



Seawater intrusion impacts on groundwater and soil quality in the northern part of the Nile Delta, Egypt

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Abstract

Seawater intrusion (SI) is thought to be a significant threat to groundwater and soil quality in arid coastal ecosystems, causing a reduction in freshwater availability and soil productivity. This study investigated the effects of seawater intrusion on soil and groundwater quality in the Nile Delta region at 16 sites located at distances of 5–45 km from the coast. We found that groundwater and soil quality were significantly affected by seawater intrusion. Results from the investigations indicated that: (1) the salinity and alkalinity of groundwater and soil pore-water decreased with increasing distances towards the inland, and showed significant positive correlations for EC, SAR, Na⁺ and Cl⁻ by 0.80, 0.46, 0.78 and 0.66 respectively offshore (45 km); (2) there were significant positive correlations between salinity and alkalinity of both groundwater and soil pore-water inland up to 15 km distance from the coast; (3) mixing ratio values (F%) of seawater and groundwater were 9.30 to 37.56% in different sites, recording a maximum value close to the sea (5 km), while a minimum value was observed offshore (45 km); and (4) increasing seawater intrusion had negative impacts on the quality of groundwater and soil up to 15 km from the sea, providing the possibility of exploiting irrigated land in Nile delta up to 15 km from the Mediterranean sea.

Keywords Seawater intrusion (SI) · Offshore distance · Groundwater depth · Salinity · Soil properties

Introduction

Groundwater is a significant and life-sustaining source of irrigation in many regions of the world (Rodell et al. 2009; Gleeson et al. 2012) that plays an important role in irrigated agriculture. Owing to excessive pumping of groundwater

and land subsidence, seawater intrusion (SI) into coastal aquifers and their potential salinization has become a serious concern (Sherif et al. 2018), which has been exacerbated over recent decades due to the increased scarcity of freshwater resources (Alameddine et al. 2017), climatic changes and associated sea level rises (Kheir et al. 2019; Badaruddin et al. 2015; Flower et al. 2017).

Although there is a large body of the literature available on seawater intrusion, much of this work has only focused on the effects of this issue at depth within aquifers, and has neglected the potential impacts of SI on shallow groundwater and on soil salinity (Alfarrah and Walraevens 2018). However, in arid regions that have limited freshwater resources and limited rainfall to provide groundwater recharge, SI may cause salinization near the water table in shallow aquifers, posing a salinity threat to overlying soils.

Egypt is particularly vulnerable to this issue due to its long coastline, which includes 950 km along the Mediterranean Sea in the north, 400 km along the Gulf of Suez, 300 km along the Gulf of Aqaba, and 1200 km along the Red Sea in the east. The expected effects of sea-level rise and on the resultant movement of seawater interfaces has

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the potential to cause significant impacts on groundwater quality. This, in turn, is likely to reduce soil quality and soil and crop yields in the Nile Delta and be a major constraint to agricultural development in the region (RIGW/IWACO 1998).

SI occurs when a saline water wedge penetrates the lower part of a coastal aquifer due to its higher density than fresh groundwater. As the saline water wedge progressively moves inland, the entire saturated profile of an aquifer can become salinized, potentially affecting the quality of soils that overlie the water table (Werner and Lockington 2006). Until now, most of the research has mainly focused on the effects of tides and the decline in water table levels due to over pumping, forming the saltwater interface. However, only a limited amount of research has been undertaken to assess the effects of sea level rises on the movement of saltwater interfaces in coastal aquifers and on the effects on soil salinization.

Approximately, 32% of Nile Delta area would be submerged and one-third of the groundwater resources would be lost under the condition of 1 m sea-level rise. Also, the amount of fresh water available for irrigation may be reduced by 15% if the current rate of groundwater abstraction is maintained. Provided that the sea level rise is less than 0.5 m, a decrease in the rate of groundwater abstraction by 50% could mostly sustain the current freshwater resource.

Soil salinization is the accumulation of free salts in the soil to such an extent that it tends to negatively affect vegetation growth and soil productivity (Seleiman and Kheir 2018). Salinization is normally caused by irrigation with saline water, and further triggered by changes in soil structure caused by poor soil drainage (Xu et al. 2016) and high rates of evapotranspiration from saline soils (Hernandez et al. 2004). The combined effects of saline irrigation water and effluent water, poor drainage and soil management practices can increase the salinity hazards in irrigated soils.

In coastal areas, the unwise exploitation of groundwater resources for agricultural, industrial and domestic purposes often results in an imbalance of the dynamic equilibrium among seawater and the flowing groundwater, favoring saltwater intrusion. Under these conditions, saltwater penetration can lead to serious environmental and economic problems (Moujabber et al. 2006). This problem can be controlled in a number of different ways, including the development of underground barriers in coastal aquifers to prevent the movement of the saltwater interface (Lee et al. 2019; Werner and Lockington 2006). But this requires firstly that the hydraulics and the water balance of the aquifer are quantified. This information and monitoring of the position of the saltwater interface can be used to develop management options to address specific issues associated with sea-level rise (Megdal et al. 2017).

Exploring the impacts of SI on coastal aquifers could be done using the mixing ratio approach. Since chloride is the

main dominant element in salinity, it could be used to mathematically calculate the mixing ratio of sea water and groundwater (Chambers 2014; Arslan and Demir 2013). This index varies from region to region due to changing soil elevation and texture conditions and proves its significance in the Nile Delta.

The purpose of this study was to investigate the salinization of groundwater in coastal areas in the northern part of the Nile Delta were investigated in this study, and to quantify the physical and chemical changes that have taken place to soils in areas where seawater intrusion has taken place. The findings would help scientists and decision makers to deal with land degradation, water scarcity and management, which would help ensure that agriculture in the region is agriculture.

Materials and methods

Study sites

The study area lies in the northern part of the Nile Delta between two branches (the Rosita and Damietta rivers) of the Nile River in Egypt (Fig. 1). In the study area, 16 monitoring sites along 4 transects (each having 4 sampling sites) were chosen to study groundwater levels and salinity as well as soil characteristics, from June 2015 to June 2017. The individual sampling transects run from the Mediterranean Sea in the north in a southerly direction to a distance of 45 km from the coast. The distance between each sampling transect is about 22 km. All the locations chosen for soil sampling were located far from any source of water such as irrigation canals or drains. All soils on the study sites are clayey in texture with more than 50% clay content.

The Nile Delta has an area of about 22,000 square kilometers. The delta is broadly triangular and extends about 170 km in a southerly direction from the coast and has a width of about 220 km. The soils in the northern part of the delta are fluvial-marine in origin, and the soils of the border fringes are of intermixed origin as they have been affected by water and wind actions (El-Shahawi 1994).

The region has an arid to semi-arid climate with long dry summers and minimal winter rainfall (~ 80 mm/year). The average annual temperature is 20.1 °C. Maximum daily temperature rises over 32.2 °C in summer and the minimum night temperature falls to 8.7 °C in winter, the average value of vapor pressure is about 17 millibars, the wind velocity is around 2.2 m/sec and sunshine around 77%.

Installation of observation wells for groundwater monitoring

To monitor the position of saltwater interface, observation wells were installed at same depth from soil surface (5 m) in all the locations as shown in Fig. 1. Groundwater

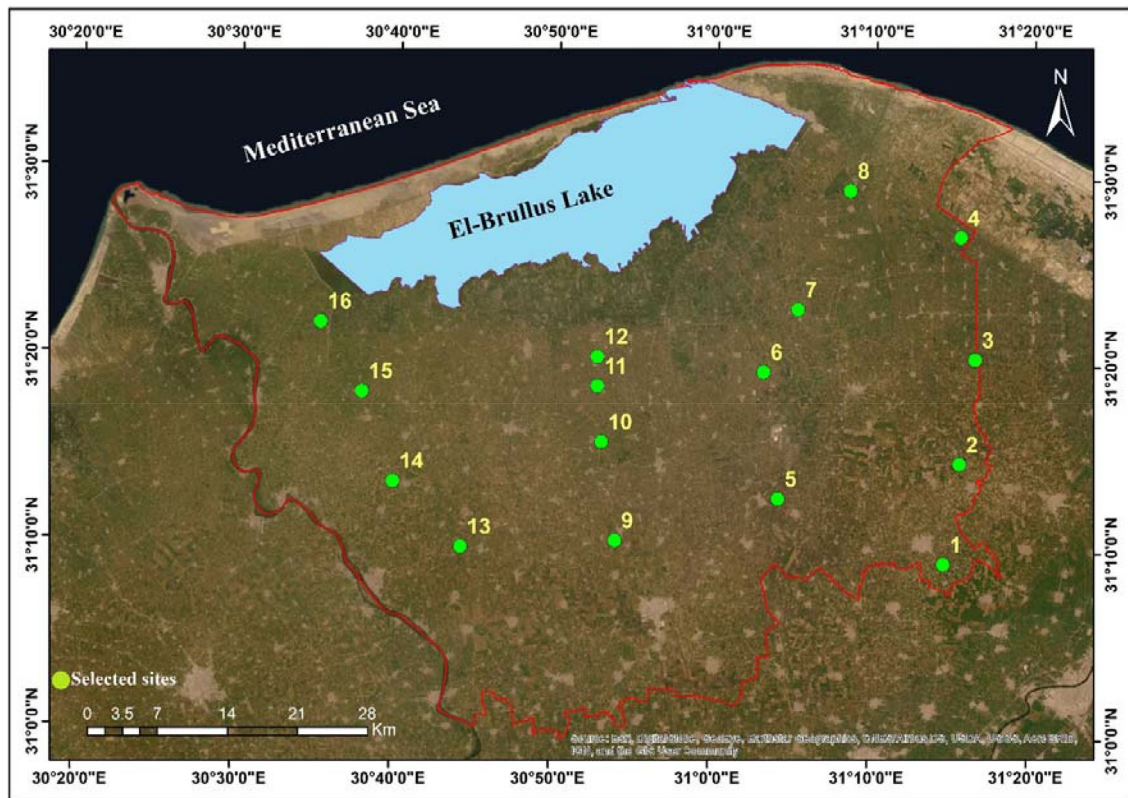


Fig. 1 Locations of the studied soil profiles and observation wells around River Nile branches

was sampled using a specific bailer from each well every 15 days for chemical analysis. Seawater samples were also taken twice per season (two each in summer and winter). Soil samples were collected at the depths of 0–20, 20–40, 40–60 and 60–90 cm at the beginning and the end of 2 years, all the samples were collected and prepared according to standard methods (Bado et al. 2016) for analysis.

Soil and water analyses

Electrical conductivity (EC_e), soluble cations and anions in the soil were determined according to (Bado et al. 2016), while soil pH was determined in 1:2.5 soil–water suspension, at 25 °C according to (Rowell 1995). Sodium adsorption ratio (SAR) was calculated according to (Richards 1954). Samples of groundwater and irrigation water were filtered prior to chemical analyses (i.e. EC_w , pH and soluble cations and anions) as described by (Rowell 1995), while soil texture was determined using the pipet method (Gee and Bauder 1986).

Data mapping and interpolation

ArcMap 10.3 was used to interpolate point data to a surface using the Inverse Distance Weighted (IDW) tool, where the

ESRI shapefile of the study area was used as the boundary and projection of the surface creation and the pixel size set to 30 m.

Calculation of saltwater interface mixing values

Simple correlations (Pearson correlation coefficients) were performed by the Microsoft Excel program according to the following equation:

$$r = \frac{\sum xy - (\sum x \times \sum y)/n}{\sqrt{\sum x^2 - ((\sum x^2)/n)} \sqrt{\sum y^2 - ((\sum y^2)/n)}}$$

where mx and my are the means of x and y variables. The p value (significance level) of the correlation can be determined using the correlation coefficient table for the degrees of freedom ($df=n-2$).

Calculation of seawater–freshwater mixing ratios using the CI value has been reported by (Somay and Gemici 2009). While mathematically, seawater–freshwater mixing percentages can be calculated with the concentrations of freshwater and seawater as described by (Custodio 1987).

Based on the conservative mass balance of Cl, theoretical blending could be calculated with the following equation (Arslan and Demir 2013):

$$F = \frac{(CL_{mix} w - CL_{iw})}{(CL_{Sea} w - CL_{iw})} \times 100,$$

where F = Mixing ratio expressed as the percentage of seawater (%), $CL_{mix} w$ = Chloride in the groundwater, CL_{iw} = Chloride in irrigation water, $CL_{sea} w$ = Chloride in seawater.

Results and discussion

Change in the characteristics of seawater, groundwater, and irrigation water with distance from the sea

The majority of the studied irrigation water samples could be classified as C2S1, with the characteristics of medium salinity and a low alkalinity. The salinity index of irrigation water is based on the presence of total soluble salts (EC, dSm^{-1}) and expressed as low (C1: less than $0.250 dSm^{-1}$), medium (C2: $0.250-0.750 dSm^{-1}$), high (C3: $0.750-2.250 dSm^{-1}$) and very high (C4: more than $2.250 dSm^{-1}$) salinity. The alkalinity (sodium adsorption ratio, SAR) hazard is expressed in terms of classification of irrigation water as low (S1: < 10), medium (S2: $10-18$), high (S3: $18-26$), and very high (S4: > 26).

In current study, the salinity of irrigation water ranged from 0.64 to $0.76 dSm^{-1}$ and SAR values from 5.52 to 5.94 at all the depths and distances from sea (Table 1). This water with medium salinity and low alkalinity is considered

suitable for irrigation purposes for all types of soils without harmful levels of salinity and alkalinity. Groundwater depth plays an effective role in determining soil characteristics and crop production. As shown in Table 1 and Fig. 2, the water table depths increased with increasing distances from the sea. The average values of groundwater depth were 62.18 , 70.38 , 76.77 and 88.37 cm from soil surface, respectively, for the distance of 5 , 15 , 25 and 45 km from the sea. This is likely due to seawater rise, despite the marginal elevation of the coastal area (Kheir et al. 2019). Besides, the seawater rise could decrease the hydraulic gradient of the groundwater and piezometric head in the Aquifer (Ranjbar et al. 2020). It has also been reported that deep coastal aquifers with mild hydraulic gradients were more vulnerable to submerging under the conditions of seawater rise and climate change. This is a significant finding in the Nile delta region, where 19 and 32% of the area is prone to be submerged under the conditions of sea level rises of 0.5 and 1.0 m, respectively (Sefelnasr and Sherif 2014). Moreover, the observed intrusion of seawater has already reached a distance of about 100 km inland from the coastline in this region (Sherif et al. 2012).

The salinity and alkalinity of groundwater (Table 1 and Fig. 3) decreased with increasing distance inland from the coast. The average values of groundwater salinity were 16.71 , 12.89 , 7.88 and $4.88 dSm^{-1}$, respectively, at the distance of 5 , 15 , 25 and 45 km from the sea. The corresponding values of SAR were 20.96 , 17.17 , 12.85 and 10.42 . Although the salinity of seawater on coastal areas of the Nile Delta have been affected by river and groundwater discharges, values of this parameters were still high and were 37.45 and $36.51 dSm^{-1}$. Sea-level rise would increase the inland extent of seawater intrusion, and would cause a

Table 1 Average values of some properties of sea water, groundwater and irrigation water with distance from the sea (km)

Properties	Sea water	Ground water with distance from the sea (km)				Irrigation water with distance from the sea (km)			
		5	15	25	45	5	15	25	45
Groundwater depth(cm)	0	62.18	70.38	76.77	88.37				
$EC_w (dSm^{-1})$	37.5 ± 0.1	16.7 ± 0.3	12.89 ± 0.4	7.88 ± 0.2	4.88 ± 0.2	0.76 ± 0.01	0.76 ± 0.02	0.69 ± 0.03	0.64 ± 0.01
$Ca^{++} (meqL^{-1})$	69.4 ± 0.5	30.2 ± 0.5	28.1 ± 0.6	18.7 ± 0.7	11.1 ± 0.6	1.0 ± 0.01	0.97 ± 0.02	0.9 ± 0.02	0.9 ± 0.03
$Mg^{++} (meqL^{-1})$	46.3 ± 0.8	24.0 ± 0.6	19.3 ± 0.4	13.1 ± 0.2	7.5 ± 0.4	0.8 ± 0.01	0.8 ± 0.02	0.6 ± 0.03	0.6 ± 0.01
$Na^+ (meqL^{-1})$	277.7 ± 2.5	109.2 ± 2	83.6 ± 1.5	51.7 ± 1.2	31.9 ± 3	5.6 ± 0.7	5.4 ± 0.4	5.0 ± 0.3	4.7 ± 0.4
$K^+ (meqL^{-1})$	2.5 ± 0.2	1.8 ± 0.3	1.5 ± 0.1	1.5 ± 0.1	1.4 ± 0.1	0.4 ± 0.01	0.4 ± 0.02	0.4 ± 0.03	0.4 ± 0.01
$HCO_3^- (meqL^{-1})$	19.8 ± 0.5	4.8 ± 0.5	4.7 ± 0.3	4.4 ± 0.1	4.3 ± 0.01	1.1 ± 0.02	1.08 ± 0.01	1.08 ± 0.03	1.07 ± 0.01
$Cl^- (meqL^{-1})$	269.9 ± 3.7	104.7 ± 3	80.3 ± 2	46.8 ± 1	28.9 ± 0.5	5.29 ± 0.4	5.02 ± 0.2	4.62 ± 0.1	4.26 ± 0.1
$SO_4^{--} (meqL^{-1})$	106.3 ± 3	55.7 ± 1.1	47.6 ± 1.5	33.8 ± 2	18.6 ± 0.5	1.4 ± 0.01	1.37 ± 0.03	1.21 ± 0.05	1.18 ± 0.01
PH	8.05 ± 0.03	8.18 ± 0.02	8.12 ± 0.01	8.10 ± 0.01	8.05 ± 0.02	8.07 ± 0.05	8.06 ± 0.03	8.05 ± 0.02	8.09 ± 0.02
SAR	36.51 ± 0.5	20.96 ± 0.6	17.17 ± 0.7	12.85 ± 0.6	10.42 ± 0.7	5.94 ± 0.6	5.72 ± 0.4	5.77 ± 0.3	5.52 ± 0.5

EC electrical conductivity, SAR sodium adsorption ratio, Means \pm Stdev, $n = 3$

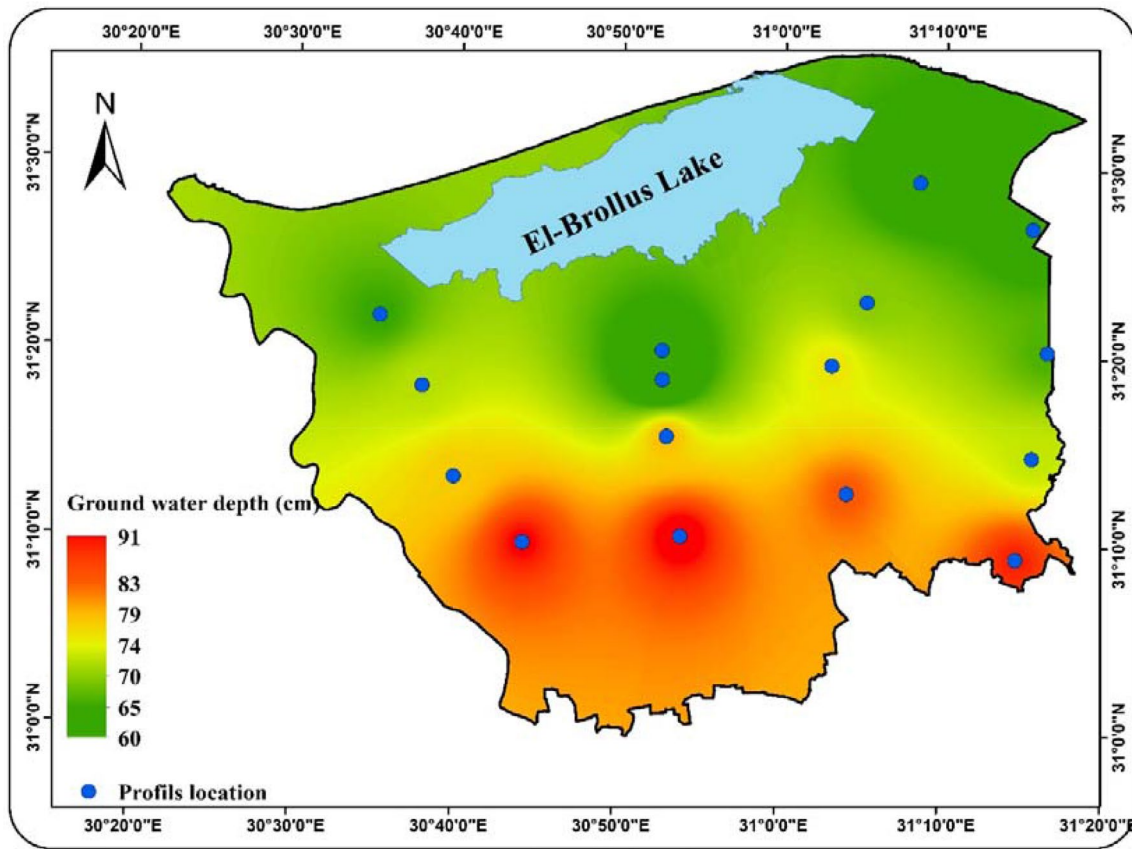


Fig. 2 Depth of groundwater (cm) with distance from the sea to inland

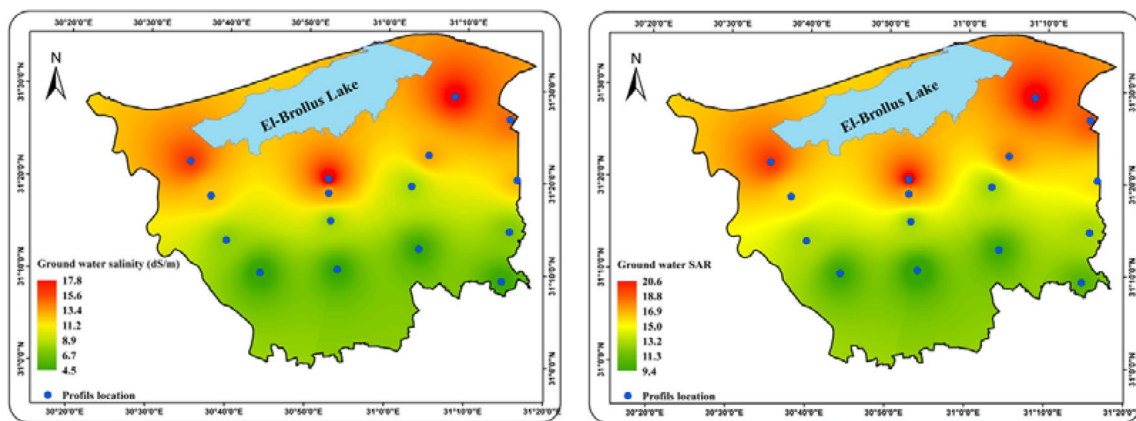


Fig. 3 Salinity (left) and alkalinity (right) of groundwater with distance from the sea

deterioration of groundwater quality in the coastal area of the Nile Delta (RIGW/IWACO 1998).

Soluble Na^+ and Cl^- were the dominant ionic species in the seawater, groundwater, and irrigation water. The contents

of soluble cations and anions had the same trend with the distances towards the inland. The higher values of soluble cations and anions were recorded close to the sea, while the

lower values recorded far from the sea. The pH of all water samples fell in a narrow range of 8.05–8.18.

Relations of water indicators for seawater and groundwater

Significant positive simple correlations were observed for EC, SAR, Na^+ , Cl^- and HCO_3^- between seawater and

groundwater in the coastal area of the Nile Delta (Table 2). The highly significant positive correlations were noticed near the sea (5 km) and continued to a distance of 25 km inland. The correlation coefficient values were 0.80, 0.46, 0.78, 0.66 and 0.71 for EC, SAR, Na^+ , Cl^- and HCO_3^- at the distance of 5 km from the sea, and 0.47, 0.19, 0.54, 0.42 and 0.40 at the distance of 25 km from the sea, respectively. This is mainly due to increasing seawater blending percentage (Arslan and Demir 2013), with a strong relationship between EC and concentration of NaCl (Fig. S1).

Table 2 Correlation between properties of sea water and groundwater with distance from the sea

Properties of sea water and ground water	Distance from the sea (km)			
	5	15	25	45
EC (dS m^{-1})	0.80**	0.56**	0.43	0.14
Ca^{2+} (meq L^{-1})	0.48**	0.05	0.60**	0.23
Mg^{2+} (meq L^{-1})	0.40*	-0.40*	0.44*	0.02
Na^+ (meq L^{-1})	0.78**	0.42*	0.54**	0.25
K^+ (meq L^{-1})	0.13	0.44*	0.70**	0.55**
HCO_3^- (meq L^{-1})	0.71**	0.37*	0.40*	0.06
Cl^- (meq L^{-1})	0.66**	0.47**	0.42*	0.31
SO_4^{2-} (meq L^{-1})	0.49**	-0.28	0.59**	0.20
pH	0.50**	0.09	-0.10	0.25
SAR	0.46**	0.35*	0.19	0.23

** $p < 0.01$ level, * $p < 0.05$ level

Soil chemical property changes with distance from the sea

Average values of salinity (EC), alkalinity (SAR), pH, soluble cations and anions in the soil with distance from the sea are shown in Table 3. The results show that EC, SAR, soluble cations and anions for soil samples increased with increasing soil depth irrespective of distances from the sea except for K^+ . The average values of soil salinity were 2.94, 3.06, 4.20 and 4.60 dS m^{-1} at 45 km, 3.98, 4.58, 6.31 and 8.19 dS m^{-1} at 25 km from the sea for the depths of 0–15, 15–30, 30–60 and 60–90 cm, respectively. The corresponding values were 4.53, 5.85, 7.86 and 9.79 dS m^{-1} at 15 km, 5.61, 7.43, 10.24 and 13.26 dS m^{-1} at 5 km from the sea, respectively. The results also showed

Table 3 Salinity, sodicity and soluble cations and anions of the soil with depth and distance from the sea (km) for the sites of study (average of initial and after 2 years)

Distance from the sea (km)	Soil depth (cm)	EC ds m^{-1}	Soluble cations meq L^{-1}				Soluble anions meq L^{-1}			pH	SAR
			Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	Cl^-	SO_4^{2-}		
45	0–15	2.94	6.04	3.83	19.65	1.34	3.31	19.40	8.15	8.11	8.86
	15–30	3.06	6.11	3.91	21.03	1.34	3.39	19.27	9.74	8.13	9.42
	30–60	4.20	7.35	5.23	29.88	1.21	3.67	27.65	12.35	8.12	11.92
	60–90	4.60	8.29	5.87	33.82	1.16	3.58	30.34	15.21	8.14	12.70
	Average		3.70	6.95	4.71	26.10	1.26	3.49	24.17	11.36	8.12
25	0–15	3.98	7.65	5.09	27.69	1.33	3.08	26.28	12.40	8.13	10.98
	15–30	4.58	8.29	5.76	32.53	1.26	3.49	29.97	14.38	8.13	12.27
	30–60	6.31	11.15	7.24	45.31	1.23	3.49	42.26	19.18	8.14	14.84
	60–90	8.19	14.73	9.49	57.77	1.25	3.64	53.77	26.15	8.14	16.53
	Average		5.77	10.46	6.89	40.83	1.27	3.42	38.07	18.03	8.14
15	0–15	4.53	8.44	5.56	31.74	1.32	2.87	29.49	14.70	8.13	11.99
	15–30	5.85	10.91	7.14	41.33	1.25	3.23	37.09	20.31	8.17	13.75
	30–60	7.86	14.37	9.54	56.53	1.26	3.13	53.36	25.20	8.13	16.36
	60–90	9.79	17.16	11.13	72.83	1.18	3.11	67.59	30.41	8.16	19.44
	Average		7.01	12.72	8.34	50.61	1.25	3.09	46.88	22.65	8.15
5	0–15	5.61	11.03	7.22	38.31	1.34	2.97	35.71	19.21	8.14	12.76
	15–30	7.43	14.14	9.02	51.72	1.25	3.08	47.30	25.53	8.13	15.30
	30–60	10.24	17.57	12.03	73.61	1.27	2.87	68.76	33.24	8.11	19.18
	60–90	13.26	21.06	14.65	96.52	1.26	3.54	90.31	39.75	8.11	22.86
	Average		9.14	15.95	10.73	65.04	1.28	3.12	60.52	29.43	8.12

EC electrical conductivity, SAR sodium adsorption ratio

soil sodicity values at different soil depths and distances from the sea had a similar tendency with soil salinity but differed in magnitude.

Salinity and alkalinity for soil rose slightly after 2 years and increased 0.34 dS m^{-1} and 0.19 units, respectively (Figs. S1 and S2). Concentrations of soluble cations and anions in the soil showed the same trends as the salinity values and Na^+ and Cl^- increased 1.32 and 0.28 meq L^{-1} respectively after 2 years. There were no significant differences in pH among all the soil samples. Interestingly, salinity and alkalinity of the soil decreased with increasing distances inland (Table 3).

The average values of soil salinity were $9.14, 7.01, 5.77$ and 3.70 dSm^{-1} for distances of $5, 15, 25$ and 45 km from the sea, and the corresponding values of SAR were $17.53, 15.38, 13.66$ and 10.72 respectively. The high salinity and alkalinity of the soil in the coastal region of the Nile Delta is caused by the shallow depth of the water table and the location of the saltwater interface, and by the capillary effects of wicked salts in shallow soils, which eventually lead to higher groundwater EC and SAR (Xu et al. 2016). The average soil salinity in the coastal area of the Nile Delta varied from moderately saline to strongly saline until a distance 25 km from the sea. This is mainly due to the increased land elevation and depth of the water table, thereby reducing the capillary effect on soil salinity at the point. Whereas EC values of the soil were recorded higher than 4 dSm^{-1} for all the depths of a soil profile. Salinity classes were determined based on system described by (Ullman 2013). Depending on these classifications, soils with salinity from 0 to 2.0 dS m^{-1} were classified as non-saline, from 2.0 to 4.0 dS m^{-1} as slightly saline, from 4.0 to 8.0 dS m^{-1} as moderately saline, from 8.0 to 16.0 dS m^{-1} as strongly saline, and over 16.0 dS m^{-1} as very strongly saline. Accordingly, the highest values of soluble ions were recorded at 5 km from the sea and the lowest values were obtained at 45 km from the sea.

The average values of $\text{Ca}^{2+}, \text{Mg}^{2+}, \text{Na}^+, \text{K}^+, \text{HCO}_3^-, \text{Cl}^-$ and SO_4^{2-} were $16, 11, 65, 1, 3, 61$ and 29 meq L^{-1} , respectively, at a distance of 5 km from the sea, and $7, 5, 26.10, 1, 3, 24$ and 11 meqL^{-1} , respectively, at a distance of 45 km from the sea. Soluble sodium and soluble chloride in soil solution were the dominant ions in soil pore-water. Values of pH had a narrow range for all the soil samples and ranged from 8.11 to 8.17 .

Soil properties (EC, Na^+, Cl^- and SAR) had almost the opposite trend to that encountered with groundwater depth (Fig. 4). The results indicated that the values of groundwater depth increased with increasing distances from the sea but the values of EC, Na^+, Cl^- and SAR decreased. This indicates that, EC, Na^+, Cl^- and SAR in soil solution of shallow water table depth increased in the coastal areas of the northern Nile Delta. Values of EC, Na^+ and Cl^- values in the soil showed similar trends to those in groundwater (Fig. 5).

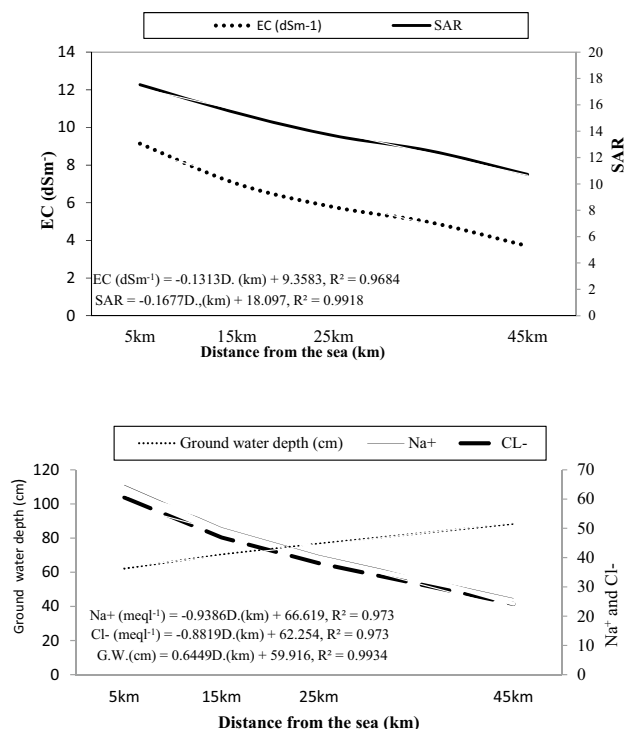


Fig. 4 Relationship between groundwater depth (cm) and ions of Na^+ and Cl^- (meq l^{-1}) as well as EC (dS m^{-1}) and SAR of soil with distance from the sea

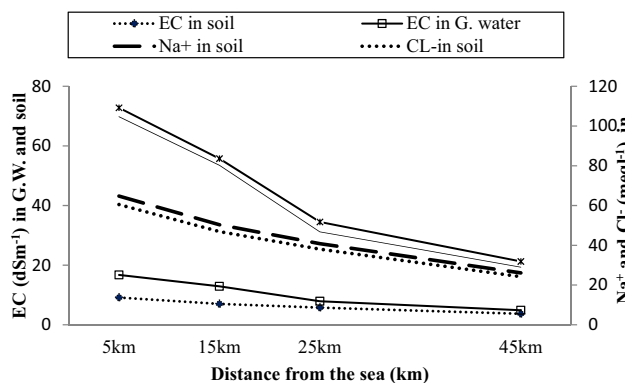


Fig. 5 Trend of EC (dSm^{-1}), Na^+ and Cl^- (meq l^{-1}) of groundwater and soil with distance from the sea (km)

Relationship between groundwater properties and distance from the coast

The correlations values reveal that soil characteristics are mainly dependent on groundwater properties, such as salinity, alkalinity, Na^+ and Cl^- (Table 4). High significant positive correlations of EC, Na^+, Cl^- and SAR were observed between groundwater and soil at 5 km and 15 km distance from the sea. The correlation coefficients were $0.57, 0.60, 0.60, 0.72$ at 5 km and $0.48, 0.54, 0.64, 0.43$ at 15 km

Table 4 Correlations between some properties of groundwater and soil with distance from the sea

Properties (groundwater and soil)	Distance from the sea (km)			
	5	15	25	45
EC (dSm ⁻¹)	0.57**	0.48**	0.07	0.05
Ca ²⁺ (meqL ⁻¹)	0.05	0.09	0.16	-0.25
Mg ²⁺ (meqL ⁻¹)	0.03	-0.12	0.01	0.34
Na ⁺ (meqL ⁻¹)	0.60**	0.54**	0.28	0.24
K ⁺ (meqL ⁻¹)	-0.01	-0.19	-0.20	-0.15
HCO ₃ ⁻ (meqL ⁻¹)	0.55**	0.23	0.22	0.02
Cl ⁻ (meqL ⁻¹)	0.60**	0.64**	0.29	0.26
SO ₄ ²⁻ (meqL ⁻¹)	0.07	-0.51**	0.10	-0.09
PH	0.10	0.01	0.06	0.01
SAR	0.72**	0.43**	0.20	0.12

** $p < 0.01$ level, * $p < 0.05$ level

distance from the sea respectively. The simple correlations were insignificant when moving inland at 25 km or further away from the sea. This is because the depth of groundwater exceeded the thickness of the capillary fringe above water table. This indicates that, due to SI, the increase of EC, Na⁺, Cl⁻ and SAR in groundwater leads to the increased EC, Na⁺, Cl⁻ and SAR in the soil. Also, this trend indicates that the higher values of EC, Na⁺, Cl⁻ and SAR for both groundwater and soil occurred near the sea (at 15 km from the sea) only.

Mixing ratio values (F%) with distance from the sea

The lowest content of chloride (Cl⁻) measured in groundwater in the study region was used as the Cl⁻ concentration criterion for irrigation water. Chloride concentrations (Table 5) in irrigation water were 5.29, 5.02, 4.62 and 4.26 meqL⁻¹ at 5, 15, 25 and 45 km distance from the sea, respectively. Two seawater samples were collected per season for chemical analysis and indicated that the average Cl⁻ concentration for seawater was 269.86 meqL⁻¹. The

average Cl⁻ concentrations (Table 5) in the mixed groundwater were 104.73, 80.26, 46.76 and 28.96 meq L⁻¹ for 5, 15, 25 and 45 km distance from the sea, respectively. The mixing ratios of seawater in groundwater samples ranged from 9.30 to 37.59%. Results in Table 5 and Fig. 6 show the maximum F% was recorded near the sea (5 km) and the minimum was recorded at a distance of 45 km inland, which indicates the impacts of excessive seawater intrusion into the area.

The effects of seawater intrusion were evident in groundwater as far as 45 km inland. Groundwater depth and the blending percentage of seawater had an inverse relationship (Figure S4). Also, there was a positive relationship between the extent of seawater intrusion and groundwater quality deterioration. An increase in seawater intrusion caused negative impacts on the quality of groundwater.

Relationships between groundwater properties and F% values

Correlations between the mixing percentage with seawater (F%) and depth of groundwater are shown in Table 6. Such relationships will only be possible in very flat coastal areas such as the Nile delta, where the depth of groundwater varies uniformly with inland distances. There were significant negative correlations between groundwater depth and the mixing percent of seawater as well as quality parameters of groundwater. In contrast, a decrease in groundwater depth led to an increase in F% values, as well as increasing soluble cation and anion concentrations, SAR values and the pH of the groundwater. Significant positive correlations also occurred between the mixing percentage of seawater and quality parameters of groundwater, as well as soluble cation and anion concentrations, SAR values and the pH of the groundwater, which all increased with increasing F% values. Also, there were significant positive correlations among all the parameters of groundwater.

Table 5 Mixing ratio expressed as the percentage of seawater (%) in ground water with distance from the sea

Distance from the sea (km)	Year	Cl ⁻ concentration (meq L ⁻¹) in groundwater	Cl ⁻ concentration (meq L ⁻¹) in seawater	Cl ⁻ concentration (meq L ⁻¹) in irrigation water	Mixing ratio (F, %)	Average of F (%)
45	1st	27.68	267.79	4.26	8.89	9.3
	2nd	30.24	271.92	4.26	9.71	
25	1st	46.51	267.79	4.62	15.92	15.89
	2nd	47.01	271.92	4.62	15.86	
15	1st	79.10	267.79	5.02	28.19	28.41
	2nd	81.42	271.92	5.02	28.62	
5	1st	104.06	267.79	5.29	37.63	37.59
	2nd	105.4	271.92	5.29	37.55	

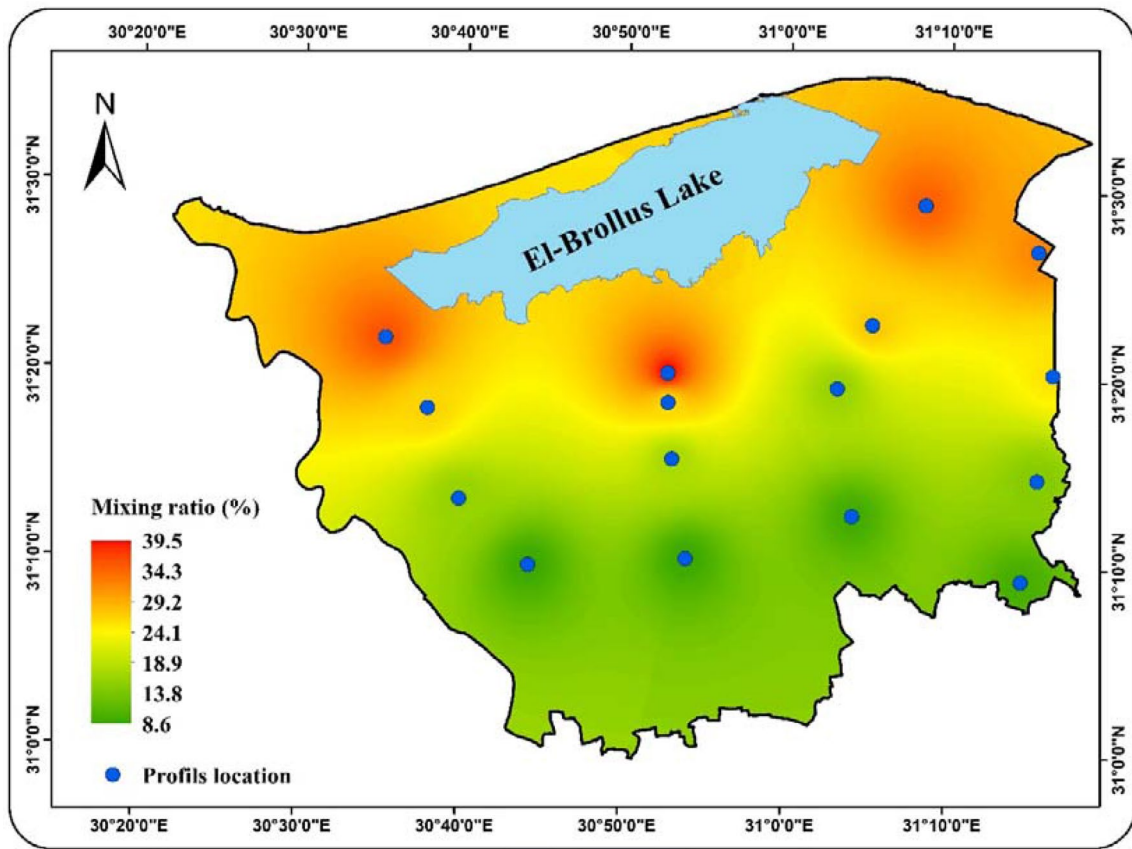


Fig. 6 Mixing ratio expressed as the percentage of seawater (%) with distance from the sea

Table 6 Correlations between some properties of ground water and *F*%

Index	F	WT level	Ecw	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	PH	SAR
F	1.00	-0.83**	0.98**	0.93**	0.96**	0.98**	0.55**	0.36**	0.99**	0.88**	0.45**	0.96**
WT level		1.00	-0.85**	-0.86**	-0.86**	-0.84**	-0.49**	-0.29**	-0.83**	-0.84**	-0.37**	-0.81**
Ecw			1.00	0.93**	0.97**	0.99**	0.53**	0.32**	0.99**	0.92**	0.48**	0.97**
Ca ²⁺				1.00	0.94**	0.92**	0.47**	0.36**	0.92**	0.94**	0.43**	0.86**
Mg ²⁺					1.00	0.96**	0.55**	0.32**	0.95**	0.94**	0.47**	0.90**
Na ⁺						1.00	0.56**	0.34**	0.99**	0.92**	0.48**	0.98**
K ⁺							1.00	0.28**	0.57**	0.46**	0.19*	0.55**
HCO ₃ ⁻								1.00	0.36**	0.26**	0.08	0.32**
Cl ⁻									1.00	0.86**	0.45**	0.97**
SO ₄ ²⁻										1.00	0.49**	0.87**
PH											1.00	0.48**
SAR												1.00

WT water table level, *F* mixing value, *EC* water salinity

***p* < 0.01 level, **p* < 0.05 level

Conclusions and future research

Significant positive correlations were observed for EC, Na⁺, Cl⁻ and SAR between seawater and groundwater, as well as between groundwater and soil in the coastal area of the Nile Delta up to 25 km from the sea. The maximum mixing percentage of seawater was recorded near the sea (5 km); while minimum mixing was observed offshore (45 km). The effects of seawater intrusion on groundwater quality were observed as far as 45 km inland from the coast. An increase in seawater intrusion caused negative impacts on the quality of groundwater more than 15 km inland from the coast. The properties of groundwater and soil in the northern part of the Nile Delta were affected by seawater as a result of seawater intrusion. However, coupling simulation models with field observations and socioeconomic aspects are suggested to be significant field for future research.

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Data availability The dataset(s) supporting the conclusions of this article is(are) included within the article and its additional file(s).

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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