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Numerical assessment of Karun river influence on salinity intrusion in the Shatt Al-Arab river estuary, northwest of Arabian Gulf

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Abstract
The influence of Karun river inflow on salinity intrusion from the Arabian Gulf towards the upper reaches of the Shatt AlArab river estuary was evaluated by using Mike11, a one-dimensional numerical modeling technique. The simulations results indicated that, during the moderate and low flow conditions of the Shatt Al-Arab river, freshwater inflow from Karun river at 10 and 40 m^3/s, respectively, could be capable of keeping salinity extent to not exceeded the confluence location of these two rivers. Additionally, the results indicated that in the case of a sharp decline of Karun river inflow, additional releasing of freshwater from the Tigris river can completely compensate for the Karun inflow. While in the case of cut off of Tigris river, the Karun inflow in the range of 60 m^3/s could be able to keep salinity extent beyond the Abo Flous station during the simulation period. Furthermore, the possibility of discharging water with high levels of salinity from the farming projects located at the lower basin of Karun river towards the Shatt Al-Arab river estuary was taken into account. In such cases, the results suggested that during low and moderate flow conditions, freshwater inflow by about 250 and 225 m^3/s, respectively, should be released from the Karun river to remains salinity extent below the Abo Flous location. A water management policy agreement between Iraq and Iran could be an effective solution to the salinity issue both in the Shatt Al-Arab river estuary as well as Karun river.

Keywords Shatt Al-Arab river estuary · Mike11 · Salinity intrusion length · Karun river · Arabian Gulf

Introduction

The highest importance of estuaries lies in their unique environment, which combines fresh and saline water nature. Hence, it represents the most productive regions and requires effective strategies to conserve in their typical situation (Lafta 2021a). The estuarine water circulation mainly depends on the interaction between the freshwater inflow and sea tide (Lafta 2014; Al- Taei et al. 2014; Abdullah et al. 2016).

The most notable challenge that facing estuaries is the water quality deterioration due to several factors which are natural or anthropogenic in origin (Abdullah 2016). The anthropogenic factors contain the construction of the dams on the rivers, coastal reclamation, and industrial activities that effluent their wastes towards these natural systems (Abdullah 2016). Meanwhile, the natural impacts could be attributed to changes in climate patterns and include the decrease of precipitation, rising sea level, and increase of the extent of saline water toward the upper reaches of estuaries, leading to a deterioration in their ecosystems (Liu et al. 2014; Wachler et al. 2020; Haddout and Maslouhi 2018). In estuarine systems, the reduction of the freshwater inflow resulting in a transfer of saline water further towards the upper reaches of the estuary, and this is known as salinity intrusion. The salinity intrusion length represents the distance from the estuary mouth to a location that has a salinity greater than the riverine water by 1 ppt (Parsa et al. 2007; Shivaprasad et al. 2013).

There are several methods to study the hydrodynamics behavior and water quality of estuaries. However, the continuous field measurements represent the most precise way to study the physical characteristics of estuaries, but they require high-cost instruments as well as long periods of observations. The second method is the construction of physical models that simulates the natural behavior of the estuarine systems on a small scale, but usually, the operation of such models is very expensive. Nowadays, the numerical modeling technique represents the most effective tool in the study of physical characteristics in estuaries, lagoons, and lakes (Kuang et al. 2014; Li et al. 2015; Nagashima and Yoneyama 2018; Lafta et al. 2019b; Balaji and Satheeshkumar 2021).

Shatt Al-Arab river estuary located in the southeast of Iraq has formed by a confluence of the Tigris and Euphrates rivers in Qurna, about 75 km north of Basrah city. There are several tributaries discharged in the Shatt Al-Arab river system. The Sweep river, drainage in the upper reaches of the Shatt Al-Arab river basin at about 6 km south of the Qurna. Garmat Ali river, which originates from Al-Hammar marsh and inflow to the Shatt Al-Arab river near the Basrah city, on the western side. While the main tributary is the Karun river, which originates from the Zagros Mountains in Iran, and discharges in the Shatt Al-Arab river estuary at about 32 km south of Basrah city, as shown in Fig. 1. Historically, the Karun river was participating with more than half of the annual amount of the Shatt Al-Arab river

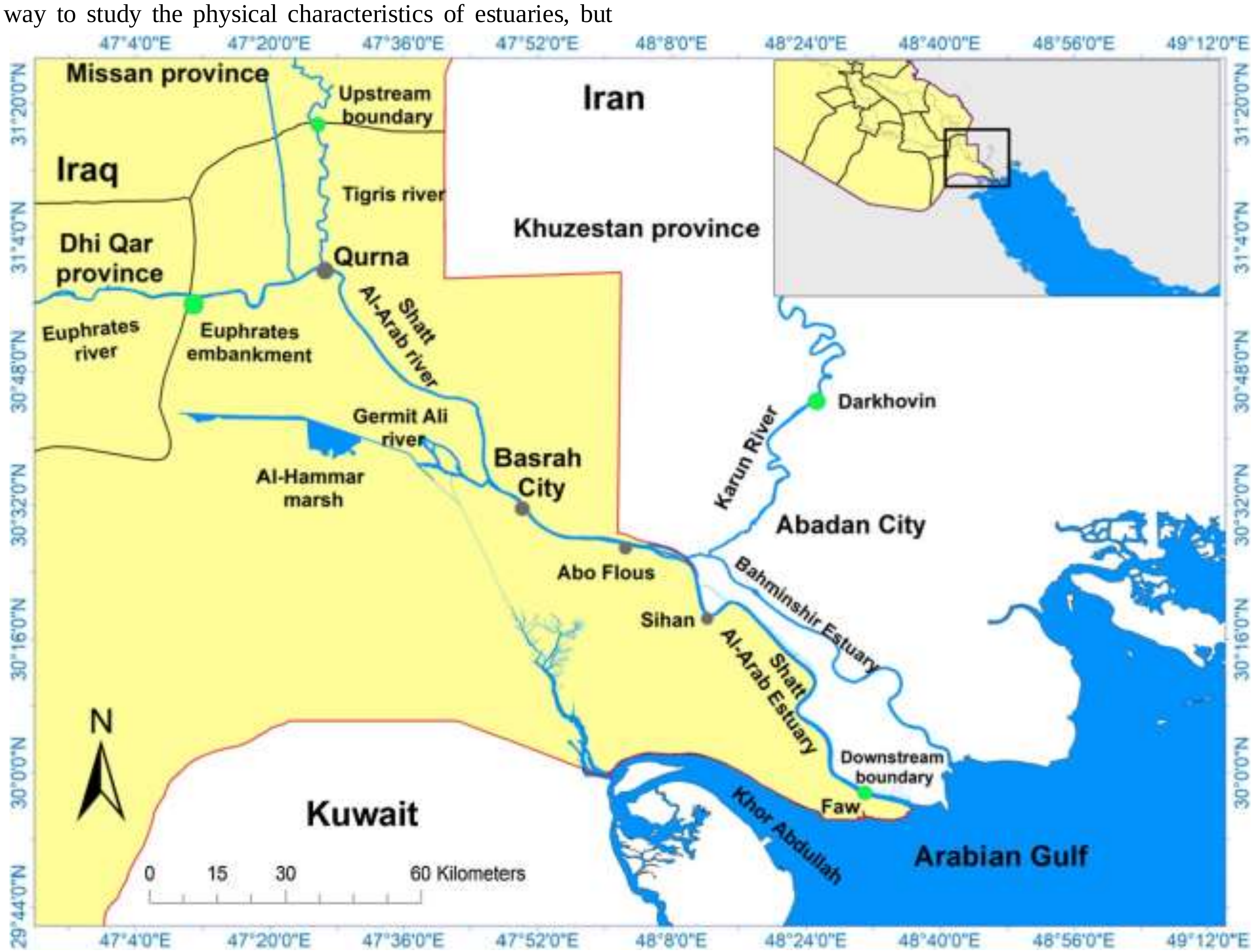


Fig. 1 Map of studied area, including measurements stations as well as model boundaries (green circles)

water before it undergoes several alterations in its hydrological regime. However, an increase in industrial, agriculture, urbanization expanding, and the construction of several dams represent the main factors that participated in the alteration of the Karun river regime (Marzouni et al. 2014; Al-Mahmood and Mahmood 2019). Historically, the Karun river was a pathway for ships and boats, and its water was very good in terms of quality and quantity, but as a result of the aforementioned reasons, the river depths, and water quality gradually declined. The reduction in the inflow of the Karun river was reflected negatively on the water quality in the Shatt Al-Arab river. Recently, particularly by 2009, the problems were exacerbated when the Karun river was converted to an Iranian side and linked with the Bahminsher channel, which discharges towards the northern Arabian Gulf as shown in Fig. 1. The inflow of the Karun river into the Shatt Al-Arab estuary is controlled by a network of regulators. They open in some periods, particularly when there is a large volume of water in the river. In addition, they open in the cases of a flood as that happened in early 2019 when the Karun river was subjected to a flash flood event leading to a disaster in most cities located on its banks. However, this event resulted in the loss of thousands of farming hectares, and thousands of residents are displaced, as reported by media at the time. Furthermore, in 2009 the Iraqi Ministry of Water Resources has constructed an embankment across the Euphrates river (Fig. 1). The embankment has resulted in the blogging water inflow of the Euphrates river towards the Shatt AlArab river. Thus, the present freshwater supplied in the Shatt Al-Arab river is mainly furnished by the Tigris river and minorly by the Karun river (Lafta 2022).

Shatt Al-Arab river represents the main source of surface water for many large cities, Basrah province in Iraq, Abadan in Iran (Allafta and Opp 2020; Lafta 2022). Furthermore, the estuary represents the major source of freshwater for the northern Arabian Gulf and plays an important role in the marine environment of the Gulf (Al-Yamani 2008). Historically, the Shatt Al-Arab basin was known as the most fertile area, with millions of palm trees on its banks. However, in the last two decades, the Shatt Al-Arab river faced many challenges leading to an obvious deterioration in its water in terms of quality and quantity (Moyel and Hussain 2015; Abdullah 2016). The continuous construction of dams and regulators on the Tigris, Euphrates, and Karun rivers in Turkey, Syria, Iran, and Iraq minimized the amounts of freshwater arrive at the Shatt Al-Arab system. Consequently, the saline water of the Arabian Gulf intruded further towards the upper reaches of the river. The severe salinity intrusion events occurred in 2009, 2012, 2013, 2015, and 2018 leading to great economic, social, and health problems in Basrah province (Al-Mahmood 2020).

There are limited studies that quantified the influence of the Karun river on the salinity intrusion in the Shatt AlArab river. Abdullah (2016) studied the salinity distribution along the Shatt Al-Arab river. He mentioned that the Karun river has a pronounced positive effect in reducing the salinity levels of the regions located near its confluence site with the Shatt Al-Arab river estuary. The flushing time for the Shatt Al-Arab river estuary was calculated by Abdulla et al. (2016). They demonstrated that the Karun river has a major role in determining the flushing capability of the Shatt AlArab river. Increasing in the Karun river inflow coincided with a reduction in the flushing time of the Shatt Al-Arab river estuary and vice versa. Al-Mahmood and Mahmood (2019) studied the influence of Karun river inflow on the salinity distribution of the Shatt Al-Arab river estuary based on the spatial observations of salinity. They indicated that the areas near the confluence of Karun- Shatt Al-Arab river show salinity less than of areas located upper and down of this confluence location. They attributed these differences to the salinity diluted by freshwater inflow by the Karun river. The main aim of this paper is to quantify the influence of the Karun river inflow on salinity intrusion in the Shatt Al-Arab river estuary. The study is based on the numerical modeling technique by assuming several scenarios to examine the impact of this tributary on the salinity status along the Shatt Al-Arab river system.

Materials and methods

Study area

Shatt Al-Arab river extent to about 204 km from Qurna until it meets the Arabian Gulf at about 10 km south of Faw city as indicated by Fig. 1. The width of the river varies from about 1000 m at the estuary mouth to 300 m in Qurna city (Lafta 2021a). The maximum water depth reaches about 20 m. The river hydrology is governed by freshwater inflow, tidal regime, and the effects of the dominant climatic conditions (Allafta and Opp 2020). The tidal behavior in the estuary is mainly controlled by the northwest Arabian Gulf tidal regime. The northwest Arabian Gulf tidal regime displays a mixed, predominantly semi-diurnal tide (Abdulla 2002; Lafta et al. 2019a, 2020; Lafta 2021b).

The Karun river represents the longest river in Iran, originated from the Zagros mountain chain and extent to about 890 km until its last section in Khuzestan province in southwestern Iran. The width of the river ranged from 250 to 900 m (Adib and Javdan 2015). Karun river represents the main source of freshwater for about 16 cities in Iran. The water flow regime of the river was regulated by constructed four mega-dams along the river course, which could be used for electrical generation, as indicated by Ahmadmoazzam et al. (2017).

The climate in the area displays a hot and long summer. The annual rainfall of the region is generally low and limited to the winter months. The region is characterized by two types of wind regimes. The northwest wind (Shamal wind) and the southeast wind (Kaus wind) (Zakaria et al. 2013; Lafta 2021b).

Data collection

Several types of data were required to conduct the study aims, includes water level, bathymetry, and salinity measurements. The measurements of water level and salinity were conducted by installed a pressure water level diver and conductivity diver, type Hopo, during March/2017 at two locations, Sihan and Abo Flous, as illustrated by Fig. 1. The water level measurements are referenced to a local datum, called Faw 1979, which is a mean sea level at Faw city. The salinity was obtained by applying the empirical formula (salinity = 0.64* conductivity). The bathymetric and topographic measurements along the Shatt Al-Arab and Tigris rivers were used to produce the geometry of the Shatt Al-Arab river model by Mike11. These measurements were conducted by the Marine Science Center/University of

Basrah during 1998 and 2005, as well as the bathymetric survey carried out by the General Directorate of Study and Design/ Ministry of Water Resources through 2012. Moreover, and due to the lack of the bathymetric data of the Karun river, the satellite data, as well as Google Earth images, has been used to create the geometry of this river.

Model set up and validation

Mike11 is a one-dimensional numerical modeling system based on solving Saint–Venant equations by using a finite difference scheme. The model was developed by the Danish Hydraulic Institute (DHI). The model simulates the hydrodynamics, water quality, and sediment transport in rivers, lakes, and estuaries. The salinity distribution is simulated by solving the Advection- Diffusion equation. More details on the model characteristics, approach, and applications can be found in the Mike11 user manual (DHI 2007).

Shatt Al-Arab river model began, at an upstream boundary, from the Tigris river at a sharing border between Al Basrah and Missan provinces. The choice of this location was to ensure that the tidal effect has vanished. Moreover, due to the lack of water level data at the estuary mouth, the downstream boundary of the model was selected to be at Faw city, located about 10 km north of the estuary mouth. The Euphrates river was combined with the Shatt Al-Arab model reaches as a branch. This branch started from the location of the embankment on the Euphrates river and extended to about 35 km until its confluence site with Tigris river in Qurna. Additionally, the Garmit Ali river was also included as a lateral branch started from the eastern Al-Hammar marsh, and extended to a distance of 18 km, and finished at Shatt Al-Arab river, north of Basrah city. Furthermore, the Karun river was included in the Shatt AlArab model by adding it as a tributary branch. This branch extended for a distance of about 50 km from the Darkhovin until its confluence with the Shatt Al-Arab river estuary, as indicated by Fig. 1. However, Darkhovin represents the limit at which the effect of tidal phenomena vanishes, as indicated by Adib and Jahanbakhshan (2013) and Adib and Javdan (2015).

At the downstream boundary condition, the model was forced by the time series of water level fluctuations in Faw city. However, due to lack of realistic measurements at this site, the water level data were obtained from the Total Tide software (UKHO 2003). Moreover, for upstream boundary conditions, the freshwater discharge by the Tigris river was used. Furthermore, the upstream boundaries for Euphrates and Germit Ali rivers were introduced as closed boundary conditions. Meanwhile, the freshwater discharge by the Karun river was used as an upstream boundary condition at Darkhovin to track its effects on the salinity intrusion in the Shatt Al-Arab river estuary.

The spatial discretization of the model was 250 m along the main model path as well as on its tributaries. The initial conditions were a cold start, i.e., surface level and water speed are equal to zero at the first time step of the simulation. The model was run for six months, from 1st January to 30th June of 2017. Based on the Courant–Friedrichs condition, the stability of the model was achieved by choosing a time step of 120 s. The salinity at the downstream boundary was set to be 35 ppt, while at upstream of the Shatt Al-Arab river as well as the Karun river was 1 ppt.

The performance of the model was tested by comparing the estimated values of water level and salinity by the model with the observations at two sites, i.e., at the Sihan and Abo Flous stations. The root mean squares error RMSE

$$RMSE = \sum_{i=1}^{N} (M_i - C_i)2 \underline{\qquad\qquad} N$$

, the statistical parameter that compares simulated results with the measurements was applied to ensure the best performance of the model. Where, M_i and C_i are a sum of measured and simulated values respectively, and N is a number of values. Several sensitivity analyses were conducted to reaches the best match between simulated and observed values for both water level and salinity.

The best performance of the model was obtained by choosing a bottom roughness (manning number) of the value 0.17 ($m^{1/2}/s$) and upstream discharges of Tigris river of 50 m^3/s and Karun discharge of 5 m^3/s. Figure 2 depicted the comparisons between the simulated and measured water levels at Sihan and Abo Flous stations with RMSE of 0.13 and 0.06 m, respectively. For the salinity comparison, the salinity measurements at the Sihan station were used, a qualitative matching was achieved between measured and simulated salinity. However, this could be attributed to the low fluctuation range of salinity at this location which does not exceed 1.15 ppt. It's worthy to mention that a comparison of salinity at the Abo Flous station is not presented since the salinity fluctuation was very low, and the model was not capable to capture such low variations.

Results and discussion

The hydrodynamics regime of the Shatt Al-Arab river is controlled by tidal effect at lower portions and freshwater discharges at the upper. The simulation results indicated that water level variations at the estuary mouth have coincided with the tidal amplitudes and displayed maximum and minimum fluctuations range during spring and neap tide phases, respectively. However, the tidal effect gradually weakens along the longitudinal path of the estuary, which

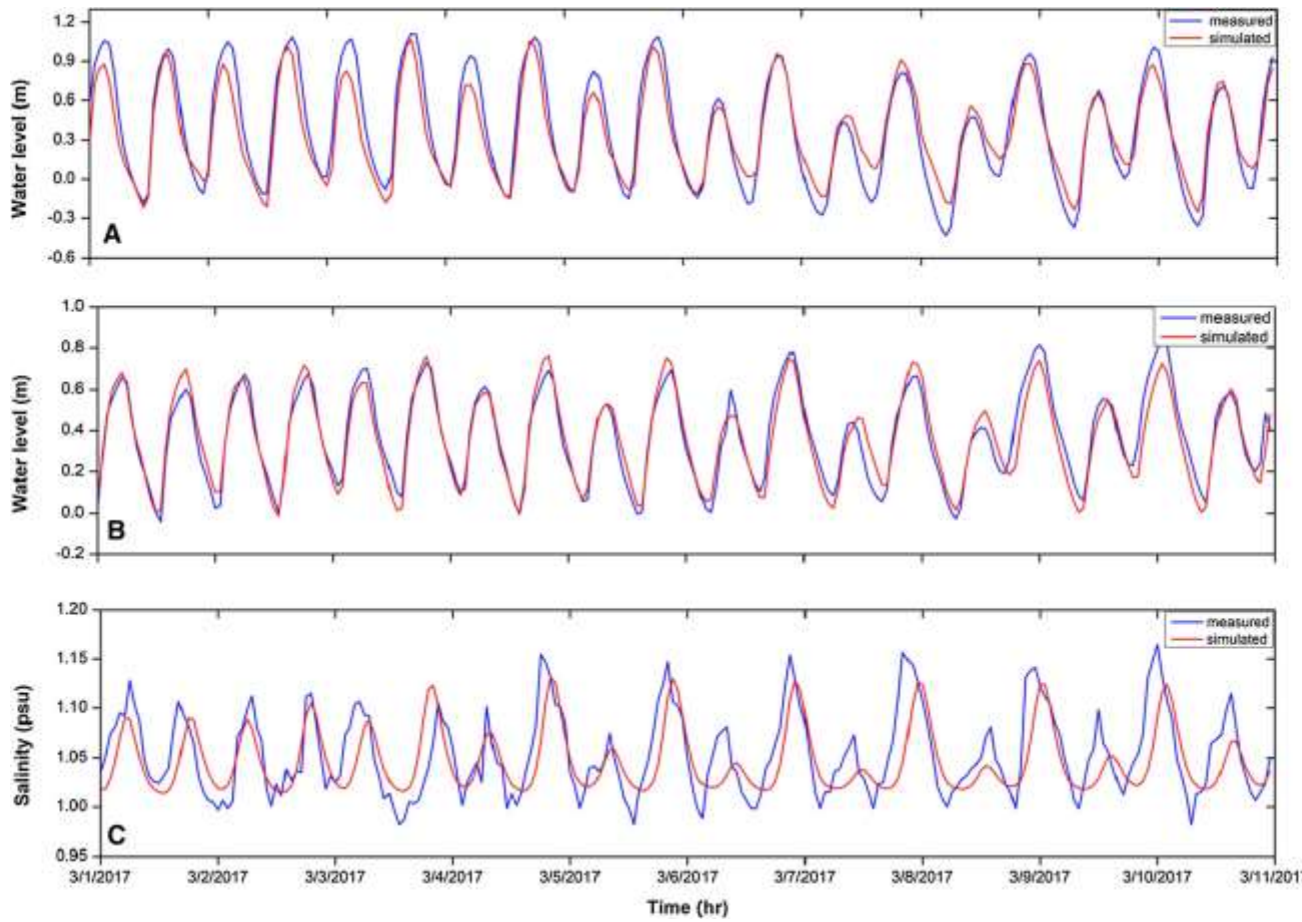


Fig. 2 Comparison between model results and measurements of water level and salinity at (**A** & **C**: Sihan, **B**:Abo Flous)

was reflected by the decline of the tidal range as we moved towards the inland direction, as indicated by Fig. 3.

The source of salinity in the Shatt Al-Arab river estuary is not only due to the seawater intrusion but also attributed to many other sources. These sources including, agriculture, domestic, and industrial activities along the river course, but the salinity intrusion from the Arabian Gulf represents the main polluter at the Shatt Al-Arab river system (Abdullah 2016). The salinity problem of the Shatt Al-Arab was exacerbated since 1989 when the water resources projects in the Tigris basin has been started. Hence, our simulation scenarios focused on the impacts of the decline of Tigris river inflow besides the deterioration of the Karun river water in terms of quality and quantity on the salinity status in the Shatt Al-Arab river system.

Positive impact of Karun river

The first scenario was based on the hydrological situation of the moderate freshwater inflow of Tigris river at 50 m^3/s, as well as 5 m^3/s from the Karun river. The results of this scenario indicated that the maximum salt intrusion length at the end of the simulation was 76 km along the longitudinal path of the Shatt Al-Arab river estuary. Approximately, this length is close to the length estimated by Abdullah et al. (2017). They indicated that salinity can introduce about 80 km when Tigris river inflow at 45 m^3/s. The influence of seasonal variations in Karun river inflow on the salinity distribution along the Shatt Al-Arab river estuary is examined by developing five scenarios. However, these scenarios assumed a fixed discharge at upstream of the Shatt Al-Arab river at 50 m^3/s (moderate condition) with corresponding flow rates of 10, 20, 30, 40, and 50 m^3/s from the Karun river. The results indicated that salinity can reach a distance of 71, 62, 53, 47, and 44 km in the case of 10, 20, 30, 40, and 50 m^3/s of Karun river inflow, respectively, as depicted by the Fig. 4. Correspondingly, the saline water was introduced to about 0.4 km along the Karun river course when its discharge was 10 m^3/s. While the salinity was completely removed from Karun river by the rest scenarios.

Another set of scenarios concentrated on the low flow situation of the Shatt Al-Arab river by considering a flow of 25 m^3/s from the Tigris river beside a Karun river inflow ranged between 10 and 50 m^3/s. This low inflow of the Tigris river represents the estimated flow rate for the period of 1989–2009, as indicated before by Abdullah et al. (2017). These scenarios aim to examine the ability of this tributary to working against the saline water of the Arabian Gulf in the case of such a decline in releasing water towards the upper reaches of the Shatt Al-Arab river system. The results indicated that the saline water interfaced with the freshwater at a distance of 96, 86, 77, 67, and 58 km when the Karun river inflow was 10, 20, 30, 40, and 50 m^3/s, respectively, as illustrated in Fig. 5. Correspondingly, the saline water can reach a distance of 25 and 8 km along the Karun river, in the case of Karun inflow, was 10 and 20 m^3/s, respectively, while salinity was completely removed by other flow rates.

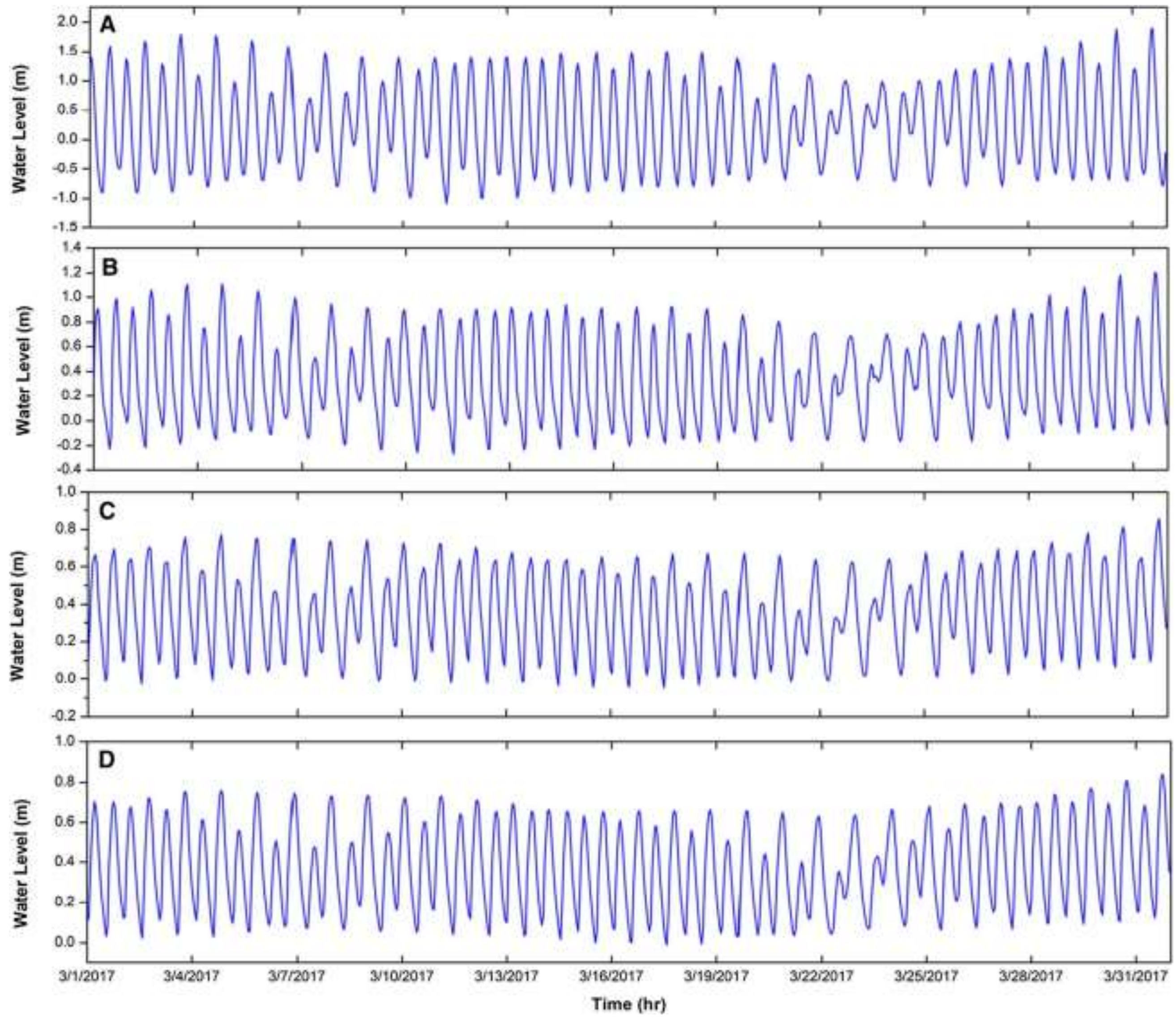


Fig. 3 Water level variations along the Shatt Al-Arab river estuary (**A**: Faw, **B**: Sihan, **C**: Abo Flous, **D**: Basrah city)

The salinity status of the Shatt Al-Arab river estuary in the case of a sharp declined of Karun river inflow (0 m^3/s of Karun flow rate) was taken into account. However, five scenarios are presented in which the ability of compensation of Karun inflow was examined by additional releases of freshwater from the Tigris river. For comparison, these scenarios assumed released water from Tigris river by the same amounts of the Karun flow rates, i.e., 10, 20, 30, 40, and 50 m^3/s in the case of low flow conditions. The results of these set of simulations showed that the salinity traveled a distance equivalent to 92, 85, 77, 67, and 58 km when the Tigris inflow was 35, 45, 55, 65, and 75 m^3/s, respectively, as shown in the Fig. 6.

However, it is obvious that from the Figs. 5 and 6, the salinity intrusion lengths in these two sets of scenarios are approximately identical. Particularly, when the Karun river inflow ranged from 30 to 50 m^3/s was completely

Fig. 4 Salinity intrusion limit corresponding to 50 m^3/s from Tigris river and different flow rates from the Karun river

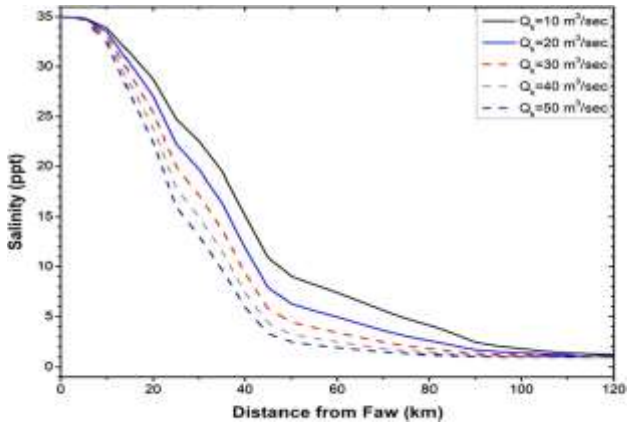
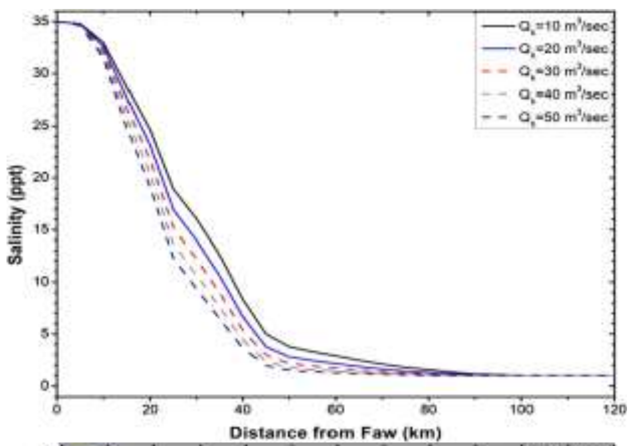


Fig. 5 Salinity intrusion limit corresponding to 25 m^3/s from Tigris river and different flow rates from Karun river



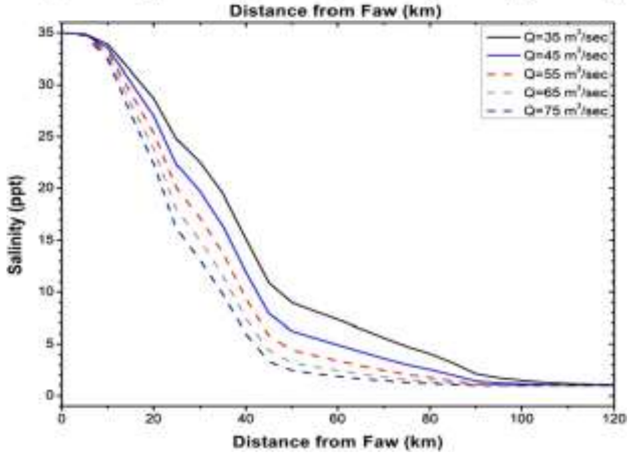
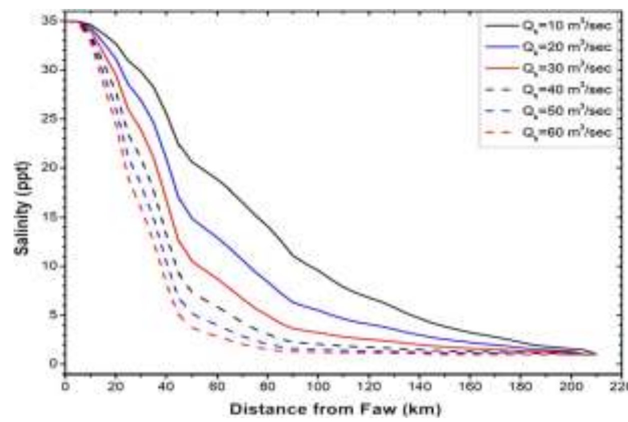


Fig. 6 Salinity intrusion limit when Karun river inflow 0 m^3/s and different flow rates from Tigris river

Fig. 7 Salinity intrusion limit when Tigris river closed, freshwater flow from Karun river only

compensated by water released in the upper reaches of the Shatt Al-Arab river system. Hence, additional releasing of freshwater from the Tigris river by the same amounts that were discharged by the Karun river can completely compensate for the Karun river inflow. This procedure has the same influence on the pushing of saline water from traveled further towards north of Basrah province.

Moreover, other scenarios supposed the possible total cut-off of freshwater inflow towards the upper reaches of the Shatt Al-Arab river. These scenarios assuming a 0 m^3/s inflow at the upstream boundary of the Shatt Al-Arab river. To examining the ability of the Karun river against saline water from transfer towards the upper reaches of the Shatt Al-Arab river, several simulations of Karun river inflow ranged between 10 and 60 m^3/s are presented. The results indicated that the low flow rate of the Karun river has no possible action to conserve the Shatt Al-Arab river from saline water intrusion. However, when the Karun inflow rate was 10, 20, 30, 40, and 50 m^3/s, the salinity transferred a distance of 184, 164, 140, 103, and 81 km, respectively, along the estuary, as shown in Fig. 7. Similarly, the saline



water could introduce a distance of 42, 29, 18, and 10 km along the Karun river at such amounts of inflow rates. Meanwhile, other results of these simulations illustrated that the Karun river inflow in the range of 60 m^3/s could be able to keep salinity intrusion below the location of Karun river confluence with the Shatt Al-Arab river estuary. The salinity was introduced to about 71 km when the Karun river inflow was 60 m^3/s.

Negative impact of Karun river

Correspondingly, the possibility of the negative impact of the Karun river on the Shatt Al-Arab river environment was taken into account.

The agriculture projects in the Khuzestan province represent the biggest polluter of the Karun river. There are five sugar cane projects constructed near the lower reach of Karun river. According to Ghadiri (2016), all lands located between Abadan and the Arabian Gulf have very shallow (1–0.6 m) and highly saline (45–70 dS/m) groundwater.

Hence, the success of the sugar cane projects required a deliberate drainage system to be put in place. The drainage system has a number of collection points where saline water is pumped into an open canal which takes the highly saline water back into the river. The operation of the first two of the five new sugar cane projects, as well as drought and lack of sufficient snowfall on Zagros mountains which significantly reduced the flow rate of the Karun river in the summer months of 2000 and 2001, leads to the rise in salinity levels of the drinking water in Abadan, Khoramshahr, and Ahwaz to well above the maximum drinking limit. This situation created a massive problem for the authorities as drinking water had to be carried to these cities using water tankers (Ghadiri 2016). Table 1 gives the flow rate and electrical conductivity of water that enters the Karun river from the two of the five sugar cane projects, knowns as the Amir Kabir project and the Eastern sugar cane project located north of Abadan city.

However, several simulation scenarios are assumed to examine the response of the Shatt Al-Arab river estuary to the inflow of water with such a high level of salinity from the Karun river. This was conducted by adding the flow rate of the Amir Kabir and the Eastern sugar cane projects (Table 1) as a point source in the Karun river branch of the Shatt AlArab river model. The salinity that used in these scenarios is based on the mean salinity as given by Table 1. In these sets of simulations, the Karun river flow rates ranged between 10 and 50 m^3/s. The first set of scenarios were corresponding to the low flow condition, while the second set was based on the moderate flow condition of the Shatt Al-Arab river system.

Table 1 Electrical conductivity of the drainage water entering the Karun river from some of the large sugar cane projects (Ghadiri 2016)

Drain name	Mean flow rate (m^3/s)	Electrical conductivity (dS/m)		
		Max	Min	Mean
Amir Kabir sugar cane project	7	69	44	45
Eastern sugar cane project	3	64	42	45

The results of these simulations revealed that during the low flow condition of the Shatt Al-Arab river, the high levels of salinity from the Karun river will resultant in introduce of salinity to areas located north of Basrah city. The salinity could reach a distance of 112 and 110 km when Karun inflow 10 and 20 m^3/s, respectively. By increasing of Karun river inflow, salinity goes back a short distance. The salinity was introduced to about 106, 104, and 103 km when the Karun river inflow at 30, 40, and 50 m^3/s, respectively, as indicated by Fig. (8A). However, it is obvious at this flow rate of the Karun river, the most important areas of Basrah province will face high levels of salinity, with severe problems in social and other activities. The overcoming of such a situation requires discharged more freshwater into the Shatt Al-Arab river system from Tigris or from Karun river itself. The first attempt was increasing the Tigris river inflow to 50 m^3/s and tracking the response of the Shatt Al-Arab river to such a situation. However, the results indicated that the salinity could reach a distance of 94, 93, 92, 91, and 90 km when Karun river inflow 10, 20, 30, 40, and 50 m^3/s, respectively, as shown in Fig. (8B). Similarly, at these flow rates, the salinity also reaches areas with high importance south of Basrah province, i.e., north Abo Flous region.

The second attempt was based on increasing the Karun river inflow. Several flow rates were tested to determine the appropriate one that can conserve both the Shatt Al-Arab and the Karun rivers from rising salinity levels. However, six simulations were conducted by releasing freshwater from the Karun river at 100, 125, 150, 200, 225, and 250 m^3/s, in addition to the 25 and 50 m^3/s flow rates from the Tigris river in the first and second rounds, respectively. The results of the simulations showed that during the low flow case of the Shatt Al-Arab river, the salinity could extend to distances of 95, 92, 89, and 86 km when Karun river inflow was 100, 125, 150, and 200 m^3/s, respectively, as indicated by Fig. 9A. Hence at these ranges of Karun inflow, also the salinity will reach the northern of Abo Flous region. While by more releasing freshwater from the Karun river at m^3/s, the salinity starts to be diluted along the Karun stream. This will be leading to salinity to return about 5 km along the Shatt Al-Arab river compared with its distance when Karun

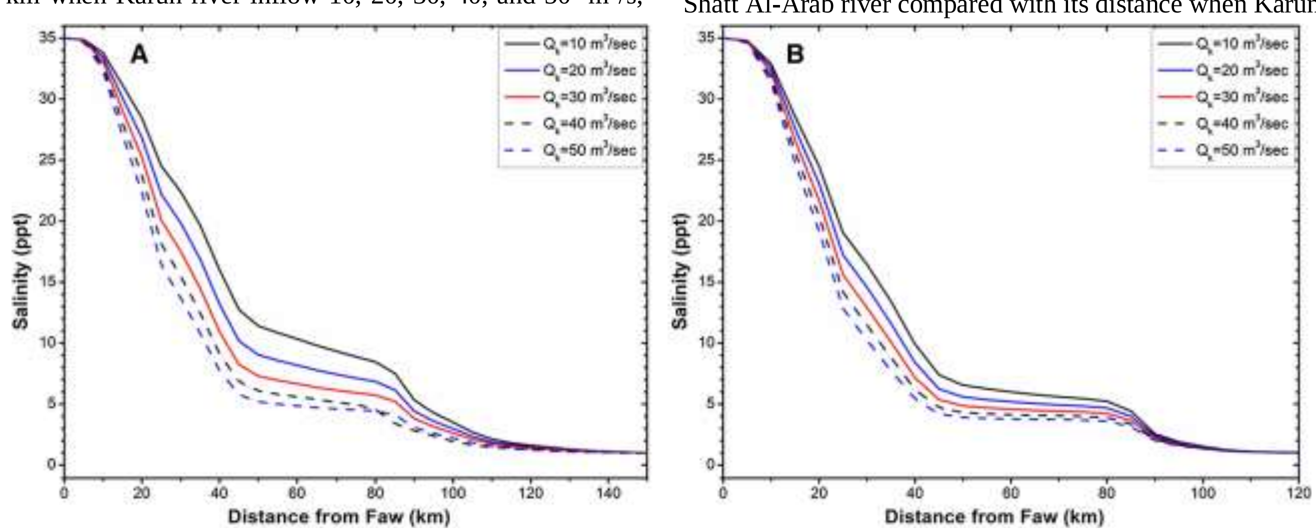


Fig. 8 Salinity intrusion limit corresponding to (**A**: 25 m^3/s and **B**: 50 m^3/s) from Tigris and different flow rates from Karun river

inflow was 200 m^3/s. By increasing the Karun river inflow to 250 m^3/s, salinity will introduce 74 km along the Shatt Al-Arab river (Fig. 9A). Hence at this rate of inflow, the salinity limit could remain below Abo Flous, and the most important areas of Basrah could be conserved from the salinity problem.

Furthermore, the simulation results indicated that during the moderate flow of the Shatt Al-Arab river, the salinity could reach 88, 87, and 86 km when Karun river inflow 100, 125, and 150 m^3/s, respectively, as shown in Fig. 9B. While by increasing of Karun river inflow to 200 m^3/s, salinity began to be diluted along the Karun river stream and will be traveled to about 80 km along the Shatt Al-Arab river estuary. Moreover, the result showed that when the Karun river inflow was 225 m^3/s, the salinity will travel a distance of 75 km along the Shatt Al-Arab river, i.e., it has remained south of the Abo Flous rgion. Consequently, the conservation of these areas required at least such amounts of freshwater to be released in the Shatt Al-Arab river system.

agriculture activities in the lower portion of the Karun river basin.

However, the results revealed that during the moderate flow condition of the Shatt Al-Arab river, the salinity could travel distances at 71, 62, 53, 47, and 44 km in the case of 10, 20, 30, 40, and 50 m^3/s of Karun river discharge, respectively. While during the low flow condition, the salinity can be reached to 96, 86, 77, 67, and 58 km, when the Karun river inflow was 10, 20, 30, 40, and 50 m^3/s, respectively. Additionally, the case of sharp declined in the Karun river inflow was taken into account by examining the possibility of compensation of Karun inflow by releasing freshwater from the Tigris river. The results indicated that the additional releasing of freshwater in the upper reaches of the Shatt Al-Arab river by the same amounts that were discharged by the Karun river, can completely compensate for the Karun river inflow. Furthermore, the ability of the Karun river to compensate for the possible cut-off of freshwater from the Tigris river was taken into account by assuming several flow rates to be released in the Shatt Al-Arab river system from the Karun river. The results indicated that the Karun river inflow in the range of 60 m^3/s could be able to keep the salinity below the Abo Flous region during the simulation period.

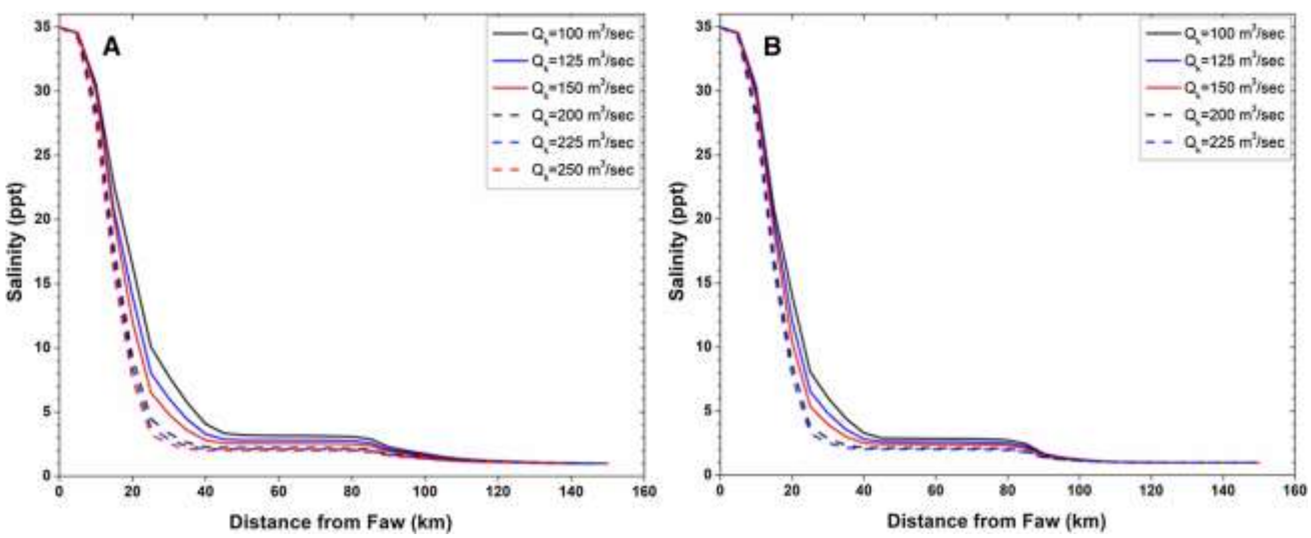


Fig. 9 Salinity intrusion limit corresponding to (**A**: 25 m^3/s and **B**: 50 m^3/s) from Tigris and different flow rates from Karun river

Conclusions

The influence of the Karun river on salinity intrusion in the Shatt Al-Arab river estuary was studied by applying one-dimensional hydrodynamics and advection–dispersion model using Mike11. The model performance was examined by comparing the model results with the field measurements for both water level and salinity. Then, the calibrated model was used to examine the response of salinity intrusion limits along the Shatt Al-Arab river estuary to the Karun river inflow. The first simulations sets were based on the positive influence of the Karun river. Meanwhile, other simulation sets were concentrated on the possible negative impact of this river on the Shatt Al-Arab river estuary due to the continuous developments in

The second set of simulations aimed to highlight the possible negative impacts of the Karun river on the Shatt Al-Arab river system. These simulations were concentrated on the effluent of water with high levels of salinity from two mega sugarcane projects near the Karun river. The results indicated that during the low flow condition of the Shatt Al-Arab river, the salinity could be exceeded the Basrah city. However, the results suggested that during such low flow conditions, it requires at least about 250 m^3/s to be released from the Karun river to keep salinity below the Abo Flous area. While the results illustrated that during the moderate flow situation of the Shatt Al-Arab river, the required amounts of freshwater from the Karun river should not least 225 m^3/s. Consequently, both Tigris and Karun rivers have the main impact on the conservation of the Shatt Al-Arab river environment from the salinity intrusion problem. The results obtained could be beneficial for water management strategies in the Shatt Al-Arab river system.

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Declarations

Conflict of interest The author declares that they have no conflict of interest.

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