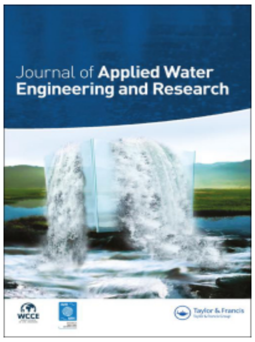

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Seawater intrusion into Shatt Al-Arab River, Northwest Arabian/Persian Gulf

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The variability of the estuary location has drawn much attention of the policymakers due to its importance in various environmental issues. This study aims to detect the spatial variation of salts in the water of Shatt Al-Arab River (SAR) in southern Iraq to show the extent of the saltwater penetration into the river during years the 2019-2020. The study used four water sample stations distributed along the southern river part. The study classified the mixing process of the river water into strong and weak stratification as well as partial and moderate stratification. The horizontal distance for the seawater intrusion into the SAR was approximately between 83.7 and 112.4 km. It seems the estuary position moves towards the upstream due to the dominance of seawaters over the river waters in the section. This study is a step towards a better understanding of the salinity issue in the complicated transitional ecosystem.

Keywords: Shatt Al-Arab River; seawater intrusion; mixing and stratification

1. Introduction

The estuary word has been used to indicate an inner coastal region where the river water mixes with seawater and measurably dilutes, extending upstream, to the extent of tidal current influence (Dyer 1997; Cloern et al. 2017; de Miranda et al. 2017; Raimonet and Cloern 2017; Gomes et al. 2021). It is a region of spatial and temporal variations of the salinity from fresh to marine (Stoker 1992; Cloern et al. 2017), due to the continuous mixing processes between freshwater inflow and seawater intrusion. Hence, the mass of the diluted estuarine water by river discharges so that the salinity values vary between 1000 and 35,000 mg/L (Pritchard 1952; Valle-Levinson 2010; de Miranda et al. 2017).

Water salinization in the estuary and seawater intrusion influence river environmental conditions, water quality, and water utilization (Aertsl et al. 2000; Mikhailova 2008; Chen et al. 2015; Cai et al. 2016); thus, these issues are very serious to the policymakers (Xu et al. 2015).

Economically, the estuary regions have been rapidly developed worldwide; human activity and urban growth cause the water resource utilization to be increasingly required and to build more dams (Yu et al. 2020). Coastal and river ecosystems and human requirements have been affected by the decline in the freshwater flow of many rivers into the sea (Yang et al. 2020), and increasing seawater intrudes into river mouths, due to changes in the force and behavior of the tidal phenomenon, thereby influencing estuarine morphology and the location of the estuary temporally and spatially, (Syvitski et al. 2009; Nienhuis et al. 2020). The longstanding problem of estuary location variability has drawn much attention due to its importance in various environmental issues, such as water management and flood prevention (Mikhailova 2008; Nguyen et al. 2018).

The Shatt Al-Arab River (SAR) region, representing the lower part of the Mesopotamian basin, is a sensitive estuarine /coastal environment. The SAR has been vulnerable to sea-level change over recent geological history (Holocene period), which has rendered complicated interaction between inland freshwater and marine gulf water (Kadhim et al. 2020).

SAR is considered the most crucial water source for the province of Basrah in the southern part of Iraq, with a population exceeding three million people according to the 2019 estimates. Over 82% of the residents rely on the river's water for domestic use (Al-Asadi and Muttashar 2022; Al-Qurnawi et al. 2022). The SAR plays a critical role in Iraq's economic plans by supporting navigation, fisheries, industrial, and agricultural uses, where approximately 105,000 hectares of agricultural fields are irrigated by the SAR (Jaradat 2003). The region also included the world's most important date palm forests, with more than 17 million trees in

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1975 (Singh 2005). The freshwater of the river also plays an important role in the health of the northern Persian/Arabian Gulf ecosystem (Al-Yamani 2008; UN-ESCWA 2013).

Many studies (Al-Tememi et al. 2015; Hamdan 2015; Al-Asadi 2016; Rahi 2018; Al-Asadi et al. 2020) have recognized that the freshwater inflow of SAR faces the challenge of water discharge reduction because of the impacts of human development and cutting off most of its main tributaries. This condition allows intruding the seawater and increasing the river salinity. There are some studies (Hameed et al. 2013; Lafta 2014; Hamdan 2016; Abdullah 2017; Al-Fartusi 2018) that have attempted to clarify the relationship between the amount of freshwater discharge and the concentration of Total Dissolved Solids (TDS) in the river course to determine the distance of seawater intrusion into the river. However, most studies have not yet addressed the changes in the estuary location based on the historical determination of the temporal and dimensional salinity fluctuation in response to a remarkable reduction in freshwater inflow.

The behavior of water flow in SAR was complex (Al-Asadi and Alhello 2019), as a result of the phenomenon of tides, distributes of a lot of side channels along the river, and the confluence of some tributaries with the river course sideways. In addition to the great temporal variation in the amount of water feeding from the tributaries of the river, especially from the Karun River which act as a natural dam that blocked or delayed the progression of seawaters (Al-Tememi et al. 2015; Al-Asadi 2017; Al-Asadi and Alhello 2019). This fact requires more studies and various scientific methods and tools to reach a more understanding of the behavior of water flow in the river.

The present study basically aims to investigate dimensional variability of the temporal, spatial, and vertical salinity in the transitional zone between the river and the gulf (estuary region) that helps to detect the distance of saltwater intrusion. It allows the variations of the salinity to be predicted. This is a forward step to better understand the dynamic of salinity issues in the complicated ecosystems, such as the SAR.

2. Materials and methods

2.1. Study area

The SAR forms the confluence of the Tigris and Euphrates rivers in the city of Qurna, 90 km north of the center of Basrah Governorate, south of Iraq (Figure 1). The river then flows towards the southeast to end in the Arabian Gulf after covering a distance of approximately 200 km. In addition to the Tigris and Euphrates rivers, the course of the river is recharged by many freshwater tributaries, the most important of which are the Karun and Karkheh Rivers that run within Iranian territory. The Karkheh River pours in the Huwaiza marsh, and its water reaches the Shatt Al-Arab through the Subway River, approximately 5 km south of the confluence of the Tigris and Euphrates. The Karun River flows into the Shatt Al-Arab, a distance of 70 km south of the Basrah City. On the right bank of the river, many tributaries flow out of the marshes, such as the Karma Ali River, approximately 5 km north of the city center of Basrah (Al-Asadi 2017).

The four main tributaries (Tigris, Euphrates, Karkheh, and Karun) provide SAR variously with freshwater. The Tigris and Euphrates Rivers, for example, fed the river with approximately 14.3 and 11.4 km^3/year out of the total freshwater, which reaches 37.5 km^3/year for the water year 1977–1978. The Karkheh and Karun Rivers contribute to supplying the river with freshwater at a range of 3.3 and 8.5 km^3/year (Ministry of Irrigation. 1979).

The water management projects established in the river basin have led to essential changes in the hydrological system. The Euphrates River was cut off before its confluence with the Shatt Al-Arab, and the Karkheh and Karun Rivers were diverted into Iranian territory. Therefore, since 2010, the SAR has been fed with freshwater from the Tigris River only, with a discharge varying between 1.6 and 2.4 km^3/year (Al-Asadi 2017). During the period 2019–2021, due to the great floods that Iran and Iraq witnessed, the four tributaries of the river have been fed to the river, and the freshwater discharge into the SAR course increased between 6.7 and 12.1 km^3/year (Ministry of Water Resources 2022).

SAR is characterized by a mixed type classified as semidiurnal mixed tide pattern (Al-Ramadhan and Pastour 1987). The duration of the tidal cycle is estimated at 13 h, distributed between 8.50 h for the ebb currents and 4.50 h for the flood currents (Albadran et al. 2001).

The water levels vary along the Shatt Al-Arab course during the day due to the variation of the tidal currents. The maximum tide range reached 1.5 and 4.5 m in Basrah and Al Fao, respectively (Al-Ramadhan and Pastour 1987). In addition, due to global warming, the sea level in the Arabian Gulf has increased since the 1980s (Kadhim et al. 2020), and it was estimated during the past three decades to reach 3.2 mm a year (Abbas et al. 2020). This increase allows the mean sea level in the gulf to rise at approximately 13 cm during the period 1980–2020; the energy of the tides also increases with time.

The course section of the SAR causes the river width to vary spatially. The river widens toward the estuary (downstream) zone, in general. For instance, in the Al Ashar station, the river width is approximately 400 m, but approximately 600 m in the Al Fao station; it further increases to reach approximately 1250 m in the Ras al Bisha station. The average river width is approximately 500 m (Al-Asadi 2017). The depth of the river water also shows variation spatially and temporally. According to the field measurements, the depth ranges between 11 and 9 m in the stations of Ras al Bisha and Al Ashar, respectively, with an average depth of 10 m.

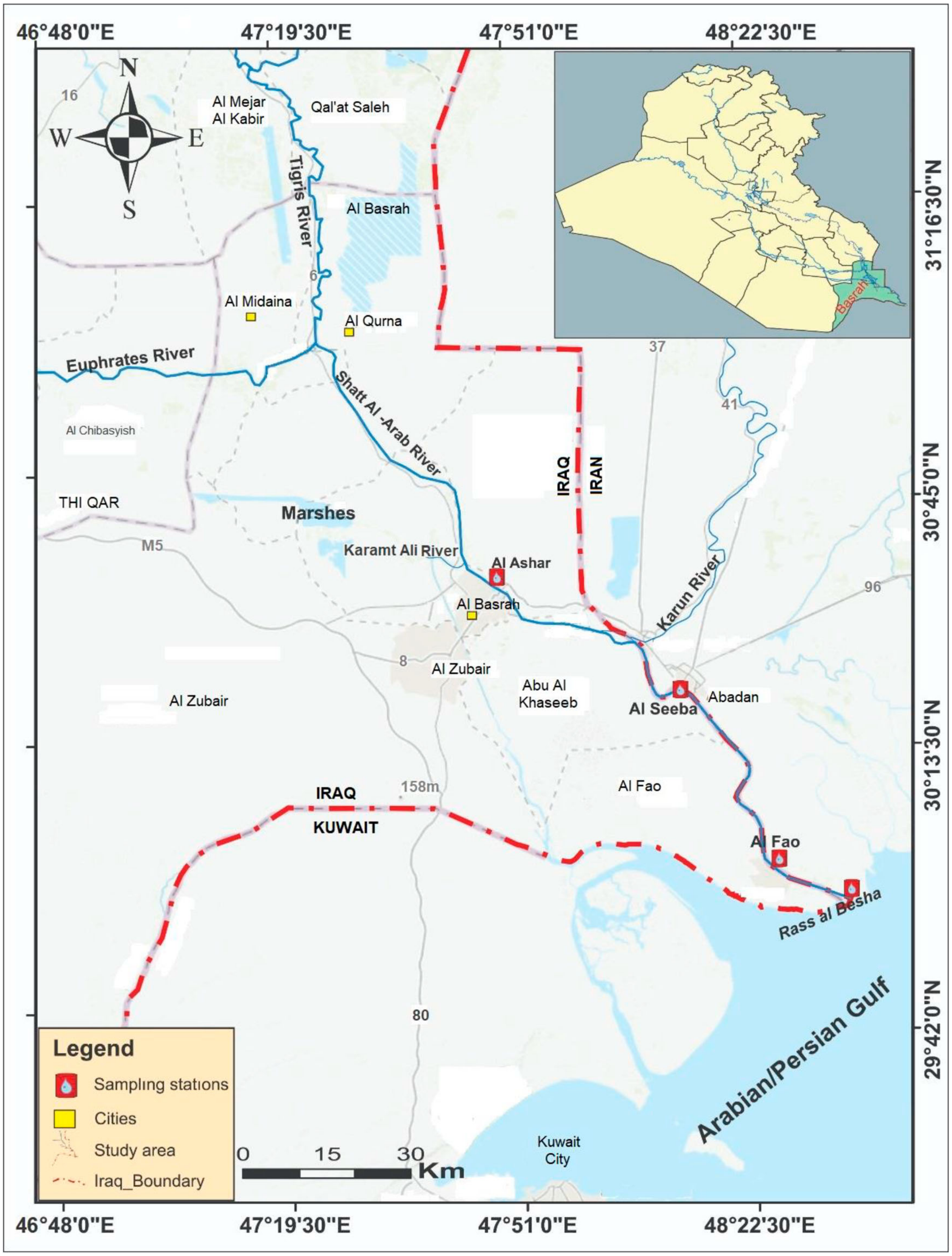

Figure 1. Map of the SAR and sampling stations.

Climatically, the study area is located within the desert climate region, which is characterized by a long period of heat and drought during summer and moderate heat and rainfall during winter. Spring and fall are short and transitional seasons between the characteristics of summer and winter. Northwest winds prevail in the Shatt Al-Arab region, and southeast winds are more frequent during summer (Italy-Iraq 2006; Abdullah 2017). The mean monthly temperature ranging from 9 to 41°C, in January and July, respectively, while the rainfall occurring among October and May, with the mean annual is about 100 mm (UN-ESCWA 2013).

A number of drainage sources feeding the SAR include marine water, untreated agricultural water drainage, municipal and industrial wastes discharged directly into the river course, in addition to brackish water flows from southern marshlands, as well as the atmospheric deposit of gaseous emissions from oil production (Al-Tememi et al. 2015; Al-Asadi et al. 2019, 2020). These sources mainly influence the levels of water salinity in the river.

2.2. Methodology

Water samples were collected from four important stations, which have been under different conditions (Table 1; Figure 1). Station No. 1 is located in the center of Basrah Governorate, representing the concentration of population density and is relatively far from marine waters, approximately 115 km north of the Gulf. In Station No. 2, the discharge of the Karun River estuary dilutes the concentration of salts and limits the penetration of marine water in the SAR. On the contrary, the impact of marine water is more prevalent in stations 3 and 4. Water samplings were carried out during fall (October) in 2020, winter (January), and summer (July) in 2021. The spring season in 2021 represents missing data due to the curfew imposed by the Iraqi government as a preventive measure against Covid 19.

The concentration of total dissolved salts (TDS) was measured in the field by considering water samples along the water column at a rate of 2 m from the surface to the bed during the tidal conditions using a Horiba U-10 device (Figure 2). All instruments and reagent were calibrated by using a standard solution before the measurement. One-liter surface water samples were collected for each season at the measuring stations in clean bottles. All samples were stored at 10–15°C, and then sent to the Water Analysis Laboratories of the Department of Chemistry and Marine Environment Pollution, Marine Sciences Center, University of Basrah. Major cations and anions were determined in the river water samples. They are calcium (Ca), magnesium (Mg), sulfate (SO_4), bicarbonate (HCO_3), and chloride (Cl), according to standard methods (APHA 2017). The sodium (Na) and potassium (K) ions were analyzed using the flame photometer (ELICO CL 361).

The mixing and stratification parameters in the river water column are obtained by applying the following formula:

$$n = \frac{\Delta S}{Sm} = \frac{Sb - Ss}{0.5(Sb + Ss)} \tag{1}$$

where n is the stratification parameter; ΔS is the vertical gradient of water salinity; Sm is the depth averaged water salinity; Sb is the water salinity at the bottom and Ss is the water salinity on the surface.

Table 1. Geographic locations of sampling stations at the SAR.

Sampling stations	Site name	Longitude	Latitude
1	Al Ashar	47˚49’15”	30˚30’39”
2	Al Seeba	48˚15’37”	30˚20’15”
3	Al Fao	48˚29’22”	29˚58’52”
4	Rass al Bisha	48˚35’33”	29˚57’51”

Figure 2. Measuring the salts concentration in the field using a Horiba U-10 device.

Strong mixing and weak stratification correspond to $n < 0.1$; partial mixing and moderate stratification, n varies from 0.1 to 1.0; saltwater wedge and strong stratification, n varies from 1.0 to 2.0 (Mikhailova 2013).

The distance of seawater intrusion into the river is obtained by applying the following formula (Mikhailova 2013):

$$ls = \ln\left(\frac{Ss}{Sr}\right)\left(\frac{BhD}{Q}\right) \tag{2}$$

where ls is the seawater penetration distance (m); Ss is the salinity of sea water (mg/L). Ss is the constant in all three seasons (41,500 mg/L); Sr is the salinity of river water (mg/L); Sr is the TDS average of the four stations of each season; B is the average river width (m), which equals 500 m; h is the average river depth (m), which equals 10 m; D is the constant. The D value is determined by taking transverse and longitudinal measurements of water salinity at several points along the mixing area. The value of D was calculated using the longitudinal gradient of water salinity. Q is the river discharge (m^3/s).

3. Results and discussion

3.1. Spatial distribution of the salinity

Table 2 shows the concentrations of the dissolved salts (TDS) in the SAR that spatially vary between the measurement stations. The spatial distribution of TDS tends to increase to the south (downstream) toward the gulf water. It can be attributed to the increase in salty seawater that breaks through and mixes with the fresh river water upon reaching the Arabian Gulf. As shown in Table 2, the annual average of the salinity at Al Ashar station reached 2300 mg/L, and those in Al Fao and Ras al Bisha stations were higher at 16,780 and 23,031 mg/L, respectively. The measurements of Al Seeba station have not been much pertinent to the actual salinity of the SAR waters due to the influence of the freshwaters of Karun River, coming from Iran and joining the SAR waters near Al Seeba location. The TDS concentrations, therefore, are relevant to the inconsistent amount of freshwater releases from the Karun River; thus, the findings of Al Seeba location revealed an anomaly compared with the other stations.

Table 2. Concentration averages of the total dissolved salts (TDS) (mg/L) in the SAR waters for the measurement stations.

		The river conditions		
Stations	The season	Flood	Ebb	Average
Al Ashar	Fall (Oct)	1797	1819	1808
	Winter (Jan.)	2850	2636	2743
	Summer (July)	2350	2349	2350
	The average	2332	2268	2300
Al Seeba	Fall (Oct.)	1534	1572	1553
	Winter (Jan.)	1538	1857	1698
	Summer (July)	2626	2659	2643
	The average	1899	2029	1964
Al Fao	Fall (Oct.)	6935	10,289	8612
	Winter (Jan.)	8723	9866	9295
	Summer (July)	29,120	35,744	32,432
	The average	14,926	18,633	16,780
Rass al Bisha	Fall (Oct.)	17,147	13,027	15,087
	Winter (Jan.)	18,623	17,369	17,996
	Summer (July)	34,517	37,504	36,011
	The average	23,429	22,633	23,031

3.2. Temporal variation of salinity

Table 2 demonstrates the variability of the TDS concentrations for the stations over the seasons of the year. The salinity increases and reaches its maximum (2743 mg/L) during the winter season at the Al Ashar station, but it decreases to its lowest (1808 mg/L) during the fall season. These differences could be ascribed to the role of rain falling on the marshes and the side-salted river lands that cause leaching into the river during the winter season (Al-Tememi et al. 2015; Rahi 2018; Alhello et al. 2019; Al-Asadi et al. 2020).

Regarding the Al Fao and Ras al Bisha stations, a correlation in the salinity variation exists during the seasons. The salinity increases during summer by 32,432 and 36,011 mg/L, respectively. The concentrations decreased to 8612 and 15,087 mg/L during the fall season for both stations. The salinity concentrations in Al Fao and Ras al Bisha stations tend to correlate more with the effects of the marine water of the Arabian Gulf than the fresh river water.

The salinity increases during the seasons with the emergence of effective southeasterly winds, especially as they are active during the summer, which causes an increase in the period and speed of tidal, thus resulting the increase in the amount of sea water compared to freshwater, leading to an increase in the salinity of the water in the river. Therefore, this is most likely the factor that caused the increased water salinity of the two stations (Al Fao and Ras al Bisha) during the summer.

For the Al Seeba station, the seasonal variation of salinity had a similar to those of the Al Fao and Ras al Bisha stations, where the concentrations are relatively high during the summer (2643 mg/L) and decrease to 1553 mg/L in the fall season. However, the Al Seeba location was affected by the freshwater released from the Karun River and causing a noticeable decline and differences in salt concentrations. This finding comes in line with the findings of Rahi (2018) and Al-Asadi and Alhello (2019). The discharge of freshwater in the Karun River about 100 m^3/s during the study year (Ministry of Water Resources 2022).

The seasonal variation of TDS in river waters (except for the Al Seeba location) showed the limited influence of

Table 3. Parameters required for the (Mikhailova) equation in the SAR.

Season	*Ss* (mg/L)	*Sr* (mg/L)	*B* (m)	*h* (m)	*D*	*Q* (m^3/s)	*ls* (km)
Fall	41,500	6765	500	10	2640.7	213	112.4
Winter	41,500	7933	500	10	1755.1	286	83.7
Summer	41,500	18,162	500	10	3834.9	254	94.3

the flow of the upstream freshwater. The remaining stations (Al Ashar, Al Fao, and Ras al Bisha) did not show a decrease in TDS concentrations as the water salinity increases even though the increase in freshwater discharge during winter and summer seasons reached 286 and 254 m^3/s, respectively, compared with the fall seasons at 213 m^3/s, over measurement time (2019–2020) (Ministry of Water Resources 2022).

3.3. *Seawater intrusion distance in the river*

Table 3 shows the parameters required to determine the intrusion distance (Ls) in the SAR based on Mikhailova's equation. The total intrusion distance of incursion decreases to about 83.7 km during the winter season. The maximum range of seawater intrusion into the river course was observed during the flood tide in the fall season, with a distance of approximately 112.4 km. The resulted Ls reveal a minor seasonal variation of marine water intrusion into the river indicated by its impact on concentrations of TDS in the river water. On average, the seawater penetrates a distance (LS) of approximately 97 km towards the upstream of the river. These findings indicate an increase in seawater intrusion distance into the river course compared with the results of Ls reported by (Abdullah 2017), which was 93 km.

The lower the freshwater inflow from the main river tributaries is, the greater the intrusion distance of seawater does, and vice versa. Therefore, this inverse relationship existed between freshwater discharge and the intrusion of seawater accounts for the variation of the intrusion distance to the seasonal variation of the flow of freshwater. Moreover, the effect of wind and seawater intrusions increases as the southeast winds increase.

3.4. *Vertical distribution of salinity*

The TDS variability of the investigated four locations is not only limited to the spatial and temporal variations but also includes the variation in the river's water column at each location. The TDS concentrations can vary greatly over the water column in the river section at the same time. This finding is attributed to the difference in the volume and water levels of the flow direction during the tidal period. Table 4 and Figures 3–6 show the vertical variations of the salinity of the SAR water in the four stations during measurement seasons. For instance, the TDS at Al Ashar station over the fall season was 2349 mg/L at the surface and the bottom (approximately 10 m in depth) below the surface during flood time. However, at the ebb time, the concentrations varied between 2304 mg/L at the surface and 2291 mg/L at the bottom. Hence, the average difference in TDS concentrations between the surface and the bottom was approximately −7 mg/L, which represents −0.28% of the average TDS on the surface. This average increases to 68 mg/L over the winter time and represents a ratio of 2.5% of the average TDS concentration at the surface.

For the Seeba station, TDS varied in the summer season between 2624 mg/L for the surface and 2637 mg/L for a depth of 10 m during the flood period. However, it was between 2656 and 2669 mg/L during the ebb at the surface and bottom, respectively. Therefore, the average difference in the concentrations was approximately 13 mg/L, with a ratio of 0.5% of the average TDS concentration for the surface. The average amount of the difference increases to 25 mg/L during the winter to represent 1.49% of the average concentrations on the surface.

During the flood, the TDS concentrations at Al Fao station varied between 6816 and 7078 mg/L at the surface and at a depth of 8 m in the fall season. At the ebb time, it was between 7078 and 12,314 mg/L for the surface and the bottom, respectively. The difference then was 2749 mg/L with a percentage of 23.18% from the rate of TDS in the surface. The average amount of the difference decreases in the summer season to 2656 mg/L, representing a percentage of 8.5%.

The TDS concentration of the Ras al Bisha station during the flood period varied between 15,836 and 18,213 mg/L for the surface and for 10-m depth, respectively. During the ebb time, the TDS varied between 10,604 and 14,246 mg/L for the surface and the bottom, respectively. Hence, the difference rate of approximately 3010 mg/L, representing a percentage of 22.77% of the average TDS on the surface in the fall season. The average difference was 4860 mg/L, representing 32.94% during the winter season.

The reason for this high variability of the TDS concentration between the two tide periods (flood and ebb) is mostly attributed to the fact that Ras al Bisha location is a transitional zone, representing the end of the river's mouth and the beginning of the sea. During flood time, the water becomes marine water that intrudes the river, but in the case of ebb time, the marine waters retreat and the freshwater increase, thereby decreasing the TDS concentrations. The reason behind an increase in salinity over the water column is ascribed to the density differentiation

Table 4. TDS gradient (mg/L) in SAR according to stations and depth.

Stations	Season	River status	The TDS concentrations (mg/L) according to the depth						Difference amount	Difference percent (%)
			Surface	2 m	4 m	6 m	8 m	10 m		
Al Ashar	Fall	Flood	1786	1779	1773	1818	1805	1818	32	1.79
		Ebb	1792	1862	1805	1824	1798	1830	38	2.12
		Average	1789	1821	1789	1821	1802	1824	35	1.96
	Winter	Flood	2803	2821	2842	2893	2852	2887	84	3.0
		Ebb	2611	2624	2630	2637	2650	2662	51	1.95
		Average	2707	2723	2736	2765	2751	2775	68	2.51
	Summer	Flood	2349	2362	2342	2349	2349	2349	0	0
		Ebb	2304	2298	2291	2291	2291	2291	13–	0.56–
		Average	2327	2330	2317	2320	2320	2320	7–	0.28–
Al Seeba	Fall	Flood	1542	1517	1523	1542	1517	1562	20	1.30
		Ebb	1568	1606	1555	1568	1542	1594	26	1.66
		Average	1555	1562	1539	1555	1530	1578	23	1.48
	Winter	Flood	1530	1536	1536	1537	1542	1549	19	1.24
		Ebb	1843	1848	1851	1859	1866	1875	32	1.74
		Average	1687	1692	1694	1698	1704	1712	25	1.49
	Summer	Flood	2624	2618	2637	2624	2618	2637	13	0.50
		Ebb	2656	2650	2669	2662	2650	2669	13	0.49
		Average	2640	2634	2653	2643	2634	2653	13	0.50
Al Fao	Fall	Flood	6816	6848	6867	7066	7078	–	262	3.84
		Ebb	7078	8698	11,866	11,488	12,314	–	5236	73.98
		Average	6947	7773	9367	9277	9696	–	2749	39.57
	Winter	Flood	7501	7251	8474	9638	9504	9971	2470	32.93
		Ebb	8435	9088	9971	10,368	9875	11,456	3021	35.82
		Average	7968	8170	9223	10,003	96,90	10,714	2746	34.46
	Summer	Flood	28,544	28,160	28,672	29,632	28,736	30,976	2432	8.52
		Ebb	33,600	34,688	36,096	36,736	36,864	36,480	2880	8.57
		Average	31,072	31,424	32,384	33,184	32,800	33,728	2656	8.55
Rass al Bisha	Fall	Flood	15,836	15,845	17,110	17,539	18,340	18,213	2377	15.01
		Ebb	10,604	11,866	13,392	13,728	14,324	14,246	3642	34.35
		Average	13,220	13,856	15,251	15,634	16,332	16,230	3010	22.77
	Winter	Flood	15,373	17,606	18,995	19,488	20,038	20,237	4864	31.64
		Ebb	14,138	15,821	17,856	18,304	19,098	18,995	4857	34.35
		Average	14,756	16,714	18,426	18,896	19,568	19,616	4860	32.94
	Summer	Flood	31,488	32,256	35,968	35,520	35,712	36,160	4672	14.84
		Ebb	35,712	36,544	37,184	38,656	38,400	38,528	2816	7.86
		Average	33,600	34,400	36,576	37,088	37,056	37,344	3744	11.14

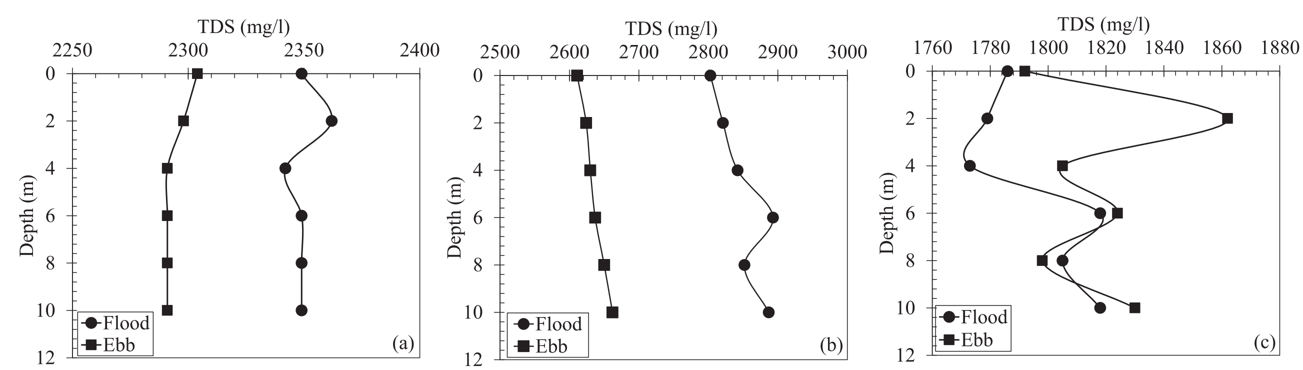

Figure 3. Shows the TDS gradient (mg/L) in the SAR water column for (a) fall, (b) winter, and (c) summer seasons at the Al Ashar station.

between salt water (the high density) and freshwater (the low density); therefore, freshwater tends to increase above salt water.

The TDS concentrations of the Ras al Bisha station varied in the tidal time between 15,373 and 20,237 mg/L for the surface and for 10 m of depth, respectively. During the

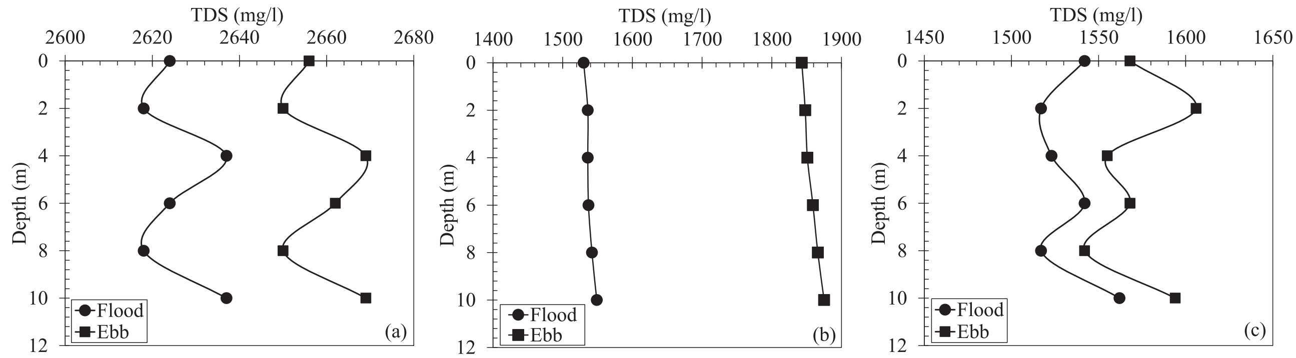

Figure 4. Shows the TDS gradient (mg/L) in the SAR water column for (a) fall, (b) winter, and (c) summer seasons at the Al Seeba station.

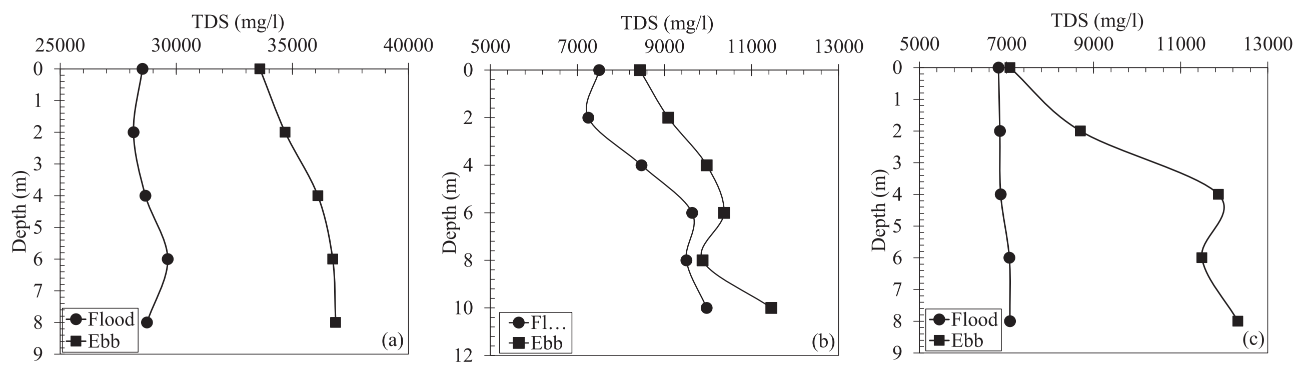

Figure 5. Shows the TDS gradient (mg/L) in the SAR water column for (a) fall, (b) winter, and (c) summer seasons at the Al Fao station.

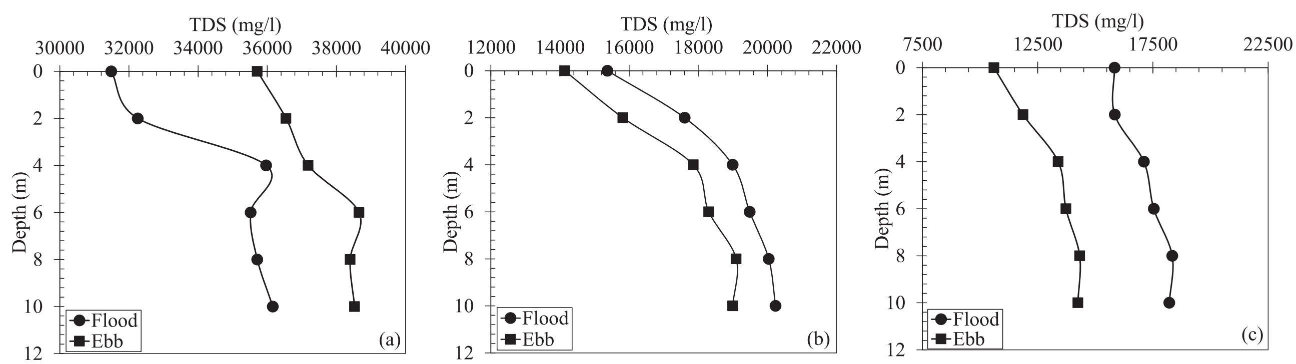

Figure 6. Shows the TDS gradient (mg/L) in the SAR water column for the (a) fall, (b) winter, and (c) summer seasons at the Rass al Bisha station.

tide period, in the case of the ebb time, it varied between 14,138 and 18,995 mg/L for the surface and 10 m of the depth, respectively, with a difference of approximately 4860, representing a percentage of 32.94%.

3.5. Mixing and stratification

Due to mixing processes along the column of the river water, there are no clear stratifications in the water properties, which causes a reduction of the differences in water salinity, density, and temperature. Therefore, when the mixing increases, the stratification of the mentioned properties fades.

The vertical stratified mixing processes of the SAR course at the meeting point of the river and marine water can be classified into three cases, namely, complete mixing with weak stratification, partial mixing with moderate stratification, and weak mixing with strong stratification.

Applying Equation (1) showed that the water mass in the SAR is characterized as strong mixing with weak stratification in the Al Ashar and Al Seeba stations, as the values of (n) ranged between 0.005 and 0.025 for the studied seasons (Table 5). The water mass in Al Fao and Ras al Bisha stations showed partial mixing and moderate stratification, as the values ranged between 0.34 and 0.082 in the Al

Table 5. Spatial and temporal variation of the n values in SAR.

		River status		
Stations	The season	Ebb	Flood	The average
Al Ashar	Fall	0.021	0.018	0.020
	Winter	0.019	0.030	0.025
	Summer	0.006	0.030	0.025
	The average	0.015	0.026	0.023
Al Seeba	Fall	0.008	0.013	0.011
	Winter	0.017	0.012	0.015
	Summer	0.005	0.005	0.005
	The average	0.01	0.01	0.010
Al Fao	Fall	0.54	0.14	0.34
	Winter	0.30	0.28	0.29
	Summer	0.082	0.082	0.082
	The average	0.31	0.17	0.24
Rass al Bisha	Fall	0.36	0.14	0.25
	Winter	0.29	0.27	0.28
	Summer	0.08	0.14	0.11
	The average	0.24	0.18	0.21

Fao station and between 0.11 and 0.28 in the Ras al Bisha station.

On this basis, the characteristics of marine water, especially salinity and density, in the mentioned stations indicated that the entry of salty marine water into the SAR at the Al Fao and Ras al Bisha stations was not considered a saline wedge but a water mass.

The strength of the mixing processes and the stratification weakness in the river water column indicate the rapid diffusion of the marine salt particles toward the upstream, due to the movement of the mass of marine water compared to the mass of freshwater which reduces the repelling force of this water and thus increases the speed of its penetration.

3.6. Spatial distribution of the major ions

The results of water samples (Table 6) illustrated that the sodium concentration is the dominant ion among cation concentration in the river water in all stations and for all seasons, where the concentration ranged from 375.53 mg/L at Al Seeba station to 3206 mg/L at the Ras al Bisha station. Potassium concentration represented the lowest concentrations of cations for all stations and seasons; it ranged between 66.40 mg/L in the Al Ashar station and 384 mg/L in the Ras al Bisha station. The average concentration of cations in the Shatt Al-Arab water is represented in the following trend: (Na > Mg > Ca > K).

The chloride ion concentration represented the highest concentration among anions in the river water for all stations, as the concentration ranged between 605.07 mg/L in the Al Ashar station and 8404 mg/L in the Ras al Bisha station. The concentration of bicarbonate was the lowest concentration for most stations, as the values varied between 168.37 mg/L in Al Seeba station and 4035.33 mg/L in Ras al Bisha station. Hence, the results demonstrated that the distribution pattern of the anions in the river water in descending order was Cl > SO_4 > HCO_3. The main factors effecting the quality of the Shatt Al-Arab water are the salt content of tributaries water feeding them, agricultural drainage water and the mixing with marsh and marine water.

The percentage change in the concentration of ions for the four stations compared with the specific characteristics of marine water in the Arabian Gulf indicates that the percentage change at the Al Ashar station was −95.41% and −97.26% for the sodium and chloride ions, respectively. As for Al Seeba station, the change rates were −95.63% and −97.26% for the sodium and chloride ions. While the percentage of change in the Al Fao station decreased to −76.02% and −78.03% for the same ions, respectively. The rate of change between the concentrations of the major ions in the Ras al Bisha station from the marine waters decreased to its lowest limits by −62.73% and −61.96% for sodium and chlorides, respectively (Table 6). This comparison evidently shows that the specific characteristics of the running water in the SAR approach the characteristics of the marine waters toward the south, strongly indicating the dominance of marine waters over the qualitative characteristics of river water in the section extending from Al Seeba to Ras al Bisha. As for the Al Ashar station, more than one source contributes to the high concentration of its salts, perhaps the most important is its combination with the water of the marshes through the Karma Ali River, which flows to the north of Basrah by 2 km (Al-Tememi et al. 2015; Rahi 2018; Alhello et al. 2019).

3.7. Estuary location

Estuary boundaries and their temporal variation are determined according to the three criteria, as detailed in the study; the spatial distribution of salts concentration in the river water (1–35 g/L), the values of mixing and stratification in the river water column, and the difference ratio for major ions between river water and marine water.

During the study year 2019–2020, the vertical mixing and stratification processes in the river water column showed that the water mass in Al Fao and Ras al Bisha stations is a pure marine water mass. According to the concentrations of major ions dissolved in river water the seawater dominance of the qualitative properties of the river water in the section extending from Al Seeba to Ras al Bisha sites.

The salinity rates in the river water indicate that the sea water limits measurably diluted by the river discharge lie between the Al Seeba stations as the estuary head, where the rate of salt concentration was low (1.96 g/L), but the estuary's mouth is located at the outer bar, as salinity increased to 35.8 g/L.

The estuary location varied seasonally, as the mouth of the estuary reached the outer bar in the fall season; it moves to the Ras al Bisha location in the summer season. The estuary of the SAR has clear spatial variations during the past 50th years (1970–2020), as it reached a distance of 5 km into the Arabian Gulf at the 70s of the last century. While the head of the estuary was in the Al Fao area with a salinity of 1.25 and 2.01 g /L during the years 1974 and 1995 (Table 7) and Figure 7(a, b). The mouth of the estuary extends to a deep distance within the marine waters of the Arabian Gulf, and the quality of water north of the city of Al Fao is the same as freshwater.

In the year 2020, the estuary of the SAR moved forward to upstream boundaries and it reaches to the borders of the city of Al Seeba (65 km north of the Gulf) Figure 7(c) and changes the environmental issues of the river. This is because the marine waters reach this site and transform this area from a freshwater environment to a brackish water environment. Therefore, the section of the river's course extending from Al Seeba to Al Fao has become brackish water. The river section from Al Fao to Ras al Bisha became saline water, as the concentration of salts increased between 16.78 and 23.03 g/L (Table 7).

In spite of many factors that affect the spatial variation of the downstream sites in the SAR, the three main factors that clearly contributed to the change in the downstream location during the study year, are as follows: A decrease in the discharge of freshwater flowing from the upstream from about 910 m^3/s for the year 1977–1978 (Ministry of Irrigation 1979) to 251 m^3/s during the year 2019–2020. Also decreased the annual mean of freshwater flow in the estuary of Karun River from about 270 m^3/s for the year 1977 to 1978 (Ministry of Irrigation 1979) to 100 m^3/s in the study year. In addition to the sea level rise by 13 cm during the period 1980–2020 (Abbas et al. 2020; Kadhim et al. 2020).

Table 7. Temporal variations of the average salts (g/L) in the water of SAR and the Gulf for the measurement stations, collected from Saad (1978); Al-Mahdi et al. (2009) and field measurements.

Stations	Years 1974	1993–1995	2019–2020
Al Seeba	0.73	0.94	1.96
Al Fao	1.25	2.01	16.78
Rass al Bisha	5.14	6.68	23.03
Outer bar	22.47	30.25	35.81
Marin water	40.50	41.50	41.50

In the future, the flow of freshwater in the tributaries of the SAR, especially the Karun River, is expected to become completely cut off due to global climate change and increase in the water required for the population (Al-Asadi 2017; Ghalib 2017; Ghalib et al. 2019). In addition, the possibility of rising the sea level which additionally contributes to increasing the intrusion of marine waters upstream of the SAR, then increasing the salt concentration in the water body. This finding indicates an increasing distance of the estuary area toward Basrah city.

4. Conclusions

The current study aims at determining the spatial, temporal, and vertical distribution of dissolved salt behavior in the

Table 6. The seasonal concentration of the major ions (mg/L) at the measuring stations and the difference percentage (%) of the spatial variation of the average concentrations compared with the marine water.

Stations	Season	Na	Ca	Mg	K	Cl	SO_4	HCO_3
Al Ashar	Fall	232.2	128	145.8	21.8	674.5	290.5	195.2
	Winter	580.5	451	144	68.4	252.7	1313.5	183
	Summer	372	200	194	109	888	154	158.6
	Average	394.9	259.67	161.27	66.4	605.07	586	178.93
Al Seeba	Fall	232.2	128	145.8	21.8	674.5	284.9	175.7
	Winter	255.4	80	145.8	28	603.5	192	158.6
	Summer	639	240	194	183	1243	175	170.8
	Average	375.53	149.33	161.87	77.6	840.33	217.3	168.37
Al Fao	Fall	1299	538	896	84	2845	1014	1092
	Winter	1927.3	1000	850.5	451	3550	1685	4880
	Summer	2961	3800	1580	494	8165	1685	3965
	Average	2062.43	1779.33	1108.83	343	4853.33	1461.33	3312.33
Rass al Bisha	Fall	2414	968	1424	160	5687	1807	1736
	Winter	3589	3570	1458	479	10,650	3287	6100
	Summer	3615	3610	1652	513	8875	1935	4270
	Average	3206	2716	1511.33	384	8404	2343	4035.33
The Gulf water		8601	471	1337	434	22,090	2667	1135
Difference percent from Al Ashar (%)		− 95.41	− 44.87	− 729.04	− 553.61	− 97.26	− 78.03	− 84.24
Difference percent from Al Seeba (%)		− 95.63	− 68.30	− 725.97	− 459.28	− 96.20	− 91.85	− 85.17
Difference percent from Al Fao (%)		− 76.02	277.78	− 20.58	− 26.53	− 78.03	− 45.21	191.84
Difference percent from Ras al Bisha (%)		− 62.73	476.65	11.53	− 13.02	− 61.96	− 12.15	255.54

tidal waters of the SAR. Understanding the nature of the mixing between the river and marine waters allows binding of the extension of the marine water intrusion and the estuary zone.

The spatial distribution pattern of the TDS concentration in the river water tends to increase the concentration averages south toward the Gulf. The reason for this condition can be attributed to the increase in the effect of saline

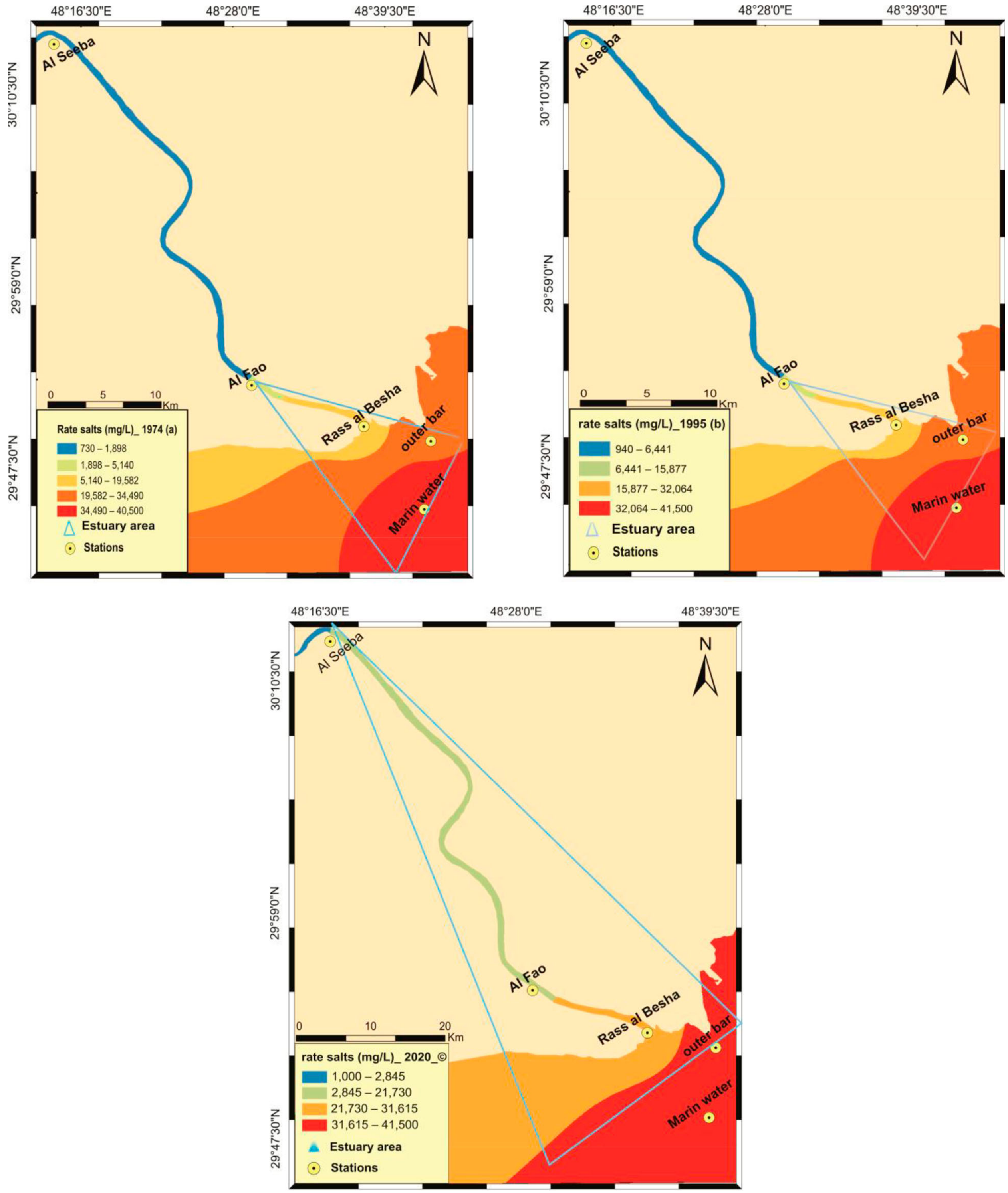

Figure 7. Map of the estuary locations of the SAR for the years 1974 (a), 1995 (b), and 2020 (c).

marine water. The Al Seeba station, which is an exception to this pattern, due to the freshwater inflow of the Karun River reduces the TDS concentration. The TDS source is not only the marine water (the southern stations), but it is also the inflow of the salty marsh water that shows a noticeable influence in measurements of the Al Ashar station.

Applying the marine intrusion distance equation revealed a seasonal variation of the penetration distance towards the upstream of the river, with 83.7 and 112.4 km during the winter and fall, respectively. This high intrusion of seawaters can be elucidated by the steep decrease in the freshwater into the river course.

According to the mixing equation between freshwater and seawater, the study classified river water into two features based on the vertical mixing and stratification processes. The water mass in Al Ashar and Al Seeba stations is featured by high mixing and weak stratification. The water mass in Al Fao and Ras al Bisha stations showed partial mixing and moderate stratification. Since both stations (Al Fao and Ras al Bisha) have a pure marine water characteristic (salinity), the saltwater wedge is delineated at these two stations. The seawater characteristics are shown in the entire column of the river water at these stations, providing a robust indication of the lack of fresh river water that reaches these stations, specifically the Ras al Bisha station.

The study showed that the [Na] and [Cl] were the highest major ions concentration dissolved in river water for all stations and seasons. While the [K] and the [HCO_3] recorded the lowest rates. The average concentration of the major dissolved ions in the river water has taken a pattern represented by the following formula: ($Na > Mg > Ca > K; Cl > SO_4 > HCO_3$).

Results of the qualitative water properties of the studied sites and seawaters showed a clear difference in the concentrations of the major ions in the Al Ashar station and the marine waters. However, this difference decreases in the Ras al Bisha station. The proximity of the qualitative characteristics of the river water to the features of the seawater in the downstream direction provides an apparent indication of the dominance of seawater over the qualitative properties of the river water in the section extending from Al Seeba to Ras al Bisha sites.

The horizontal and vertical variations of the concentration of total dissolved salts were essential to understand the change in the river estuary boundaries. The study showed that the estuary zone has moved up to the upstream and reached the Al Seeba site (65 km north of the Arabian Gulf), bringing about fundamental changes in the ecologic system of the river. The three main factors that contributed to the transgression of the estuary location toward the upstream are lack of the freshwater inflow from the rivers recharging the SAR, such as the Tigris, Euphrates, and Karun Rivers, as well as the rise in sea level.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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