Analysis of Possible Actions to Manage the Longitudinal Changes of Water Salinity in a Tidal River

Abdullah, Ali Dinar; Popescu, Ioana; Dastgheib, Ali; van der Zaag, Pieter; Masih, Ilyas; Karim, Usama F.A.

DOI
10.1007/s11269-017-1634-5

Publication date
2017

Document Version
Final published version

Published in
Water Resources Management

Citation (APA)
Abdullah, A. D., Popescu, I., Dastgheib, A., van der Zaag, P., Masih, I., & Karim, U. F. A. (2017). Analysis of Possible Actions to Manage the Longitudinal Changes of Water Salinity in a Tidal River. *Water Resources Management*, *31*(7), 2157-2171. https://doi.org/10.1007/s11269-017-1634-5

Water Resour Manage (2017) 31:2157–2171
DOI 10.1007/s11269-017-1634-5

Analysis of Possible Actions to Manage the Longitudinal Changes of Water Salinity in a Tidal River

Ali Dinar Abdullah[1,2] **· Ioana Popescu**[1,3] **·**
Ali Dastgheib[1] **· Pieter van der Zaag**[1,4] **· Ilyas Masih**[1] **·**
Usama F. A. Karim[5]

Received: 21 April 2016 / Accepted: 16 March 2017 /

Abstract In previous studies we have ascertained that inflows and seawater intrusion in the Shatt al-Arab River (SAR) are two key physical factors behind fluctuating and sharply escalating salinities observed in recent years. Such levels require a series of countermeasures and investigative studies to translate physical factors into a salinity dynamics model to understand the problem and its impact as these factors vary in location, time and quantity. A one-dimensional hydrodynamic and salt intrusion numerical model was applied to simulate the complex salinity regime in the SAR based on hourly time-series data for the year 2014. The model was used to analyse the impact of different management scenarios on salinity under

---

✉ Ali Dinar Abdullah
a.abdullah@unesco-ihe.org; alidinar77@gmail.com

Ioana Popescu
i.popescu@unesco-ihe.org

Ali Dastgheib
a.dastgheib@unesco-ihe.org

Pieter van der Zaag
p.vanderzaag@unesco-ihe.org

Ilyas Masih
I.Masih@unesco-ihe.org

Usama F. A. Karim
u.f.a.karim@utwente.nl

[1] UNESCO-IHE Institute for Water Education, Westvest 7, 2611 AXDelft, the Netherlands

[2] Department of Civil Eng, Basra University, Basra, Iraq

[3] Faculty of Civil Engineering, Politechnica University of Timisoara, Timisoara, Romania

[4] Water Resources Section, Delft University of Technology, Delft, the Netherlands

[5] University of Twente, P.O. Box 217, 7500 AE, Enschede, the Netherlands

different conditions. The results show a high correlation between seawater intrusion and river discharge. Increased use of water upstream and local water withdrawals along the SAR will increase seawater intrusion and salinity concentrations. Improving the quantity and quality of the upstream freshwater sources could reduce salinity levels. Discharging the drainage water into the river could be used to counteract the salt intrusion, considering that its location affects both the salinity distribution and extent. A scenario analysis based on a numerical model constructed for the longitudinal salinity variation associated with different sources in a tidal regime, can efficiently screen alternative water management strategies.

Keywords Salinity · Shatt al-Arab River · Hydrodynamic modelling · Salt intrusion · Water management

1 Introduction

Water quality degradation is the main cause of reduced water availability and consequently reduces its use. Increasing salinity is a major water quality problem in many rivers in the world; in particular in downstream and delta regions, often associated with intensive human activities (Peters and Meybeck 2000; Roos and Pieterse 1995; Shiati 1991; Thomas and Jakeman 1985; Van der Zaag 2007). According to WHO (1996) at salinity levels greater than 1 ppt (g/l) water will become undrinkable; and at levels above 3 ppt water becomes no longer suitable for most agricultural uses. Irrigation with high saline water causes yield reduction (Ayers and Westcot 1985; Rahi and Halihan 2010). Water salinity is also a major factor affecting estuarine ecosystems. The salinity distribution reflects the biota habitat condition of an estuary (Jassby et al. 1995).

Several studies have examined salinity intrusion in estuaries (e.g. Nguyen and Savenije 2006; Becker et al. 2010), and the main influences of the river discharge management on the salinity of estuaries (e.g. Fernandez-Delgado et al. 2007; Myakisheva 1996). Also many researchers have investigated the salinity changes in river water attributed to irrigation practices (e.g. Kirchner et al. 1997; Quinn 2011; Roos and Pieterse 1995; Shiati 1991; Thomas and Jakeman 1985), but little is known about the salinity management considering a combination of different salinity sources in a river that is under tidal influence.

Therefore, there is need to study the factors that determine the salinity of rivers under tidal influence, including irrigation practices, industrial effluents, urban discharges, quality and quantity of upstream river inflow, and seawater intrusion. This will provide a scientific basis to explore the effective measures for controlling water salinity and resource management to ensure sustainable development.

The Shatt al-Arab River (SAR) is considered the main surface water resource for Basra, the second major city in Iraq. The rise in salinity of the river water is due to natural and anthropogenic sources and has increased the salt content in the soil and deforested the date palms along its banks. The SAR is experiencing environmental crisis as a consequence (Abdullah et al. 2015; Hameed and Aljorany 2011; Maser et al. 2011). As from 1980, little effort has been made by researchers and policy makers to comprehensively study and address the issues related to river salinity.

Recently, some environmental studies were conducted in the Shatt al- Arab region, mainly of biological (Ajeel and Abbas 2012; Al-Meshleb 2012) and chemical nature (Al-Saad et al.

2011; Mohammed 2011). Limited investigations were made of the physical processes in this region influencing the dynamics of salinity.

Understanding salinity changes driven by natural and anthropogenic sources is essential to provide the basic step for predicting salinity dynamics and better water allocation strategies. Longitudinal salinity distribution is highly dependent on a combination of salinity sources that are controlled by freshwater and brackish water discharges and tidal forces. Releases from the marshes and a number of tributaries into the system with different discharge and salinity concentrations complicate further the problem. A high spatial and temporal gradient requires numerical model support to simulate such a complex water system (Abdullah et al. 2016).

Numerical models have been used in several studies to investigate the hydrodynamic and transportation processes of heat, sediment, and salinity. An often used numerical model is Delft3D, which is an integrated modelling system for simulating the hydrodynamic and related process such as the transport of salinity (Lesser et al. 2004). The study presented here uses the 1-D version of Delft3D. This hydrodynamic simplification is used to investigate only the longitudinal dimension along which water salinity changes and salinity sources are simulated. This is to understand the changes of salinity which is multi-variate and highly variable, caused by many factors and uncertainties associated with it along the SAR. The present study is the first modelling study based on systematic monitoring of water salinity with simplified assumption applied to reduce a rather complex 3-D spatiotemporal water system into a manageable 1-D model. The study looks at salinity gradients caused by combining impacts of tides, retuned flow and domestic effluents, while dealing with scarcity of data associated with discharges and salinity levels of different sources. The model has been developed to correlate water flows and salinity concentrations along the SAR taking into account the tidal effect of the Gulf at the mouth of the river. The main purpose of the study is to investigate the salinity dynamic along the river due to different water resources management strategies, by:

- evaluating daily and seasonal effect of a combination of salinity sources on the longitudinal salinity changes which determine the salinity gradient along the estuary;

comparing the effect of both river flow and tidal forces on salinity changes;

- evaluating the capability of the numerical model to predict salinity changes driven by natural and human activities;

analysing some water management scenarios;

- exploring and determining the most influential parameters among the tide and river characteristics influencing salinity changes.

2 Case Study

2.1 Study Area

The Shatt al-Arab estuary is one of the major world estuaries located in the south of Iraq, and bordering Iran (CUR 1993). The SAR delta is formed by four main tributaries including the Tigris, Euphrates, Karkheh, and Karun. The first two originate in Turkey and the other two in Iran. The river is formed at the confluence of the Tigris and Euphrates rivers near Qurna city (Fig. 1). The river length is approximately 195 km, of which the most downstream 95 km forms the border between Iraq and Iran. Currently the Tigris River is responsible for most freshwater inflows.

The lower portion of the Tigris-Euphrates basin represents the greatest wetland region in the Middle East and Western Eurasia, the Mesopotamian marshlands which covers under natural conditions an area of 20,000 km^2 (UNEP 2001). The rural communities, for whom agriculture and livestock are their main sources of livelihood, use the water system for their activities and discharge back their waste. The centre of Basra city is located in the middle course of the SAR, which is the only surface water source for the city and the receptacle of its industrial and domestic effluents.

A series of large-scale water developments have been installed in all the riparian countries (Turkey, Syria Iraq and Iran) in response to increasing demands for freshwater. The watershed has witnessed the construction of a number of dams that have regulated the flow of the rivers, reducing average flow to approximately 0.14 × 10^9 m^3/yr. and 0.19 × 10^9 m^3/yr. for the Tigris and Euphrates respectively (Abdullah et al. 2015). In addition, the negative impact of water supply contamination by the surface and subsurface drainage from domestic, industrial, and agricultural fields increases the salinity concentrations.

Seawater is thus not the only source of salinity along the SAR. Due to the combined effect of natural and man-induced as well as marine and terrestrial salinity sources, salinity has

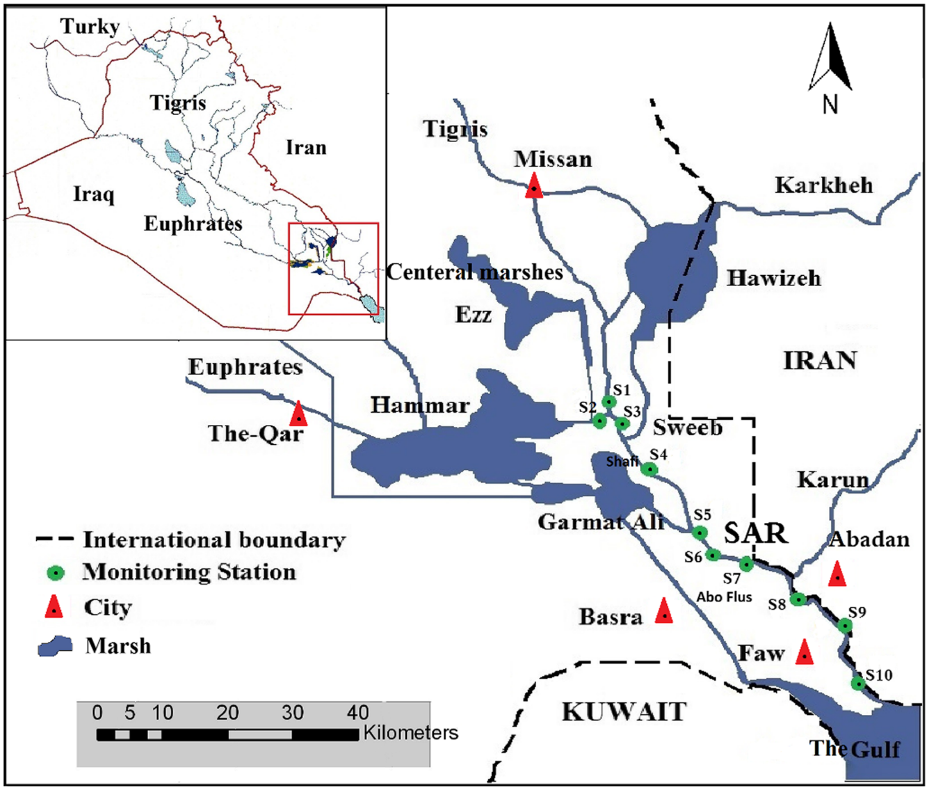


Fig. 1 The main features of the SAR system and the location of measurements points along the river

increased and changed in a complex pattern over space and time. The water salinity concentration is increasing annually as more adverse water activities relating to industrialization and population growth are developing within the basin (Abdullah et al. 2015).

2.2 Survey Campaign

Field data used for this study include hourly time series of the water level, temperature and salinity for the entire hydrological year 2014 of 10 monitoring stations along the entire SAR (Fig. 1). These stations were installed upstream and downstream of each identified salinity source. Daily time series of the Tigris River discharge were obtained from the water resources authority in Basra. River cross sectional data were based on a survey carried out in 2012 by GDSD (the General Directorate of Study and Design).

The irrigation system of the SAR is highly linked to the tidal frequency of the Gulf, especially in the lower course. Several canals are used to provide irrigation water to the surrounding farms at high water level of the SAR tidal cycle, returning draining flows at low tide. This makes it difficult to estimate water consumption and return flows accurately. There is no accurate information on water withdrawals and return flows from the Iranian side for the Karun River and some irrigation channels.

2.3 Solution Approach

A Delft3D hydrodynamic model was developed and used in this research. Delft3D is a software tool, which is a flexible integrated program, composed of several modules. Delft3D-FLOW is at the heart of it and can simulate water flows, waves, water quality, morphology, sediment transport, and salinity dynamics. The model can be used in natural and manmade environments, and can include density-driven flows. It solves non-linear differential equations of conservation of mass and momentum, under hydrostatic and non-hydrostatic free-surface flow conditions as described in detail in Lesser et al. (2004). Delft3D-FLOW has been used by several researchers to simulate tidal currents, sediment transport, and salinity changes in coastal areas, lakes (El-Adawy et al. 2013), estuaries (Van Breemen 2008), and rivers (Van den Heuvel 2010).

3 Model set-Up

The present study is based on the analysis of the collected data and available secondary data described in Abdullah et al. (2016). Using 2-D or 3-D numerical models to simulate salinity changes requires sufficiently fine grids implying intensive computational time compared to a 1-D model. Furthermore, the SAR is considered a well-mixed estuary and the transport mechanisms are dominant in the longitudinal direction. Therefore, 1-D model setup was chosen. This is sufficient to simulate salinity along the length of river course including along its estuary. Daily and seasonal salinity variations and a solution time step of 10 min are used for testing different management scenarios. This 1-D representation purposely serves to identify the bigger picture from which optimization studies aid an overall best-practice decision for the large-scale problem.

3.1 River Geometry

The bathymetry of the riverbed has been determined using the average depth at every cross section at 500 m intervals over the longitudinal axis. The cross-sectional area over the average water depth determines the width of the grid. The number of discretization cells on the longitudinal axis was 388, and the cell size was 300 × 500 m. The river was extended in the upstream direction to a non-tidal area resulting in a computational domain length of 221 km.

3.2 Boundary Conditions

The Tigris contributes the majority of freshwater volume (30 to 100 m^3/s) discharged into the SAR at the upstream portion. Therefore, the Tigris is treated as the main-stream of the system, while the other rivers are treated as tributaries. The water contributions into the SAR from each of the other regulated tributaries (except the Karun) ranged between 0 to 10 m^3/s (estimated by the local water resource authority). This is a relatively small value compared to the tidal flux and Tigris discharge. The Tigris River discharge was measured at the most downstream water regulator, located out of the tidal range. Time series of daily river discharges for the year 2014 are specified at the upstream boundary, and hourly measured tide elevations near the mouth for the year 2014 are specified as the downstream boundary. The water levels and salinity concentrations during the first time step of the simulation periods at all station were specified as the initial conditions.

3.3 Model Calibration

Water level variation is substantial at the mouth of the river influenced by tidal amplitude, however this influence gradually becomes weaker along the estuary and further upstream. Moreover, at the lower portion of the river salinity is driven by tidal impact, while at the upper portion they are driven by river discharge (Abdullah et al. 2016). Tidal amplitudes and salinity changes are highly correlated at the downstream portion. Therefore, water elevations are calibrated for the entire year 2014 considering only two stations (S8 and S9) as these are located in the lower portion of the river, where the tide is dominant.

Several irrigation canals mainly in the downstream part branch from the SAR, amounting to 140 canals on each bank. During the flood period of a tidal cycle, water is extracted from the river, while during ebb water returns back by these canals into the river. To simulate this process, the water level is calibrated using two operation points considering water consumption and water losses of the system. A comparison of modelled and observed water levels at S8 and S9 is shown in Fig. 2. Two periods have been chosen to present the model results, consisting of 8 days each, including spring and neap tide during February and October respectively. Spring and neap tide represent the highest and lowest water levels during a tidal cycle, therefore, the result of those periods have been presented just to show the performance of the model during these extreme conditions. The results indicate a good agreement between the simulated amplitudes and phases of tidal elevations with observations. To assess the accuracy of the model outcomes, a quantitative evaluation was used to compare the predicted and measured values. The method of root mean squared error (RMSE) was used to define the accuracy of the model. Another statistical index of agreement, the coefficient of determination

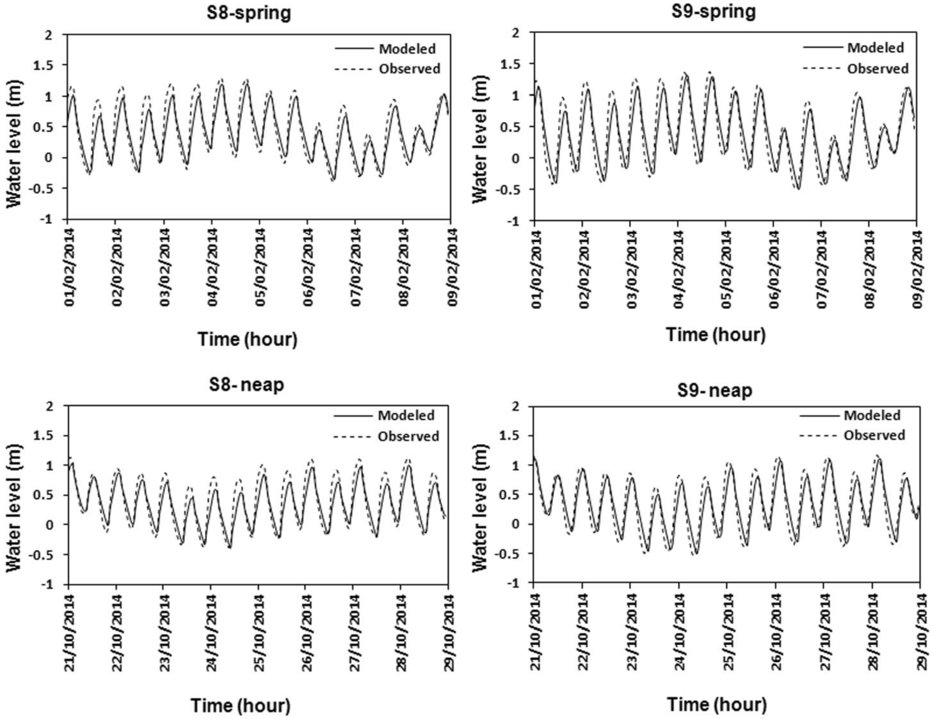


Fig. 2 Comparison between modelled and observed water levels at S8 and S9

(R^2), was used to measure the correlation between the simulated and observed water levels. The equations used are as given below:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}} \sum_{i=1}^{n} (P_i - O_i)^2 \tag{1}$$

$$R^2 = \frac{\left(\sum_{i=1}^{N}\left(O_i - \overline{O}\right)\left(P_i - \overline{P}\right)\right)^2}{\sum_{i=1}^{N}\left(O_i - \overline{O}\right)^2 \sum_{i=1}^{N}\left(P_i - \overline{P}\right)^2} \tag{2}$$

where P and O are the simulated and observed variables and $\overline{P}$ and $\overline{O}$ are simulated and observed means, respectively. R^2 values of 0.82 and 0.85 at S8 and S9 respectively show that the simulated water levels correlate well with the observed water levels. The *RMSE* of the tidal levels are 0.16 and 0.19 m at S8 and S9 respectively. These could be attributed to two main reasons; firstly, the measured water elevations may have been affected by the influences of wind and navigation along the river, and secondly, the operation processes of the river system could affect the tidal amplitudes and phases.

The calibrated hydrodynamic model is expanded with salinity. This is done by adding the hourly series of measured salinity at S1 to the river discharge at the upstream, and measured salinity at S10 to the tidal elevation at the downstream boundary. Salinity from other sources including return flows, domestic and industrial effluents along the river is added to the calibrated water levels as open boundaries at the corresponding locations. Salinity caused by the Euphrates and Garmat Ali rivers and connected marshes is represented by the measured salinity at S2 and S5 respectively. Station S2 recorded the salinity of the Euphrates at 3 km from its confluence point with the SAR. Therefore, the model was first developed for the upper part only to determine the salinity of the Euphrates at the confluence point. The salinity caused by the Shafi and Abo Flus irrigation schemes and surrounding communities are represented by measured salinity at S4 and S7, while the salinity at S8 reflects the impact of the Karun River. The model was verified with S3, S6, and S9 data for the entire year 2014. The water salinity shows large variability within a day and between days. Fig. 3 shows a comparison between measured and simulated salinity for S3, S6, and S9 at the upstream, middle, and lower portion of the river respectively. Generally, the results reflect a good agreement between the simulated and measured salinity for all those stations despite a few deviations that can be explained.

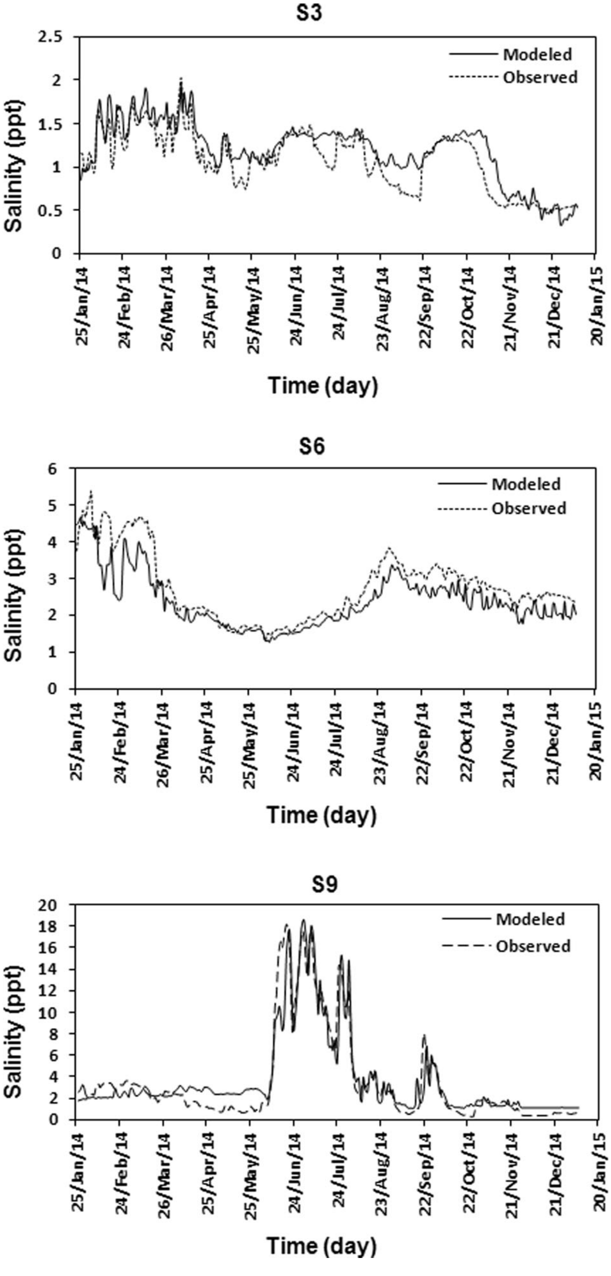
The model could not capture some of the low salinity concentration as can be seen in S3 during a few days in September and in S9 during a few days in April. Also the model under estimated the salinity at S6 during a few days in February. This could be caused by local fresh or saline water inflows. S3 and S9 recorded salinity levels lower than its upstream and downstream stations during certain periods; this could be attributed to local freshwater discharges from the Sweeb River in the case of S3 and the Karun system in the case of S9. The high salinity concentration at S6 during February could be caused by wastewater effluents, whose impact increased during rainstorm events (Abdullah et al. 2016). The high salinity concentration at S9 was during June and July that they represent the core of summer season, the drought period, where there is less river inflow. Also, water releases from the upstream tributaries is low as there are no major irrigation activities during summer period. Generally, the salinity distribution is highly affected by the operation processes including water withdrawals for domestic, industrial, and irrigation use, and the quantity and quality of return flows. The *RMSE* of salinity concentrations to the observed ones are 0.2, 0.5, and 1.4 ppt, and the calculated R^2 are 0.78, 0.84, and 0.89 for S3, S6, and S9 respectively. The good correlation between the simulated and observed salinity implies that the model can reasonably simulate salinity changes caused by combined terrestrial and marine sources.

3.4 Management Scenarios

The validated model was used to study the salinity distribution under different management scenarios. A series of model simulations were developed to investigate a number of strategic actions considering natural and anthropogenic salinity sources (Table 1).

The SAR system is under increasing pressure due to decreasing water inflows into the river. This is attributed mainly to continuous water developments at the upstream of the SAR. The Tigris which considers the main tributary to the system, its flow declined over time (Abdullah et al. 2015). The declining rate was approximately 5.4 m^3/s over the 1990–2010 period. In order to investigate the impact of the upstream developments on salinity, driven by tidal forces in the river, nine scenarios were developed (A-I). Scenarios A, B, and C investigate the impact of the river discharge. The major water resources developments in the Tigris basin started in 1989 (Abdullah et al. 2015). Therefore, three periods were considered for this study including high flow, normal, and low flow periods. The high flow period was taken as the average discharge in 1988 (200 m^3/s) representing the natural condition before most engineering

Fig. 3 Comparison between simulated and observed salinity in the river at stations S3, S6, and S9



projects. The average and minimum discharge of the period 1989–2009 was used to represent the normal and low flow periods, 95 and 25 m^3/s respectively.

The local salinity pollution caused by wastewater from the agricultural, domestic, and industrial sectors increases salinity especially at midcourse of the river Abdullah et al. (2016). Several suggestions have been made in the past to divert all drainage water away from the SAR. Also, the main strategic course of action taken by the

Table 1 Simulation scenarios of management actions, considering fixed values for downstream salinity (30 ppt), where S_{in} is the distance of seawater intrusion

Action	Scenario	Details	Consumption m^3/s	Drainage water m^3/s	S_{in} km
The impact of upstream management on the salt intrusion	A	River discharge =200 m^3/s and upstream salinity = 1 ppt	-	-	24
	B	River discharge =95 m^3/s and upstream salinity = 1 ppt	-	-	28
	C	River discharge =25 m^3/s and upstream salinity = 1 ppt	-	-	43
	D	River discharge =95 m^3/s and upstream salinity = 1 ppt	40	-	33
	E	River discharge =95 m^3/s and upstream salinity = 1 ppt and drainage water salinity = 2.7 ppt	40	20	31
	F	River discharge = 45 m^3/s and upstream salinity = 1 ppt	40	-	80
	G	River discharge =25 m^3/s and upstream salinity = 1 ppt	40	-	120
	H	River discharge = 45 m^3/s and upstream salinity = 1 ppt, drainage water within the salt intrusion range (18 km from the mouth)	40	20	80
	I	River discharge = 45 m^3/s and upstream salinity = 1 ppt, drainage water within the salt intrusion range (60 km from the mouth)	40	20	70
Managing seasonal variation	J	Seasonal river discharge of 2014, upstream and drainage water salinity represented by measured salinity at S1 and S6, respectively.	40	20	
	K	Same as in J with seasonal river discharge of 1988	40	20	
	L	Same as in J with upstream salinity of minimum 0.25 ppt	40	20	

local authority is to supply all the water demands in the upstream portion of the SAR, and distributing to different users along the river. An artificial canal with a capacity of 40 m^3/s is under construction for that purpose. The other three pairs of scenarios (D-I) investigate the impact of drainage water, water consumption, and the location of drainage water, respectively. The average annual salinity at S6 (2.7 ppt) is specified as the salinity for drainage water, where the major impact from irrigation return flows and wastewater effluents were observed (Abdullah et al. 2016).

Furthermore, the combined seasonal effects of tidal forces, upstream developments, and local drainage on salinity distribution along the river were investigated. For this purpose another set of model simulations were performed (J, K, and L). These scenarios are to compare the seasonal salinity distribution before and after water resources developments in the basin. Here, use is made of the average monthly river discharge of the year 1988 (scenario K) and 2014 (scenario J). The measured salinity at S1 represented salinity of the receiving water for both periods. Drainage water was accumulated at one point near the middle course. The salinity concentration of the drainage water was represented by the measured salinity at station S6.

4 Result and Discussion

4.1 Managing Salt Intrusion

Longitudinal salinity distributions for a two-month simulation period during wet (A), normal (B), and dry (C) conditions are illustrated in Fig. 4. The results show the maximum salt intrusion length at the end of the simulation period; 24, 28, and 43 km respectively. Large-scale developments obviously changed flow patterns, reduced river discharge, and extend seawater intrusion further upstream. The impact of upstream developments increased with time. Declining quantities of water flowing into the river is considered the main cause of escalating salinity threats. Recent observations of increase in the amount of salt intrusion confirm this. This threatens productivity of the estuary ecosystem and large date palm plantations located along its banks.

To simulate the combined impact of water withdrawals and water drainage on salinity extent, the analysis was run assuming normal conditions. Water withdrawals of 40 m^3/s were specified at the upstream end of the river domain. The simulation applies two conditions of drainage water: firstly, discharging drainage water away from the river course (D) and secondly, discharging drainage water at the downstream portion (E). The volume of drainage water considered is 20 m^3/s, including marsh water, domestic, and industrial effluents (10 m^3/s), and 25% of water consumption (minimum drainage volume according to the Iraqi specification). Fig. 5a shows that discharging drainage water at the lower portion can serve to reduce the intrusion length rather than drain it out of the system.

The river discharge is seasonally changing. It can be 45 or 25 m^3/s during dry periods. Considering the design capacity of the supplying canal (40 m^3/s), the river discharge could be close to or even less than the water withdrawals along the SAR. To compare the combined effect of water consumption and the changing river discharge, two simulation scenarios were developed to predict salinity changes in both situations, excluding drainage water. Fig. 5b shows the same pattern of salinity distribution when water withdrawals are equal (F) or more than the river flows (G). The main difference is in the length of salt excursion, and in seawater being induced deeper as more water is diverted from the system. It can reach up to 80 km in the

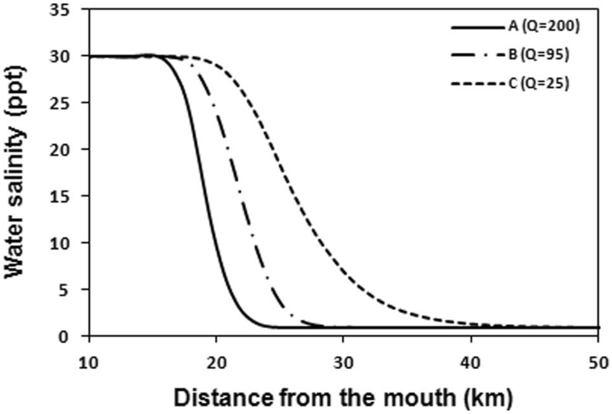


Fig. 4 Seawater extent during wet, normal and dry periods

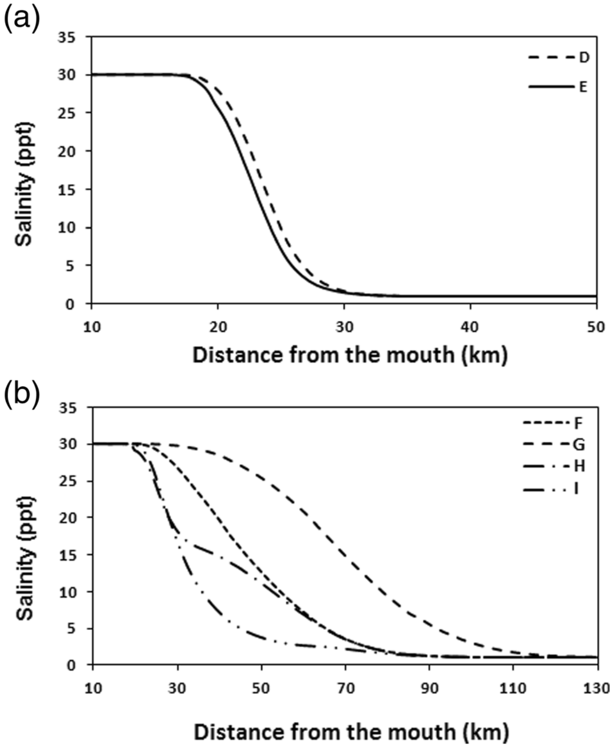


Fig. 5 The impact of the water consumption and return flow on the salt water extent, **a**) water consumption and drainage water under normal conditions of the river discharge, **b**) changing the river discharge and different location of the drainage water, at 18 and 60 km from the mouth in scenarios H and I respectively

case of consumption close to the river discharge. Salt intrusion length can reach up to 110 km when water withdrawal is 15 m^3/s higher than the river discharge. This situation frequently happens during dry periods, so not only decreasing the volume of water inflows has an effect on the salt intrusion, but also the water withdrawals along the SAR clearly exacerbate the problem. A considerable volume of water is leaving the system during flood periods of tidal cycles through several canals branched from both sides of the river. This, combined with water consumption, allows for further seawater intrusion.

To assess the impact of different effluent points, the location of the outfall of the drainage water was examined. Based on equal water consumption and river discharge scenario F, the impact from drainage water was investigated at two different locations. The first location was chosen in the salt intrusion domain H and the second one at the saline-fresh water interface point I. Draining water within the salt intrusion limit decreased salinity concentration without affecting the intrusion length (Fig. 5b). Compared to F, salinity concentrations decreased almost by half at the downstream part and then followed the same pattern at the upstream part, while the salt intrusion distance remains almost the same. The result of I shows that draining water at the salt intrusion limit reduced the salinity concentrations at the upstream part to the same levels as in the previous one and also reduced the salt intrusion length (Fig. 5b). Therefore, draining water at the saline-fresh water interface point can maintain both the concentration of salinity and the length of intrusion. Salinity concentrations and seawater extent will be mainly controlled by the water quality and quantity of the drainage water.

4.2 Managing Seasonal Variation

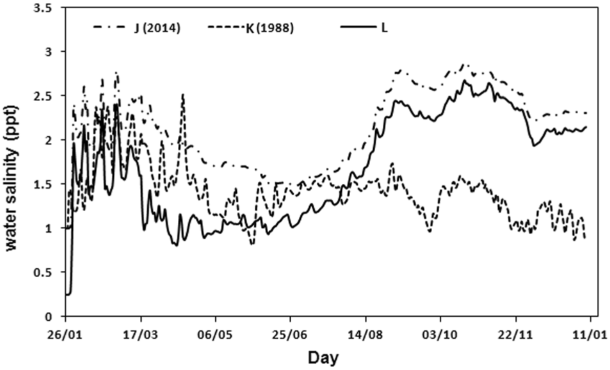
Fig. 6 presents the seasonal salinity distribution under changing river discharge at midcourse near the city of Basra. The impact of the upstream salinity and local return flows increased with decreasing water quantities over the simulation periods. The impact of the return flows increased further during the end of 2014 when river discharge was significantly reduced. To compare the improvement of using high river discharge or low salinity concentration on salinity changes, a lowest salinity level (0.25 ppt) recorded at S1 was used together with the river discharge of 2014 (scenario L). Generally, Fig. 6 shows a clear improvement over the entire year, and salinity found to decrease more during the February–July period where locally, drainage was relatively low, considering the volume of water flowing into the river. High river discharge during 1988 (average flow 200 m^3/s), compared to the year 2014 (55 m^3/s), reduced average salinity near Basra from 2.1 to 1.4 ppt. Using river discharge with average salinity of 0.25 ppt compared to 1 ppt during the year 2014 reduced salinity to 1.7 ppt. Based on the river flow conditions of 2014, increasing river discharge or decreasing its salinity concentrations four times each could reduce the salinity with 34% and 21% respectively.

5 Conclusion

For the first time, the longitudinal salinity variation caused by the combination of salinity sources along the SAR was simulated. The simulation was conducted by using a 1-D hydrodynamic and salt water intrusion numerical model. The model was calibrated and verified using hourly time-series of observed water level and salinity data of the year 2014. Subsequently, the model was used to analyse the effect of different water resources management scenarios on the water and salinity regimes in the SAR.

The analyses were performed with a fixed downstream boundary condition. However, different conditions were specified at the upstream and along the river. The longitudinal salinity distribution was investigated before and after major water developments, considering the tendency of the river discharge, classified into three distinct periods: wet, normal, and dry. The obtained results verify the high correlation between the river discharge and salt intrusion distance. Human interferences have changed the pattern of river flow and significantly reduced the freshwater discharge,

Fig. 6 Annual and seasonal impacts on salinity distribution near Basra city in the SAR middle course



resulting in deeper seawater intrusion landward. The seawater intruded upstream up to 24, 28, and 43 km during the wet, normal, and dry period, respectively.

Another set of simulation models were developed to investigate the quantitative changes of water flowing into the riverbed considering the water withdrawals and return flows. The model results show significant increases in the salt intrusion distance and salinity concentration along the estuary. Furthermore, extracting water which exceeded the river discharge allows for more volume of seawater to intrude landward, increasing the seawater intrusion. Discharging drainage water into the river, though with high salinity, could be used to counteract the seawater intrusion. The location of the outfall point affects both the distribution and extent of seawater. The optimal location is determined by several factors such as topography, drainage water quality, and the allowable distance of seawater intrusion.

Salinity changes due to the seasonal variation of river discharge was investigated using average monthly river discharges during period of high and low flows, in 1988 and 2014 respectively. The analysis shows that the drainage water combined with the influences of astronomical tides has notably increased the salinity profile during low flow conditions. Managing both upstream water quality and water quantity could mitigate salinity changes along the river but at different levels. Increasing the quantity of upstream releases is more effective in decreasing the salinity concentration along the SAR than improving its quality.

It can be concluded from the results that the salinity variation along the river is a result of combined factors; these are mainly upstream water quantity and quality, local water withdrawals and effluents of agricultural, industrial and domestic wastes, and seawater intrusion. The fact that the river is located in an arid region exacerbates the problem of salinity increments. Seawater only affects the lower portion, and seawater intrusion could only reach the maximum distance around 80 km corresponding to extremely low river discharge. The salinity of the upper portion is dominated by upstream influences and local conditions. The model presented in this study can support the ongoing management efforts describing the salinity variation along the SAR. The availability of further measured data of each salinity source, including salinity concentration, discharges, as well as current direction and velocity, could improve the predicting skill of the model.

References

Abdullah A, Karim U, Masih I, Popescu I, van der Zaag P (2016) Anthropogenic and tidal influences on salinity levels and variability of the Shatt al-Arab River, Basra, Iraq. International Journal of River Basin Management 14(3):357–366

Abdullah A, Masih I, Van der Zaag P, Karim U, Popescu I, Al Suhail Q (2015) The Shatt al Arab system under escalating pressure: a preliminary exploration of the issues and options for mitigation. International Journal of River Basin Management 13:215–227

Ajeel S, Abbas M (2012) Diversity of Cladocera of the Shatt al Arab River southern Iraq. Mesopot J Mar Sci 27: 126–139

Al-Meshleb N (2012) Systematic and ecological study of recent Ostracoda from al Faw town, south of Iraq. MesopotJ Mar Sci 27(2):88–103

Al-Saad HT, Farid WA, Al-Adhub AY (2011) Uptake and depuration of water-soluble fractions (WSF) of crude oil by the bivalve Carbicula fluminea (Muller) from Shatt al- Arab River. Mesopotamian Journal of Marine Science 26:134–145

Ayers S, Westcot W (1985) Water quality for agriculture, FAO irrigation and drainage paper 29 rev. 1. Food and agriculture Organization of the United Nations, Rome

Becker M, Luettich R, Mallin M (2010) Hydrodynamic behaviour of the cape fear river and estuarine: a synthesis and observational investigation of discharge-salinity intrusion relationships. Estuar Coast Shelf Sci 88:407–418

CUR (1993) Hydrology and water management of deltaic areas. Report 93–5, Ministry of transport, public works and water management, The Netherlands

El-Adawy A, Negm A, Elzeir M, Saavedra O, El-Shinnawy I, Nadaoka K (2013) Modeling the hydrodynamics and salinity of el-Burullus Lake (Nile Delta, northern Egypt). Journal of Clean Energy Technologies 1:157–163

Fernandez-Delgado C, Baldo F, Vilas C, Garcia-Gonzalez D, Cuesta J, Gonzalez-Ortegon E, Drake P (2007) Effects of the river discharge management on the nursery function of the Guadalquivir River estuary (SW Spain). Hydrobiologia 587:125–136

Hameed H, Aljorany Y (2011) Investigation on nutrient behavior along Shatt al-Arab River, Basra, Iraq. J Appl Sci Res 7:1340–1345

Jassby A, Kimmerer W, Monismith S, Armor C, Cloern J, Powell T, Schubel J, Vendlinski T (1995) Isohaline position as a habitat indicator for estuarine populations. Ecol Appl 5:272–289

Kirchner J, Moolman J, Du-Plessis H, Reynders A (1997) Causes and management of salinity in the Breede River valley, South Africa. Hydrogeol J 5:98–108

Lesser G, Roelvink J, Van Kester M, Stelling G (2004) Development and validation of a three-dimensional morphological model. Coast Eng 51:883–915

Maser M, Son M, Yasser A (2011) Assessing the risks of invasions of aquatic invertebrates in the Shatt al-Arab River. Russian Journal of Biological Invasions 2:120–125

Mohammed M (2011) Modified method for the determination of cobalt (II) and copper (II) ions by adopting Schiff base complexes in water of Shatt al Arab River. Mesopotamian Journal of Marine Science 26:170–181

Myakisheva N (1996) The influence of seasonal and year-to year variability of water discharge from the Lake Ladoga-Neva River system on the salinity regime of the Baltic Sea. Hydrobiologia 322:99–102

Nguyen A, Savenije H (2006) Salt intrusion in Multi-Channel estuaries: a case study in the Mekong Delta, Vietnam. Hydrol Earth Syst Sci 10:743–754

Peters N, Meybeck M (2000) Water quality degradation effects on freshwater availability: impact of human activities. International Water Resources Association, Water International 25:185–193

Quinn N (2011) Adaptive implementation of information Technology for Real-Time, basin-scale salinity Management in the san Joaquin Basin, USA and Hunter River basin, Australia. Agric Water Manag 98: 930–940

Rahi K, Halihan T (2010) Changes in the salinity of the Euphrates River system in Iraq. Reg Environ Chang 10: 27–35

Roos J, Pieterse A (1995) Salinity and dissolved substances in the Vaal River at Balkfontein, South Africa. Hydrobiologia 306:41–51

Shiati K (1991) A regional approach to salinity Management in River Basins, a case study in South Iran. Agric Water Manag 19:27–41

Thomas G, Jakeman A (1985) Management of Salinity in the river Murray Basin. Land Use Policy 2(2):87–101

UNEP (2001) The Mesopotamian marshlands: demise of an ecosystem, early warning and assessment technical report, UNEP/DEWA/TR.01-3 rev. 1 division of early warning and assessment United Nations environment Programme Nairobi, Kenya

Van Breemen M (2008) Salt intrusion in the Selangor estuary in Malaysia. MSc dissertation, University of Twente

Van den Heuvel S (2010) Modeling the hydrodynamics and salinity of the Pontchartrain Basin. MSc dissertation, Delft University of Technology

Van der Zaag P (2007) Asymmetry and equity in water resources management; critical institutional issues for southern Africa. Water Resour Manag 21:1993–2004

WHO (1996) Guidelines for drinking-water quality - second edition - volume 2 - health criteria and other supporting information. World Health Organization, Geneva