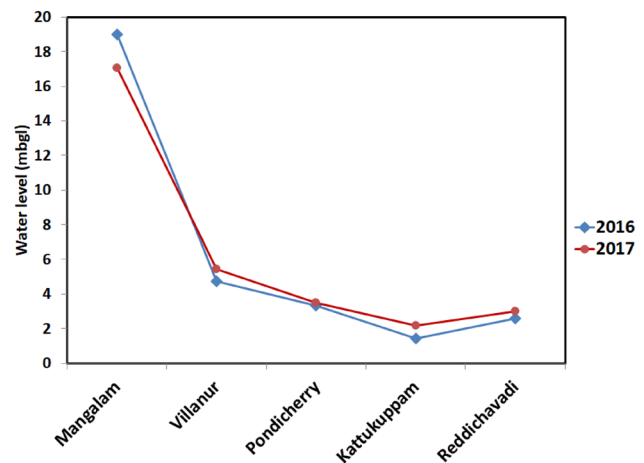

Fig. 3 Total average annual water level (mbgl) from the period of 2016 and 2017

4.3 Physico-chemical parameters

The EC values range between 469–3830 µS/cm in NEM and 751 – 2343 µS/cm in SWM. Maximum concentration of EC during NEM is observed in the Thavalakuppam reflecting the mixing of saline water, 51% of samples were identified with higher EC exceeding the desirable limit of 1400 µS/cm, and during SWM, higher EC is noted at Thengaithittu location. According to classification by Saxena [14], most of the samples are within brackish to saline nature.

The pH ranges between 6.7 and 7.9 in NEM, highly alkaline water is noted in Nesal sample location, and acidic samples are noted in Gangamadevi location. During SWM, the pH ranges between 5.2 and 9.5. However, the temperature ranges between 26–32ºC and 29–34 ºC for NEM and SWM, respectively. The TDS varies between 310 and
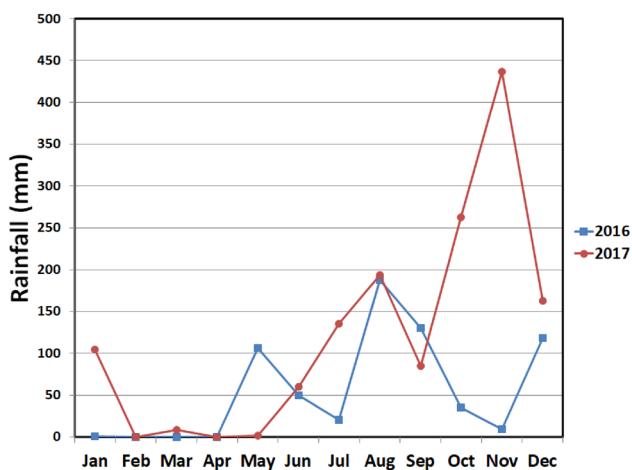
Fig. 4 Monthly rainfall in millimeter for the year 2016 and 2017

2367 mg/L; higher TDS is observed in Thavalakuppam. 59% of the samples in NEM exceed the permissible limit of TDS [65]. Around 62% of samples have higher TDS values than the acceptable limit in SWM, and maximum TDS was noted at Ellaipillaichavadi.

The physico-chemical parameters of groundwater were described in Table 3 for NEM. A higher concentration of ions such as Na, Cl, K, Ca, Mg, NO_3 and high EC [66, 67] shows the influence of sea water into the aquifer. Calcium level in the samples varies from 20 to 228 mg/L during NEM and from 16 to 124 mg/L during SWM. The maximum desirable limit [65] for Ca is 75 mg/L. 37% of total samples are above the desirable level; Kadaperikuppam is the location with the higher Ca during NEM. The magnesium in the samples ranges between BDL and 84 mg/L during NEM and 2.4 to 84 mg/L during SWM. The concentration of Na above permissible level of 200 mg/L leads to salted taste and also health hazards [67]; 37 percent of NEM samples are above the WHO standard. The sodium concentration varies from 11 to 561 mg/L. Korakeni is the location with higher Na concentration during NEM. The sodium in the

study area aquifer is mainly due to the saline sources [68]. In SWM, Na ranges between 43 and 394 mg/L, and higher value is represented in Madukarai location. 49% of total sample are higher than the admissible limit of Na in SWM. Potassium in groundwater samples during NEM ranges between BDL and 88 mg/L and in SWM ranges between 2 and 248 mg/L. Extensive use of agriculture fertilizer leads to high K in study region aquifer. According to WHO [65], 6% of samples during NEM and 9% during SWM have NO_3 greater than the 45 mg/L. The concentration of Cl^- in groundwater samples shows that 41% exceed the permissible limit in SWM and 70% of total samples exceed the permissible limit in NEM. The higher level of Cl and EC in the groundwater reflects the influence of sea water intrusion [69, 70]. The silica content in groundwater of study area ranges between 2 and 265 mg/L during NEM and 33 and 258 mg/L during SWM. Higher silica was observed in NEM.

The variation in EC value depends upon all the ion concentration in the groundwater; essentially, it is influenced by Cl^- concentration. Three regions were identified in Fig. 5 based upon EC and Cl value, i.e., mixing zone, strong mixing (intrusion) and freshwater zone. Chlorine (above 250 mg/L) and EC (above 1400 µS/cm) present in the groundwater samples were influenced by infiltration of saltwater. These samples were categorized with an EC of 1400 and 2400 µS/cm as a mixture of saltwater and freshwater. The seawater signature is defined by samples with EC more than 2400 µS/cm. Most of the samples have higher EC and Cl^- during NEM which reflects saline nature of groundwater (Fig. 5a). Approximately 38% of samples were represented in Ca–Mg–Cl and Na-Cl class with greater EC and Cl^- during SWM (Fig. 5b). In the southwest and southeast region, the groundwater quality was observed to be good, with lower EC values. In the northwest and northeastern portions of the study zone, higher EC (greater than 3000 µS / cm) concentrations were observed (Fig. 6) and it is noted that the samples were extremely contaminated by saline intrusion. SWM

Table 3 Evaluation of physico-chemical parameters of collected groundwater samples (all values in mg/l except pH, temperature (°C) and EC (µS/cm)). The numbers in bold indicate the highest value recorded

		pH	EC	TDS	Ca^{2+}	Mg^+	Na^+	K^+	Cl^-	HCO_3^-	SO_4^{2-}	PO_4^{2-}	Si	NO_3
NEM($N=68$)	Max	7.9	**3830**	**2367**	**228**	**84**	**561**	88	**914.3**	512.4	**2.5**	11.9	**265**	65.1
	Min	6.7	469	310.2	20	2.4	11.4	0.5	53.2	24.4	0	0	6	0
	Avg	7.3	1774	1126	92.4	19.4	173.6	25.7	357.2	270	0.4	0.6	123.4	13.1
SWM ($N=68$)	Max	**9.5**	2343	1773	124	84	394.3	**247.8**	514.03	**597.8**	0.99	**17.98**	258	**184.1**
	Min	5.2	751	494.2	16	2.4	42.7	1.7	68.63	73.2	0.03	0	33	0
	Avg	6.8	1476	1046	63.3	23.3	190.1	30.78	250.8	320.9	0.52	1.02	143.2	16.2
WHO (66)		6.5–8.5	1400	1000	100	50	200	20	250	300	250			50

Fig. 5 **a** Relationship of chloride with EC in categorizing the fresh water (FW), sea water intrusion (SW) and mixing (FW + SW) during NEM. **b** Relationship of chloride with EC in categorizing the fresh water (FW), sea water intrusion (SW) and mixing (FW + SW) during SWM
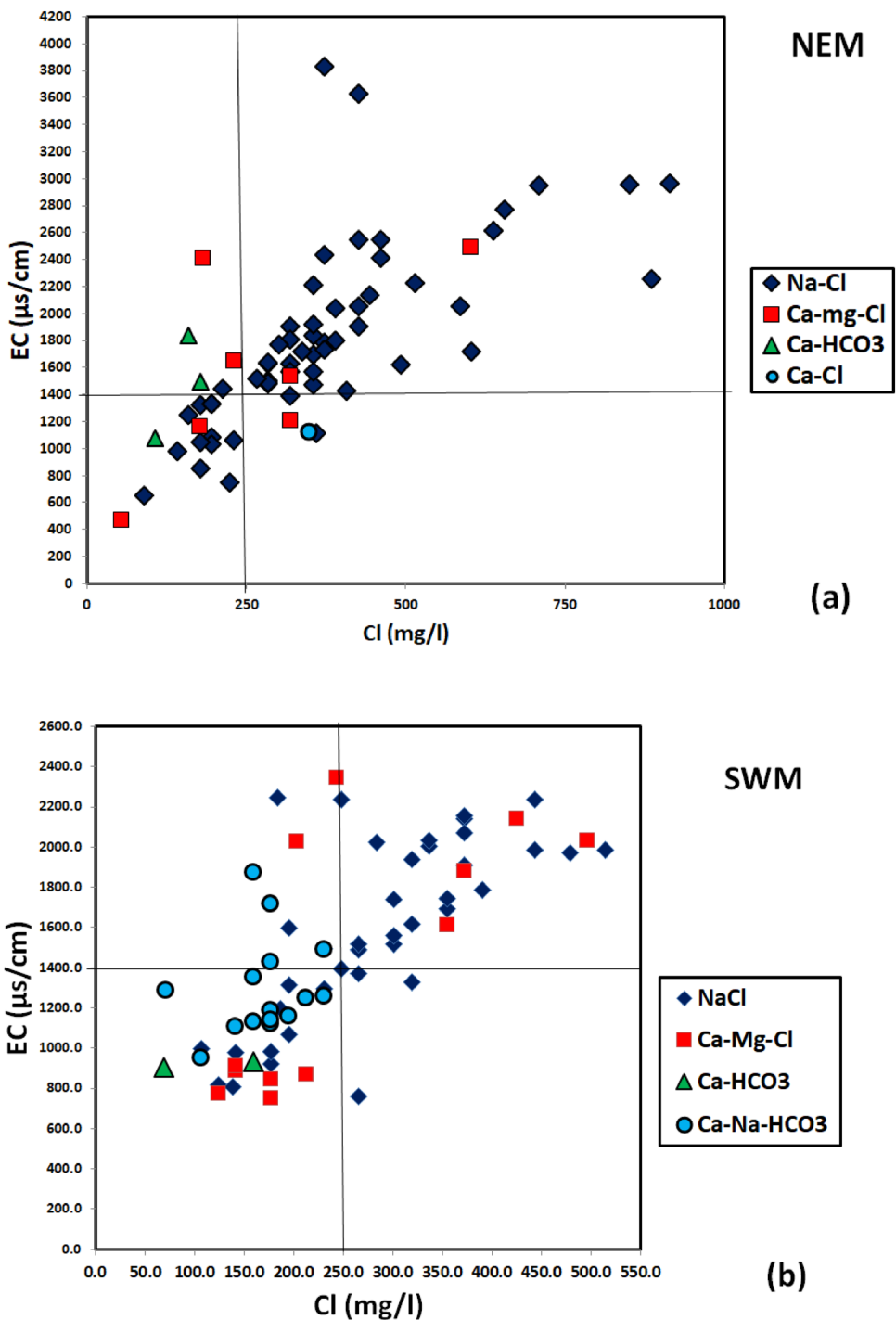
samples showed higher EC values (Fig. 7) in the southern and central parts of the study region.

The Ca–Mg–Cl and Na-Cl are the significant water types noted (Fig. 8a) during NEM. Most of the samples have high sodium and chloride, inferring the removal of other minor ions from the water through either adsorption or by precipitation [71, 72] due to saturation or infiltration of seawater [63]. Migration of samples from mixed Ca–Mg–Cl type

to Na-Cl type reflects seawater intrusion in groundwater of the study area. The intrusion of sea water is attributed to the decline in precipitation, decrease in water level and extensive groundwater use. The saline water intrusion in this region is also attributed to rigorous use of groundwater for domestic purposes, thus increasing Na with respect to Ca and Mg in cations; Cl exceeds HCO_3 and SO_4 in anions [73]. In the discharge zone, the Na-Cl type of water is
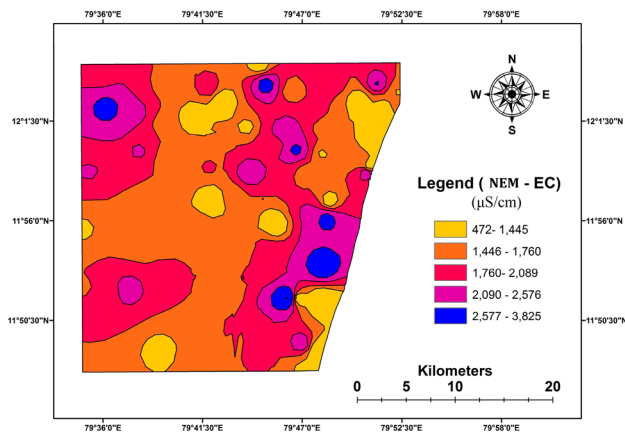
Fig. 6 Spatial distribution of EC (µS/cm) for groundwater samples collected during NEM

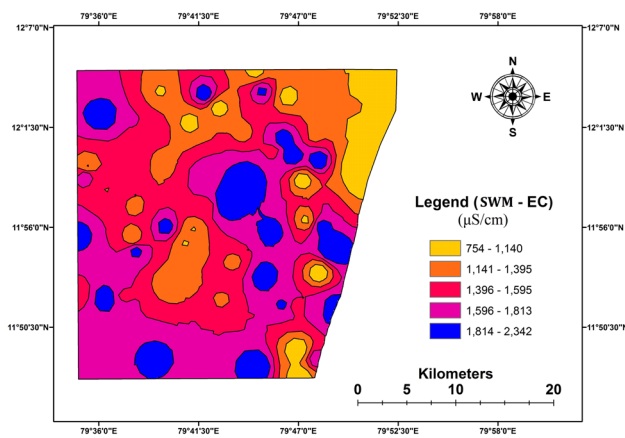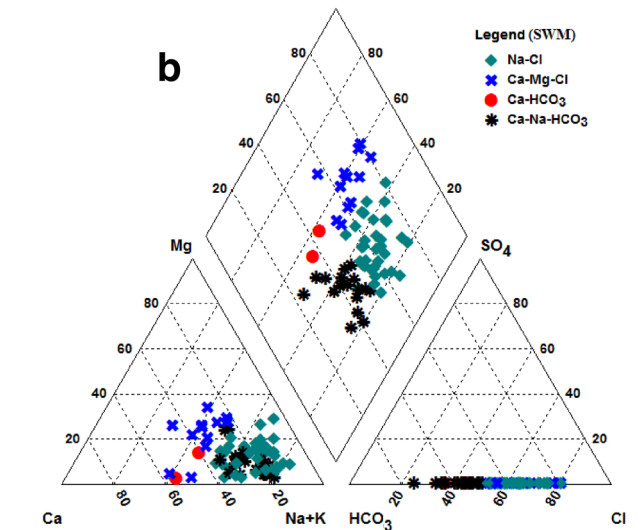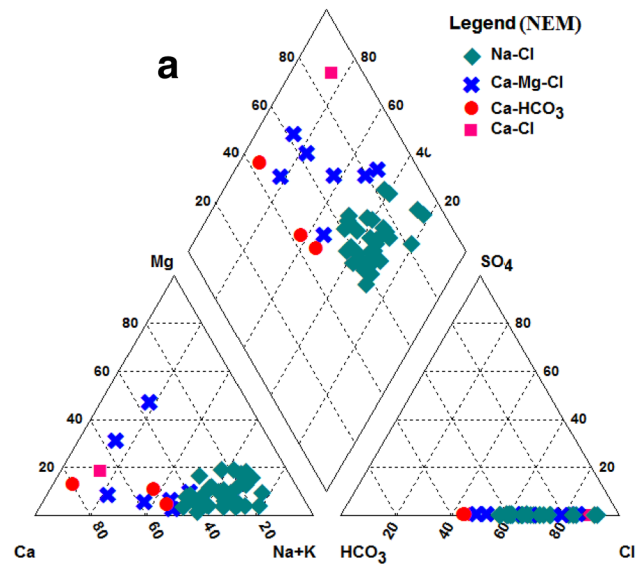**Fig. 7** Spatial distribution of EC (µS/cm) for groundwater samples collected during SWM

Fig. 8 a Major water types of the water samples during NEM are depicted in the Piper diagram. **b** Major water types of the water samples during SWM are depicted in the Piper diagram

noted [74]. During SWM, most of the samples (Fig. 8b) fall within the Na-Cl and Ca-Na-HCO₃ water type. Few samples in SWM fall in the zone of the Ca–Mg-Cl type representing rock–water interaction and ion exchange reaction [73, 75]. The decline of Na and Cl percentage with increasing salinity is primarily an effect of Na reduction due to reverse ion exchange [73, 75]. The occurrence of reverse ion exchange in the study area is also manifested from the Chadha diagram. In both the NEM and SWM seasons, Na and Cl are the dominant ions controlling the groundwater chemistry.

The distribution of electric conductivity is shown in Fig. 9. The groundwater is considered as freshwater if the values of EC are lower than 750 µS/cm [76, 77]. During NEM and SWM (Fig. 10), about 3% of the samples have low EC value (< 750 µS/cm) during NEM and it is suitable for the irrigation purpose. 77% and 99% of the samples were ranging from 751 to 2250 µS/cm during NEM and SWM,

respectively, representing doubtful for irrigation [78–81]. The 17 percent and 1 percent of samples during NEM and SWM show that EC ranges between 2251 and 3000 µS/cm and about 3 percent of groundwater sampling wells were observed to have EC values > 3000 µS/cm during NEM. The samples of above 2250 µS/cm EC are not suitable for irrigation [76].

4.4 Ionic Ratios

A hydrochemical graph is [82] considered in this study to interpret the hydrochemical processes that occur within
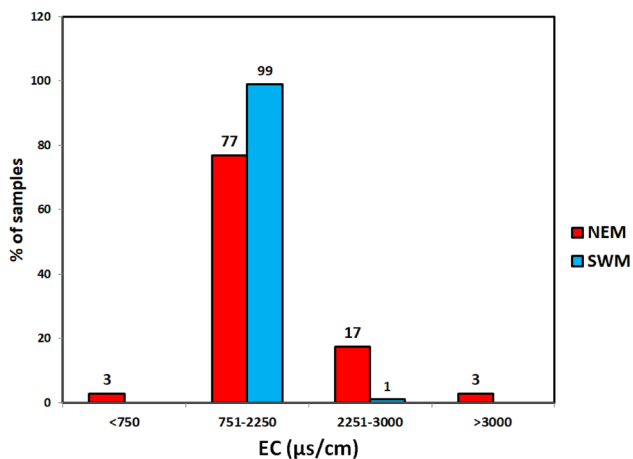
Fig. 9 EC Variations in groundwater representing different ranges with respect to season
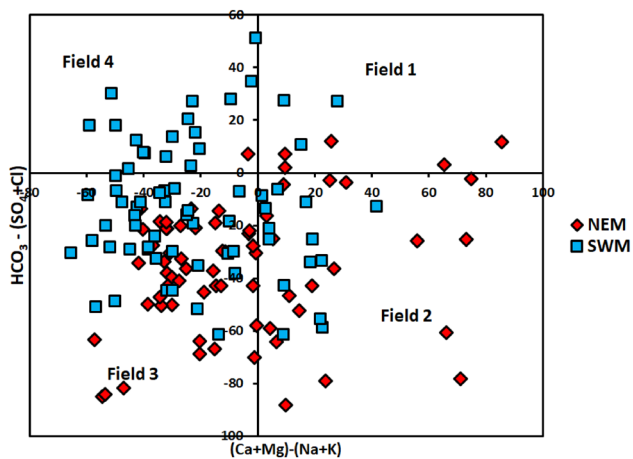
ion exchange process. Thus, it can be inferred that reverse ion exchange is also a key process responsible for the hydrochemical variation in the study area during NEM and SWM [85]. However, ion exchange process is more dominant in SWM compared with NEM.

To understand the saltwater intrusion process, the Cl^--to-Na^+ ionic ratio was considered. The Na/Cl ratios for groundwater samples show that most of the SWM samples exceed the ratio of seawater (0.88) and that of the NEM samples are marginally greater than the value (Fig. 11 a). The higher value of the ratio indicates the predominance of Na to Cl indicating the influence of fresh water during SWM (Fig. 11b) and highlighting the recharge region suggesting the freshwater in the aquifer. The values lower than the seawater ratio may be due to the replacement of cations due to the ion exchange process subsequent to the seawater intrusion into the freshwater aquifers which

Fig. 10 Geochemical process evaluation plot for groundwater samples (after Chadha [82])
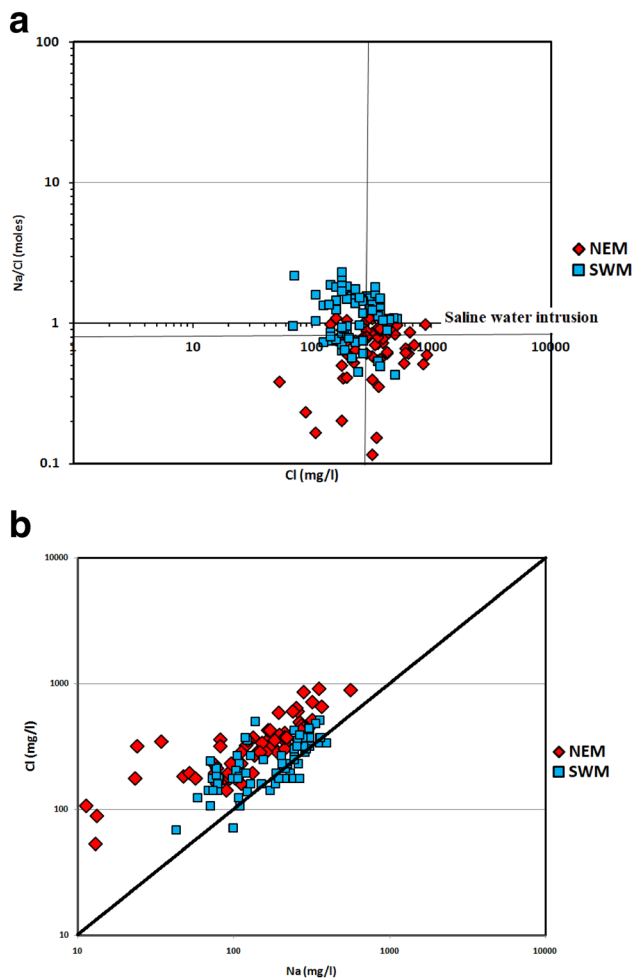
Fig. 11 a The relationship between the Na^+/Cl^- ratio and the Cl^- values to determine the saline intrusion. **b.** The bivariate plot between the Na and Cl to determine the sea water intrusion process

the study area. The same method was effectively associated with a coastal aquifer [83, 84] to classify the two distinctive hydrogeochemical processes. During NEM, the maximum numbers of samples are observed in Field 3 (Na-Cl) (Fig. 10) which indicates influence of seawater mixing and is usually bound to the coastal zones. Field 1 (recharging water) contains only few samples. Regardless of the samples with reverse ion exchange in field 2, the process of base ion exchange in water is indicated in field 4 (Na-HCO_3) in few samples. During SWM, the predominance of samples in Fields 3 (Na-Cl) and 4 (Na-HCO_3) reflects reverse ion exchange (Field 2) and recharge waters (Field 1) during SWM (Fig. 10). The samples near to the coastal zone have high Cl and Na^+, hence predominantly falls within Field 3 with less representation in Field 2. Moreover, most of the samples representing a high Na and Cl, also represent a high concentration of Ca, Mg, HCO_3, Cl and SO_4 reflecting

are consequential in a reduction of the surplus of Na and Ca.

As shown in Table 4, 21% of NEM samples and 10% of SWM samples show elevated Na/Cl, and it is also observed that the 53% of NEM samples and 77% of SWM samples have ratios of Ca/(HCO$_3$ + SO$_4$) greater than unity [86].

The disgraceful management and transfer of household wastewater may be the major cause of salinization within the coastal aquifer during SWM [87]. The groundwater samples contaminated by sewage effluent have Na/Cl value greater than unity and comparatively higher than SO$_4$/Cl (0.09) [88]. The higher values of these ratios are due to intensive use of NaCl salts and residential wastewater infiltration. The lower K/Cl values in the shallow aquifers indicate an anthropogenic impact. Source of K is mainly anthropogenic which is supported by the K/Cl ratio; 13 percent and 18 percent of the samples during NEM and SWM, respectively, reflect the anthropogenic influence. The Ca/(HCO$_3$ + SO$_4$) ratio indicates the influence of salt-water intrusion in the study area.

4.5 Statistical analysis

4.5.1 Correlation matrix

Correlation matrix (Table 5) describes the inter-relation among the variables to identify the source of contaminates in the groundwater. Positive correlation is observed between pH, EC, TDS Na, Cl, and HCO$_3$ during NEM. Strong positive correlation among EC and TDS with ions of Na, Cl and HCO$_3$ reflects the influence of these ions to increase the EC and TDS values. Cl shows positive correlation with Na indicating the influence of sea water intrusion and secondary leaching of salts [62, 89]. During SWM, pH is positively correlated with HCO$_3$. Strong positive correlation is observed among EC, TDS and Na. Likewise, the good correlation between Na and Cl indicates percolating of secondary salts and impact of the saltwater in the groundwater of the study area [62]. Mg also has good correlation with Cl. In general, there is a good correlation existing between Na and Cl in both the NEM and SWM seasons which indicates

a strong influence of sea water on the groundwater of the study area especially in the samples located in the coastal region.

4.5.2 Factor Analysis

To identify the processes responsible for the groundwater contamination of the study area, factor analysis (PCA) was carried out. There were four factors extracted during NEM and five factors during SWM (Table 6 and 7).

Factor I with strong positive loading of Na, K, Cl, HCO$_3$, EC and TDS (Table 6) could be linked to the saline source during NEM [90, 91]. The factor II with strong positive loading of pH, HCO$_3$ and SO$_4$ is typically influenced by the contaminant from agricultural activities [58]. The chemical weathering or silicate dissolution might be related to high Si in factor III [92]. Similarly, in factor IV, there is a positive loading of Ca and Mg with very low loading of Na and K, which clearly implies the base ion exchange process. The factor I with positive loading of Mg, Na, Cl, TDS and EC (Table 7) is linked to percolation of secondary salts during SWM [60, 71] deposited in the pore spaces during previous summer. The factor II, with a positive loading of K and PO$_4$, indicates the influence of anthropogenic sources mainly from agricultural activities [93]. The positive loading of factor III with Na$^+$ and HCO$_3$ indicates weathering process [94]. The high loading of NO$_3$ in factor IV could be related to impact of fertilizers applied in farming lands. The positive loading of Ca and SO$_4$ in factor V is due to anthropogenic activities [95].

5 Conclusion

Intensive groundwater extraction in the study area has resulted in saline water intrusion into the aquifer. The shallow aquifer signifies less resistivity, which might be due to dominant clay layers or seawater intrusion in southeast regions. Rainfall plays an important role in water level fluctuation. Reduction in amount of rainfall during SWM of 2016, has led to the saline water intrusion in the deeper aquifers of the study area. Higher values of EC were noted in the groundwater samples of NEM. The hydrochemistry shows that TDS values are higher and above the standard limits for most of the samples with 59% and 62% of both NEM and SWM samples, considered unsuitable for drinking purposes. The spatial representation of the EC values shows that the groundwater samples are more saline during NEM and are represented along the southeastern part of the study region. The Na-Cl and Ca–Mg–Cl are the dominant water types in the groundwater samples during NEM, and representation of Cl-HCO$_3$ type is noted in the SWM, indicating the recharge process. Seasonal variation

Table 4 Range of ionic ratio in sea water compared to the NEM and SWM samples to determine the seawater intrusion

	Sea water intrusion	NEM (%)	SWM (%)
Na$^+$/Cl$^-$	0.86–1	20.6	10.3
K$^+$/Cl$^-$	0.05	13.2	17.6
SO$_4^{2-}$/Cl$^-$	0.02	0.0	0.0
Mg$^+$/Ca^{2+}	>5	0.0	0.0
Ca^{2+}/(HCO$_3^-$ + SO$_4^{2-}$)	0.35–1	52.9	76.5

Table 5 Correlation analysis of groundwater samples for NEM and SWM (numbers in italics indicate the correlation coefficient of SWM samples; numbers in bold indicates the good to significant positive correlation)

	Ca	Mg	Na	K	Cl	HCO$_3$	NO$_3$	PO$_4$	SO$_4$	Si	TDS	EC	temp	pH
Ca	1													
	1													
Mg	−0.18	1												
	0.08	*1*												
Na	0.14	0.20	1											
	0.01	*0.31*	*1*											
K	0.06	0.25	0.46	1										
	−0.08	*0.01*	*0.09*	*1*										
Cl	0.36	0.36	**0.83**	0.41	1									
	0.26	***0.61***	***0.69***	*0.11*	*1*									
HCO$_3$	0.16	0.28	0.48	0.46	0.26	1								
	0.23	*0.28*	***0.65***	*0.22*	*0.26*	*1*								
NO$_3$	−0.11	0.20	0.30	0.24	0.17	0.17	1							
	0.12	*0.22*	*0.17*	*0.35*	*0.22*	*0.18*	*1*							
PO$_4$	−0.13	−0.09	−0.18	−0.18	−0.21	−0.16	0.11	1						
	−0.01	*−0.10*	*0.008*	*0.45*	*−0.004*	*0.05*	*0.01*	*1*						
SO$_4$	0.12	−0.15	0.07	0.05	−0.06	0.18	−0.04	0.03	1					
	0.33	*0.22*	*0.20*	*0.09*	*0.33*	*0.19*	*0.24*	*0.01*	*1*					
Si	0.09	0.09	0.02	0.10	0.10	0.14	−0.27	−0.23	−0.007	1				
	0.09	*0.07*	*−0.01*	*−0.25*	*0.12*	*−0.13*	*−0.09*	*−0.16*	*−0.005*	*1*				
TDS	0.33	0.35	**0.65**	0.47	**0.66**	**0.62**	0.28	−0.26	0.06	0.09	1			
	0.31	***0.53***	***0.82***	*0.27*	***0.77***	***0.75***	*0.37*	*0.07*	*0.39*	*0.07*	*1*			
EC	0.33	0.34	0.70	0.49	**0.69**	**0.62**	0.35	−0.26	0.06	0.02	**0.98**	1		
	0.22	*0.49*	***0.59***	*0.22*	***0.72***	*0.44*	*0.41*	*0.08*	*0.36*	*0.11*	***0.82***	*1*		
temp	0.12	−0.08	−0.18	−0.05	0.02	−0.28	−0.21	−0.03	0.007	0.05	−0.24	−0.26	1	
	−0.02	*0.10*	*0.24*	*0.08*	*0.11*	*0.32*	*0.32*	*−0.24*	*−0.01*	*0.23*	*0.26*	*0.18*	*1*	
pH	0.18	0.08	0.09	0.10	−0.03	**0.57**	−0.05	−0.09	0.26	0.15	0.21	0.20	−0.09	1
	−0.14	*−0.01*	*−0.15*	*−0.08*	*−0.02*	*−0.32*	*0.05*	*−0.12*	*−0.18*	*0.03*	*−0.26*	*−0.17*	*0.19*	*1*

in groundwater salinity was observed during seasons. The inverse ion exchange process also plays a vital role in hydrochemical variation in groundwater during both the seasons. The factor analysis shows that the major factors which influence the groundwater quality of the study area are anthropogenic activities, ion exchange process and saline water intrusion. The process of seawater intrusion is substantiated by positive loadings of Na and Cl in both NEM and SWM samples. Though the salinity of SWM monsoon samples are higher, the ratios and ion relationships indicate that the leaching of salts plays a major role in the geochemistry of SWM samples apart from sea water intrusion. The NEM samples are mainly influenced by the sea water intrusion due to higher extraction for agricultural practices and failure of NEM. The samples of NEM also reflect signature of fertilizers and ion exchange process. Hence, integrating the results of lithologs, resistivity values, rainfall and water level variation along with the groundwater geochemistry the study infers that the groundwater along the southeastern part are more influenced by the sea water intrusion irrespective of the season. Further with more detailed analysis, including isotopes and trace elements will provide a more vivid picture, corroborating with the conclusion derived from the present study. The time series analysis of the available geochemical data, trend of rainfall, freshwater demand, increase in population, change in landuse pattern would provide a lucid management solution for the resource.

Table 6 Factor scores of GW samples and varimax factor matrix of chemical constituents during NEM (numbers in bold indicates the positive loadings of the parameters in the factor)

NEM	1	2	3	4
Ca^{2+}	0.36	0.09	0.17	0.72
Mg^+	0.38	− 0.01	0.18	0.63
Na^+	**0.84**	0.05	− 0.06	0.01
K^+	**0.59**	0.14	0.09	− 0.19
Cl^-	**0.88**	− 0.21	0.12	0.10
HCO_3^-	**0.52**	**0.70**	0.09	− 0.17
NO_3	0.39	− 0.002	− 0.59	− 0.31
PO_4	− 0.28	0.005	− 0.57	0.006
SO_4	− 0.02	**0.55**	− 0.13	0.41
Si	0.02	0.12	**0.76**	− 0.09
TDS	**0.88**	0.24	0.04	− 0.02
EC	**0.91**	0.23	− 0.03	− 0.02
temp	− 0.14	− 0.38	0.32	0.39
pH	0.05	**0.81**	0.21	0.03
Initial eigenvalues of variance explained by each other (in %)	30.65	13.02	11.05	10.33
Cumulative of variance (in %)	30.65	43.67	54.73	65.06

Table 7 Factor scores of GW samples and varimax factor matrix of chemical constituents during SWM (numbers in bold indicates the positive loadings of the parameters in the factor)

SWM	1	2	3	4	5
Ca^{2+}	0.05	− 0.16	0.15	− 0.006	**0.80**
Mg^+	**0.75**	− 0.10	− 0.08	0.02	0.06
Na^+	**0.70**	0.002	**0.54**	0.14	− 0.14
K^+	0.11	**0.79**	0.04	0.31	0.01
Cl^-	**0.91**	− 0.04	0.03	0.002	0.16
HCO_3^-	0.31	0.10	**0.80**	0.29	0.07
NO_3	0.23	0.30	− 0.14	**0.68**	0.33
PO_4^{2-}	0.04	**0.74**	0.008	− 0.23	0.008
SO_4	0.27	0.07	0.05	0.03	**0.70**
Si	0.15	− 0.58	− 0.13	0.06	0.08
TDS	**0.78**	0.09	0.49	0.23	0.23
EC	**0.78**	0.11	0.18	0.18	0.25
Temp	0.08	− 0.26	0.16	**0.83**	− 0.13
pH	0.03	− 0.13	− 0.66	0.32	− 0.28
Initial eigenvalues of variance explained by each other (in %)	24.5	12.71	12.63	11.66	10.97
Cumulative of variance (in %)	24.5	37.2	49.90	61.56	72.53

Compliance with ethical standards

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