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Environmental impact of RO units installation in main water treatment plants of Basrah city/south of Iraq

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HIGHLIGHTS

- The impact of brine water discharge is clear in the upstream reach of the study area.
- When RO units have 85% recovery percent, the max TDS increase is 5.9 % that exceeds the allowed salinity limit.
- When RO units have 50% recovery percent of, the max TDS increase is 2.7% that is less than the allowed salinity limit.
- The TDS increase values vary over the range (8.8-226.3 mg/l) which are < 4ppt (the regulation criteria limit).

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ABSTRACT

The citizens of Basrah city are suffering from the problem of high salinity water supply. This problem is proposed to be solved by installing RO units in 16 water treatment plants of Basrah city. RO units produce high-salinity brine water. The aim of this study is to predict the environmental impact of RO units installation measured in terms of TDS increase of Shatt Al-Arab River water. The TDS increase was predicted using HEC-RAS software. The software was applied to simulate twelve cases of TDS distribution in water of Shatt Al-Arab River. During each of the twelve simulation cases, the proposed RO units were assumed to have recovery percent (RP) of 50% and 85%. The simulation results indicated that when the proposed RO units have RP of 85%, the max percentage of TDS increase is 5.9%. While, when the proposed RO units have RP of 50%, the max percentage of TDS is 2.7%. The comparison of these results with the regulation criteria of brine water discharge shows that; when the installed RO units have RP of 85%, the percentages of TDS increase will exceed the salinity limit of most regulation criteria (5%).

1. Introduction

In south of Iraq, Basrah city is depending on Shatt Al Arab River as a main source of water supply. Until the year 2006, this river received fresh water from three main sources; Tigris, Euphrates and Al Karun Rivers. However, now it is receiving fresh water from Tigris River only. The downstream end of Shatt Al Arab River is affecting by tide phenomenon from the north west of the Arabian Gulf. The decrease of fresh water flow causes the increase of salt intrusion into Shatt Al Arab River during tide period, which led to increase the salinity level of its water. In addition, Basrah city is supplying with potable water of low salinity by Sweet Water Canal (SWC). The SWC has suffered numerous failures since it was commissioned and requires continuous maintenance and monitoring. Several long sections of the canal embankment are structurally unstable, resulting in steadily worsening performance and an increasing rate of failure [1].

All the above circumstances led to supply Basrah city citizens with high salinity water. Many workshops have held in Basrah city to put solutions to the problem of high salinity water supply. One of these workshops was held on 15–16/Feb./2014, which is titled "Basrah Water Crises and Shatt Al Arab Salinity Increase: Measures to Control". During the workshop, a paper was submitted titled "Practical Solutions for Water Supply Problem of Basrah City". The paper suggested the installation of reverse osmosis (RO) units in main water treatment plants of Basrah City to desalinate their product water and subsequently enhance the quality of water supply. After the submission of this paper, a question was asked about the environmental impact of RO units installation on water salinity of Shatt Al Arab River. This question is behind the performance of this study and its results will give the answer.

Desalination process cannot be accomplished without environmental and ecological inferences [2]. There are many environmental impacts depending on type of the applied desalination technology, such as

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energy consumption, land use, produced the emission of regular fuel combustion products, and discharge brine during regular operation. The most important environmental impact produced by desalination plants is the discharge of brine water [3,4,5]. The characteristics of reject brine water depend on feed water quality, type and recovery percent of desalination process and the chemical additives used [6]. Brine water might adversely affect water and sediment quality, reduce biodiversity, impairs marine biota or the vital functions of coastal ecosystems [7].

An increased awareness of the environmental impact of discharging the brine water of desalination plants into the surface waters has prompted environmental studies in existing plants as well as increased attention to this issue in both the design and siting of new plants and plants now in the planning stage [8]. Generally, the first paper to note that the brine and chemical discharges from desalination plants may impair the marine environment probably appeared in 1979 (cited in [9]). However, it took until the 1990s before the scientific interest in the marine environmental concerns of desalination plants became more pronounced, as reflected in the large published number of studies. Examples of these studies include those conducted by; Höpner and Windelberg [10], Morton et al. [11], Oldfield and Todd [12], Höpner and Lattemann [13], El-Samanoudi et al. [14], El-Gamal and Abdrabbo [5], Elabbar and Elmabrouk [8], Medeazza [15], Tularam and Ilahee [16], Lattemann and Höpner [7,17], Münk [18], Abo Qdais [19], Fernández-Torquemada et al. [20], Al-Dousari [21], Dupavillon and Gillanders [2], Ahmed and Anwar [22], Dawoud and Al Mulla [23], Darwish et al. [24], Naser [25], Fernández-Torquemada et al. [26] and Hu [6]. The review of these studies shows that; most of them either examined and compared the environmental impacts of MSF and RO desalination processes or conducted by collecting field data from existing desalination plants.

With regard to the use of modeling techniques (which is the tool used in this study) in studying the environmental impact of desalination plants, the review of previous studies shows that there are three commercial numerical softwares (CORMIX, VISUAL PLUMES, and VISJET) for modeling brine jet discharge. Palomar et al. [27] analyzed and validated these softwares and indicated that they are limited to near field region modeling and CORMIX is a steady-state model. In addition, Purnama et al. [28] developed a one-dimensional tidally averaged mathematical model to assess the impact of seawater desalination plants on water salinity of the Arabian Gulf and the Red Sea. They modeled each of the Arabian Gulf and the Red Sea as a semi-enclosed sea with simple depth topography, parabolic cross sections, and its valley bottom is uniformly descending. Also, Al-Barwani and Purnama [29] developed a model to simulate the long-time (or far field) brine plumes steadily discharged into the seawaters using a two-dimensional advection-diffusion equation. The model considered the effect of a tidally oscillating flow on the long-time brine plume assuming a highly simplified vertical beach profile, and vertically well-mixed (over the water depth) brine plume.

2. Regulatory criteria for brine water discharge

Brine water discharge alternatives include [5]; surface water discharge, disposal to sewage treatment plants, deep well disposal, land applications, evaporation ponds and brine concentrators. Surface water discharge is the most used brine disposal method. Since the most direct waste product of desalination plants is the concentrated salt brine discharge, all the regulatory criteria of surface water discharge are concerning the impact of increasing the salinity of the receiving stream. Jenkins et al. [30] reviewed the regulations or guidelines for brine discharges around the world as listed in Table 1.

Table 1 shows the variation in the putting regulations, however, nearly all have two common elements; a salinity limit and a boundary of mixing zone. The salinity limit is defined as an increment of no more than 1 to 4 ppt or 5% percent relative to ambient.

3. Overview on Basrah City water supply system

Basrah governorate is supplied with water by 37 main water treatment plants (WTPs), out of which 20 WTPs are located in Basrah city and its surrounding area, to which the raw water is fed from Shatt Al Arab River and SWC. The rest is located outside of Basrah city. Table 2 shows the source of water and the design capacity of Basrah city WTPs and Fig. 1 shows their locations.

All of the WTPs of Basrah city apply conventional water treatment processes which include; pretreatment, chemical coagulation, rapid mixing, flocculation, sedimentation, filtration and disinfection. Thus, these WTPs are not provided with facilities for reducing the TDS of water. To highlight the problem of high TDS water produced by WTPs in Basrah city, the readings of TDS in treated water were analyzed for the number of readings that satisfy the Iraqi standards for drinking water (max. TDS of 1000 mg/l). These readings were monthly taken during the years (2011–2014) by the staff of Central Laboratory of Water Analysis/ Basrah Water Administration. The results of analysis shows that; 735 out of 4477 readings satisfy the Iraqi standards and the max TDS of water supply in Basrah city is 9400 mg/l. These results indicate the urgent need for installing desalination units in WTPs of Basrah city.

Table 2 shows that WTPs No. 17, 18, 19 and 20 (indicated with yellow color in Fig. 1) are receiving water from SWC only. When the available raw water from the SWC is reduced, the water is conveyed to these WTPs as a priority and the other plants use the water of Shatt Al Arab River. Therefore, the water of these treatment plants has low TDS and there is no need for installing RO units in them. Thus, these WTPs shall not be considered in this study, i.e., the RO units are proposed to be installed in WTPs No. 1 through 16.

4. Water desalination using reverse osmosis

RO process is used to produce freshwater by removing dissolved salts from seawater and brackish water, helping to overcome the problem of freshwater shortage. RO plant consists of pre-treatment, high-pressure pump units and membranes, Fig. 2. The membranes are set in series within a pressure vessel. A pretreatment must be provide for feed water in order to remove inorganic solids and suspended solid, and for save the membranes from damage and fouling. The process starts by pumping the feed water (brackish water or seawater) under the forces of a pressure head that exceeds the osmotic pressure of the solution through the pressure vessel. As shown in Fig. 2, the fresh water permeates through the membranes, while, the brine water (high concentrated solution) is left behind [17]. The main design parameters of RO plants are; recovery percent, feed and osmotic pressures.

Table 1
Regulations for selected desalination brine discharges [30].

Region/authority	Salinity limit
US EPA	
Increment ≤ 4 ppt	
Carlsbad, California	
Absolute ≤ 40 ppt	
Huntington Beach, California	
Absolute ≤ 40 ppt	
Western Australia guidelines	Increment < 5%
Oakajee Port, Western Australia	
Increment ≤ 1 ppt	
Sydney, Australia	
Increment ≤ 1 ppt	
Gold Coast, Australia	
Increment ≤ 2 ppt	
Okinawa, Japan	
Increment ≤ 1 ppt	
Abu Dhabi	Increment ≤ 5%

Table 2
Water source and capacity of main WTPs in Basrah City.

WTP no.	WTP name	Water source	Design capacity (m^3/day)
1	Al Hartha 25	Shatt Al Arab and SWC	120,000
2	Basrah Unified	Shatt Al Arab and SWC	96,000
3	Garma - 1	Garmat Ali and SWC	38,400
4	Garma - 2	Garmat Ali and SWC	8400
5	Al Maqil	Shatt Al Arab and SWC	13,500
6	Al Maqil-1	Shatt Al Arab and SWC	14,400
7	Jubaila Old	Shatt Al Arab and SWC	24,000
8	Jubaila - 2 CU	Shatt Al Arab and SWC	24,000
9	Ribat CU	Shatt Al Arab and SWC	14,400
10	Brad'ia - 1	Shatt Al Arab and SWC	24,000
11	Brad'ia - 2	Shatt Al Arab and SWC	24,000
12	Brad'ia - 3 CU	Shatt Al Arab and SWC	4800
13	Shatt Al Arab Old	Shatt Al Arab and SWC	24,000
14	Shatt Al Arab CU	Shatt Al Arab and SWC	9600
15	Abu Al Khasseb UP	Shatt Al Arab and SWC	14,400
16	Abu Al Khasseb CU	Shatt Al Arab and SWC	19,200
17	R-Zero	SWC	120,000
18	Al-Shauaiba Old	SWC	19,200
19	Al-Shauaiba CU	SWC	19,200
20	Khor Al Zubair UP	SWC	19,200

The recovery percent (RP) of the RO system is calculated as;

$$RP = \frac{Q_P}{Q_f} \times 100 \tag{1}$$

where; Q_p and Q_f are the flowrates of product water and feed water, respectively. The flowrate of brine water (Q_b) is obtained as [31];

$$Q_b = (1 - \mathrm{RP}/100) \times Q_f \tag{2}$$

The concentration of total dissolved solids (TDS) in the brine water is obtained as [31];

$$\mathrm{TDS}_b = \mathrm{CF} \times \mathrm{TDS}_f \tag{3}$$

where TDS_b and TDS_f are the TDS values of brine water and feed water, respectively, and CF is the concentration factor which is defined as [31];

$$CF = 100/(100 - RP) \tag{4}$$

5. Methodology

In this study, HEC-RAS (Hydrologic Engineering Centers-River Analysis System) software was used to study the impact of discharging brine water from the proposed RO units on salinity distribution (measured in terms of TDS) in water of Shatt Al Arab River. HEC-RAS is an open access software includes four one-dimensional river analysis models for simulating; (1) steady flow, (2) unsteady flow, (3) sediment transport, and (4) water quality.

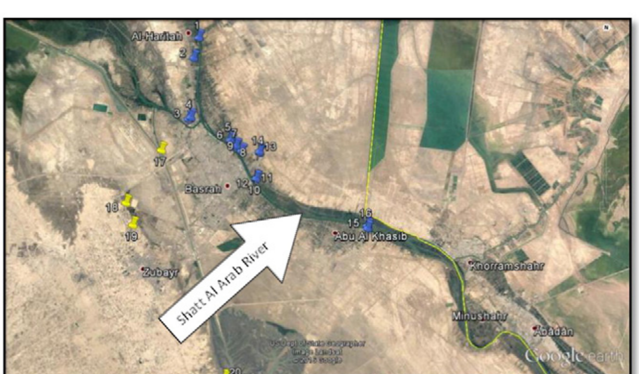


Fig. 1. Locations of main WTPs in Basrah city.

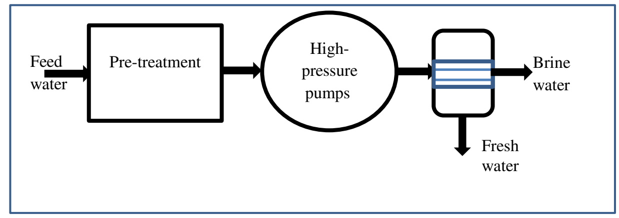


Fig. 2. Schematic diagram of RO process.

In order to apply HEC-RAS software to simulate TDS distribution in water of Shatt Al Arab River, it is necessary to run the water quality model. This model requires the input of unsteady flow field of the study area. Thus, the unsteady flow model was run, at first, to simulate the unsteady flow of this river. Then, the results of this model were used as inputs to run the water quality model. This section describes the applications of these two models to simulate the unsteady flow and TDS distribution in Shatt Al Arab River.

5.1. Modeling of Shatt Al Arab River flow

The data required to model the unsteady flow of Shatt Al Arab River applying HEC-RAC software are those necessary for specifying the geometry of the study area and boundary and initial conditions.

5.1.1. Geometry of the study area

The following steps specified the geometry of the study area:

1. Draw of a schematic diagram of Shatt Al River reach. The considered reach has a length of about 147 km starts from Al-Hartha city and ends at Al-Fao city as highlighted by red color in Fig. 3.
2. Define the bathometry of the study area using data of 32 cross sections along the river reach. These sections are ordered in the reach from highest river station upstream (section No. 32, Al Hartha city) to lowest river station downstream (section No. 1, Al Fao city), Fig. 3. The data of each cross section includes; cross section coordinates, downstream reach length, Manning's roughness coefficient (n) values (constant n value of 0.03 was used for all the cross sections) and main channel bank stations. However, after running the flow model, a warning appears if the specified cross sections in geometric data are not sufficient (the distance between the specified sections is too large). The warning message is combined with a request for adding new cross sections and can be ended by specifying more cross sections by interpolation. After adding the adequate cross sections, the final number of cross sections becomes 1465 (including the basic 32 sections) and the distance between two successive sections varies over the range from 79.0–178.5 m.

Fig. 3. Shatt Al-Arab River and cross sections distribution.

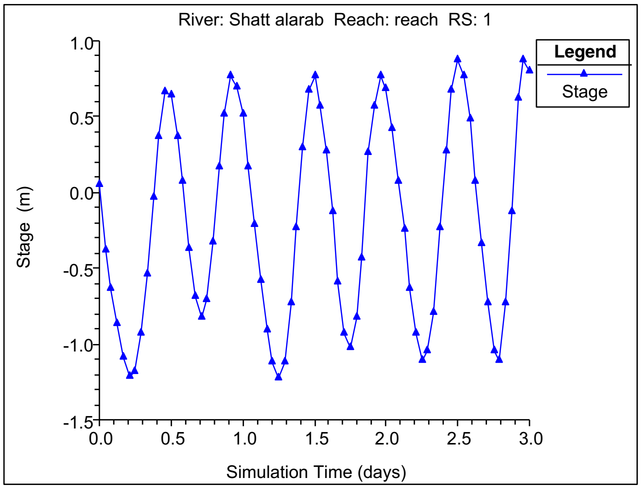


Fig. 4. Stage hydrograph for flow simulation Cases-1 & 2.

5.1.2. Boundary conditions

The unsteady flow of the study area was simulated for two statuses; (1) the absence of brine water discharges (the current status of Shatt Al Arab River) and (2) the present of brine water discharges (the proposed status after the installation of RO units). In both statuses, all the lateral branches of Shatt Al Arab River have been neglected. For simulating the current status of Shatt Al Arab River flow, the applied boundary conditions include flow hydrograph at the upstream boundary of the study area (section No. 32) and stage hydrograph at the downstream boundary (section No. 1). The flow hydrograph was developed assuming steady flowrate at the upstream boundary of the study area. This flowrate equals to the flowrate of Tigris River. Basrah Water Resources Administration measures the flowrate of Tigris River periodically at the border of Basrah city. The records of Tigris River flowrate were obtained for the years 2009 through 2014 and they were found to be varied over the range (9–97.4) m^3/s. Thus, the flow in Shatt Al Arab River was simulated applying the minimum and maximum discharge values of Tigris River; 9.0 and 97.4 m^3/s. The stage hydrograph was developed using unsteady tide levels at the downstream boundary of the study area. The tide data (levels of high and low tides) have been obtained from the tide tables published by the General Company for Ports of Iraq in Basrah for the year 2014. Generally, four cases were considered for simulating the unsteady flow of Shatt Al Arab River. The applied boundary conditions for these four cases are shown in Table 3.

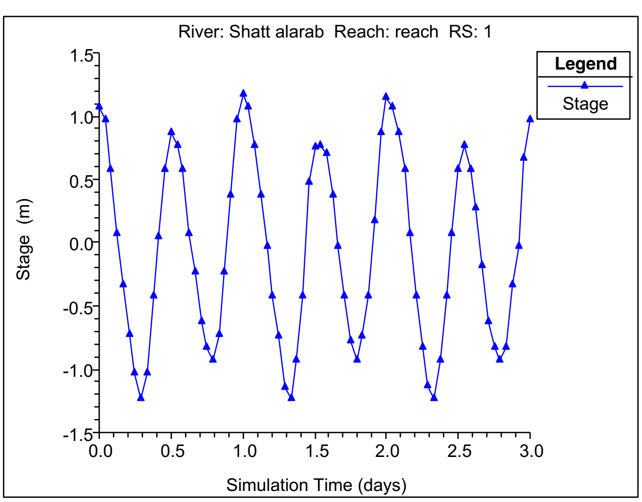


Fig. 5. Stage hydrograph for flow simulation Cases-3 & 4.

Fig. 6. Locations of field measurement stations along the study area.

For simulating the proposed status of unsteady flow in Shatt Al Arab River after the installation of RO units, additional boundary conditions were specified at the locations of point sources of brine water discharge (the considered WTPs). The additional boundary conditions include specification of lateral inflow hydrograph at brine discharge points. The lateral inflow of each point is the steady flowrate of produced brine water (assuming that the WTPs work continuously at constant rates). As was shown in Eq. (2), the flowrate of brine water is dependent on feed water flowrate and recovery percent (RP). It was found, from the literature review, that the RP of brackish water RO desalination plants might reach a value of 90%. In this study, the environmental impact of brine water discharges has been simulated applying RP values of 50% and 85%. The distances of the 16 brine water point sources measured from section No. 1 and the applied lateral inflow values for 50% and 85% recovery percentages are shown in Table 4. The lateral inflow values were calculated using Eq. (2) with adopting RO feed flowrates equal to the design capacities of the considered WTPs as given in Table 2.

5.1.3. Initial conditions

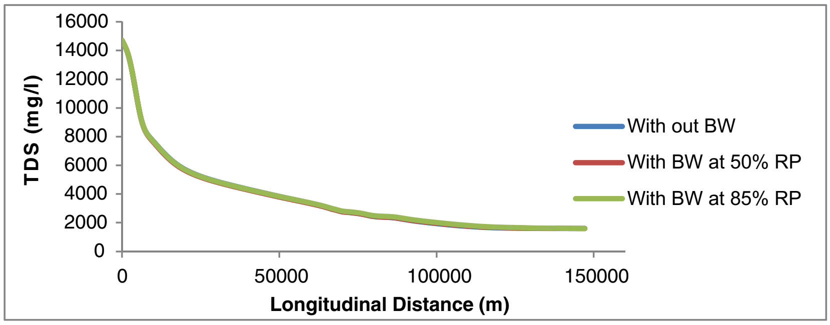
Initial conditions must be established at the start of unsteady flow simulation. They can be specified at any cross section of the river reach, but at least, they must be input at the upper end of the reach. In this study, the initial condition was specified at the upstream section of the study area (section No. 32) to be 9 m^3/s for Cases-1 and 3 and 97.4 m^3/s for Cases-2 and 4.

5.2. Modeling of Shatt Al Arab River water quality

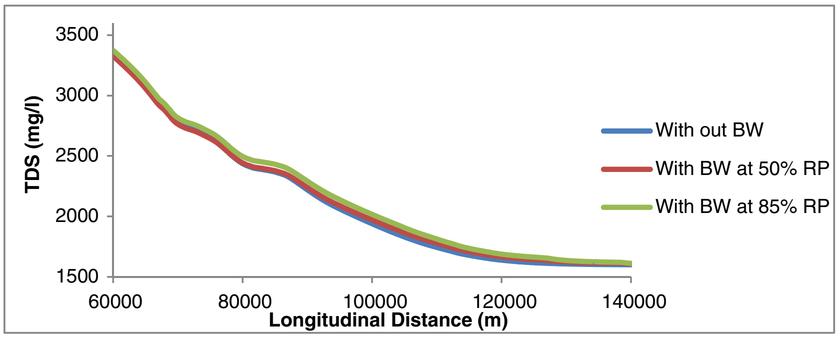
The water quality model of HEC-RAS software is capable of simulating water quality of rivers considering the one-dimensional distribution of different conservative and non-conservative constituents. It uses explicit numerical scheme to solve the one-dimensional advection-dispersion equation [32]. As in unsteady flow simulation, the water quality model has been applied to simulate TDS distribution in water of Shatt Al Arab River considering two statuses; (1) the absence of brine water discharges and (2) the present of brine water discharges. In both statuses, the run of water quality model requires the specification of flow velocity field, dispersion coefficient and boundary and initial conditions. The flow velocity field is specified using the results of flow model application on the study area and the adopted value of dispersion coefficient is 100 m^2/s.

5.2.1. Boundary conditions

A time series boundary condition must be specified for the considered constitute at all locations where flow enter the system including



(a) The whole reach of the study area

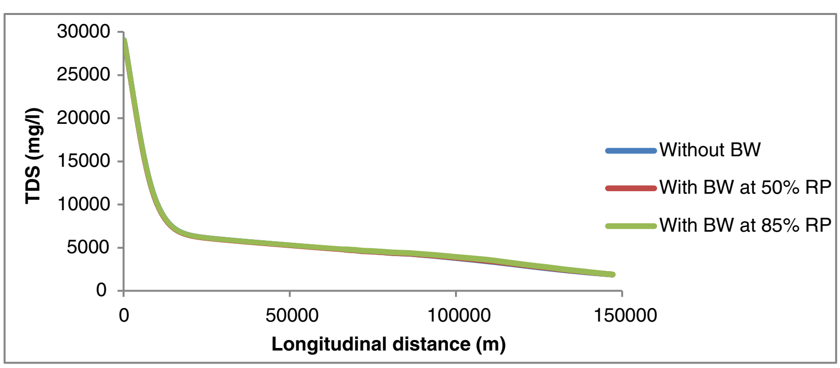


(b) The reach extends from km 60 to km 140 of the study area

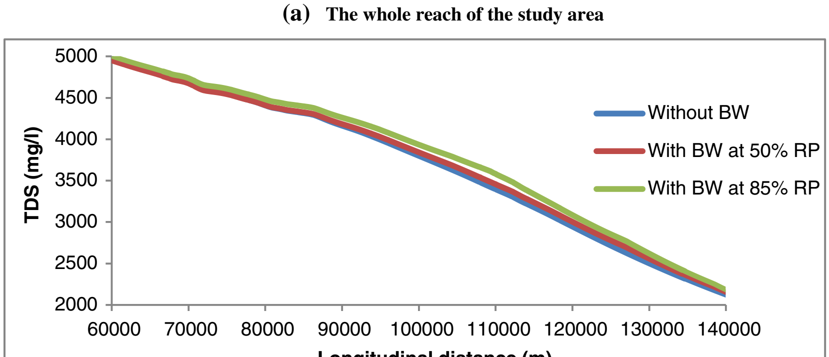
Fig. 7. Effect of BW discharge on TDS distribution in Shatt Al Arab River during HT of Case-2A.

upstream and downstream boundaries of the river and its lateral inflows. In this study, the applied boundary conditions include:

1. *Temporal varied TDS data*: This boundary condition was applied at the downstream boundary of the study area (section No. 1) where TDS value is time dependent due to tide effect. It was adopted during the simulation of TDS distribution in water of Shatt Al Arab River with and without the presence of brine water discharges.
2. *Constant TDS value:* This boundary condition was applied at the upstream boundary of the study area (section No. 32) and all internal cross sections where brine water discharge points are specified.



(a) The whole reach of the study area



(b) The reach extends from km 60 to km 140 of the study area

Fig. 8. Effect of BW discharge on TDS distribution in Shatt Al Arab River during LT of Case-3C.

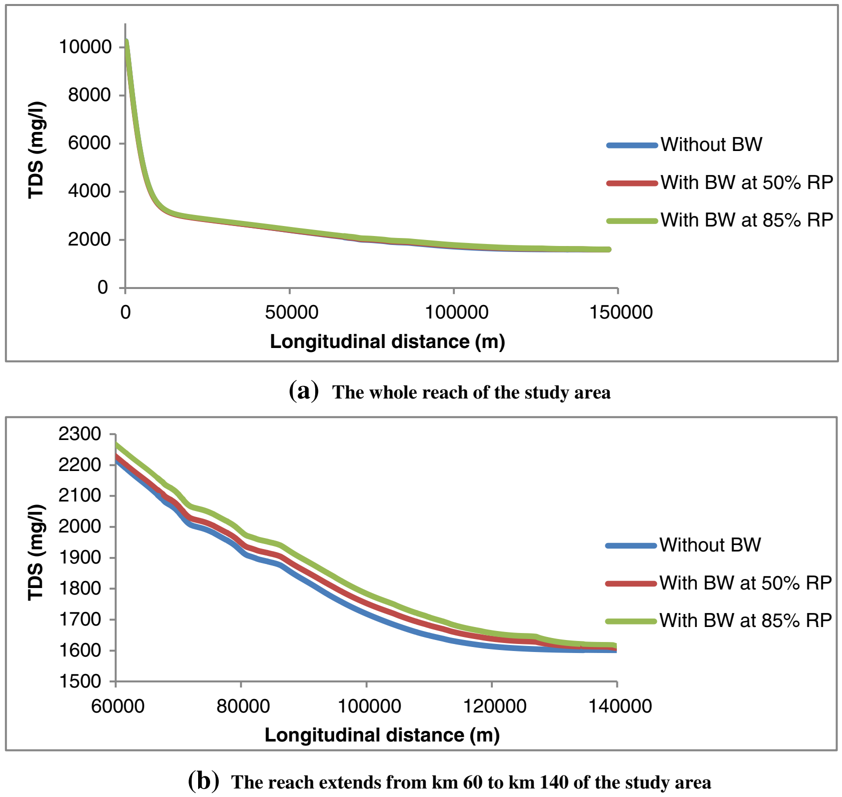


Fig. 9. Effect of BW discharge on TDS distribution in Shatt Al Arab River during LT of Case-4A.

However, the boundary conditions at the internal cross sections are applied to simulate the status of brine water discharges. Generally, for each flow simulation case, the water quality model has been run to simulate TDS distribution in water of Shatt Al Arab River considering three simulation cases; A, B and C. The applied boundary conditions at the upstream the study area is constant TDS value of 1600, 506, and 1890 mg/l for Cases A, B and C, respectively. These TDS values were selected from field measurements conducted at the corresponding location by Basrah Environment Administration and Water Resources Administration in Basrah during the years 2009 through 2014. The TDS of brine water has been determined adopting the following procedure:

a. Run of the flow model to simulate the flow of Shatt Al Arab River during a period of four days and for the status of the absence of brine water discharges.
b. Run of water quality model using the results of flow model.
c. Specification of maximum TDS of Shatt Al Arab water at the locations of brine water discharges.

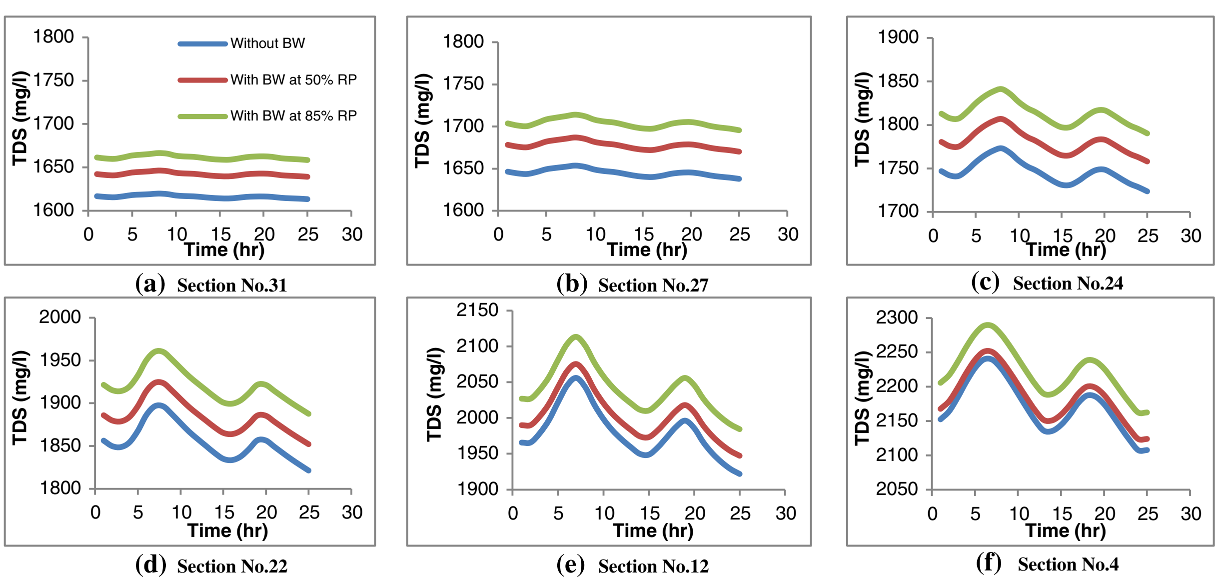


Fig. 10. Effect of BW discharge on temporal variation of TDS in 6 sections along Shatt Al Arab River during Case-4A.

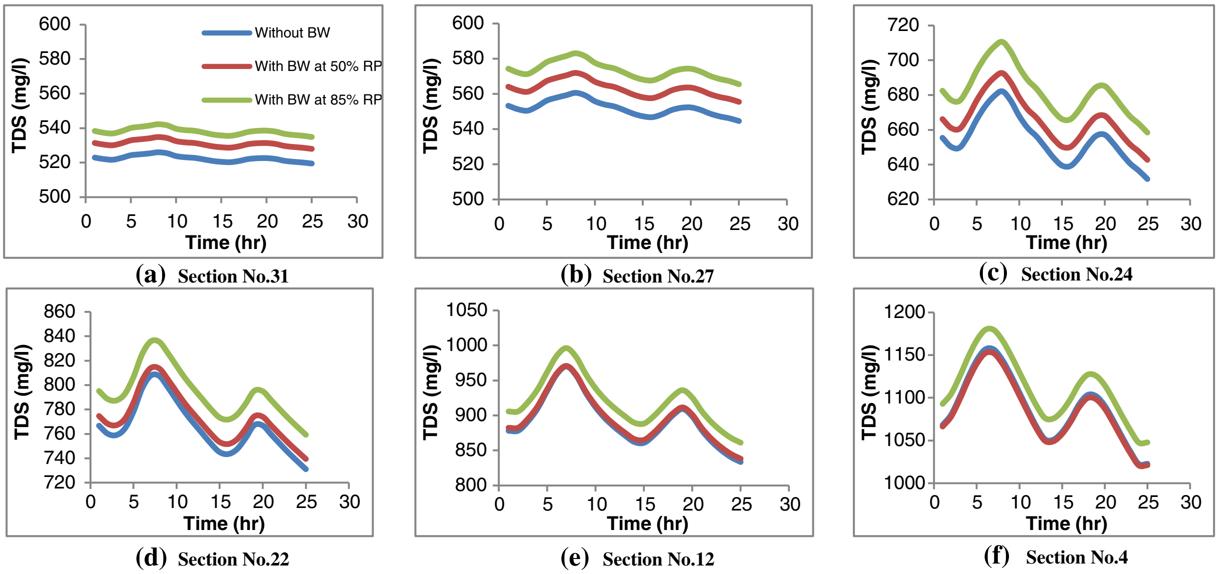


Fig. 11. Effect of BW discharge on temporal variation of TDS in 6 sections along Shatt Al Arab River during Case-4B.

d. Put of feed water TDS of each WTP equals to the maximum TDS value of Shatt Al Arab River water at the corresponding location during the considered flow and TDS distribution cases.
e. Determination of brine water TDS using Eq. (3)

5.2.2. Initial conditions

The water quality model of HEC-RAS software requires the input of at least one initial condition value for simulating the distribution of any constituent. It, then, generates a table of initial conditions at all water quality computational points by interpolation. In this study, for the first run of water quality model, the initial TDS values were specified at the upstream and downstream boundaries (section Nos. 32 and 1) as shown in Table 4. While, for the subsequent run, the obtained results of TDS values at the last time step of the first run were applied as initial conditions. In Table 5, the first notation in case number denotes the flow simulation case, i.e., Case No. 1A denotes the TDS simulation case when flow condition of Case-1 and TDS boundary conditions of Case-A are applied.

6. Results and discussion

Two models of HEC-RAS software; flow and water quality models were applied on Shatt Al Arab River. The results of the flow model are used as input data to run the water quality model. The water quality model was applied on the study area to assess the environmental impact of installing RO units in 16 main WTPs of Basrah city. The environmental impact was assessed by studying the impact of discharging high TDS brine water on TDS of Shatt Al Arab water. This section presents the results of flow and water quality models validation. It, also, presents the results of environmental impact assessment of RO units installation.

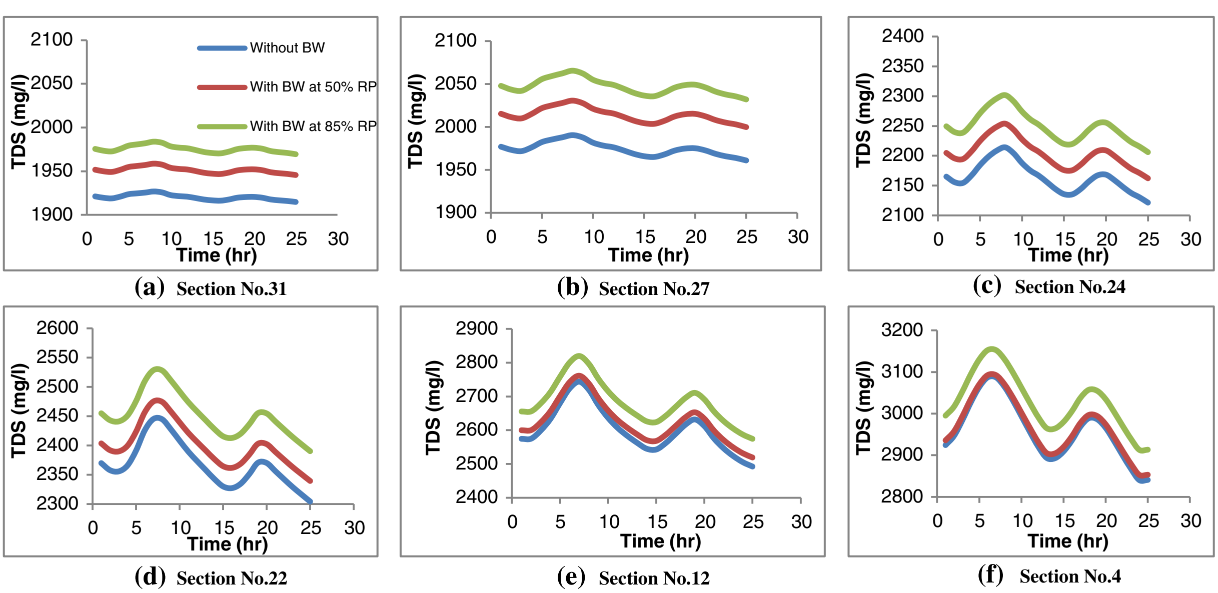


Fig. 12. Effect of BW discharge on temporal variation of TDS in 6 sections along Shatt Al Arab River during Case-4C.

Table 3
Boundary conditions for unsteady flow simulation cases.

Case no.	Boundary conditions	
	Upstream	Downstream
1	Steady flow hydrograph of 9.0 m^3/s	Stage hydrograph of unsteady tide level as shown in Fig. 4
2	Steady flow hydrograph of 97.4 m^3/s	
3	Steady flow hydrograph of 9.0 m^3/s	Stage hydrograph of unsteady tide level as shown in Fig. 5
4	Steady flow hydrograph of 97.4 m^3/s	

6.1. Flow model validation

To validate the results of flow model, the computed values of flow velocity were compared with those measured at a section located at the mouth of Umm Al Rasas Island in Shatt Al Arab River. This island is located at 35 km south of Basrah city. The flow velocity was measured by Al-Whaely et al. [33]. The comparison results are shown in Table 6. From this table, it can be noticed that the range of computed flow velocities during the four simulation cases is (0.23–0.34) m/s which is in good agreement with that of the measured values (0.25–0.32) m/s.

In addition, the computed flowrates of the four simulation cases were compared with measured ones. The flowrates were measured by Al-Maliky [34] at three stations (Nos. 1, 2 and 3) along Shatt Al Arab River. The distances of station Nos. 1, 2 and 3 measured from Al Fao city, are 10, 60 and 120 km, respectively. Table 7 shows the comparison results. From this table, it can be noticed that the computed flowrates of the four cases at the three stations are within the ranges of the measured ones.

6.2. Water quality model validation

The water quality model was validated by comparing its results with field measurements of TDS. The model results include the temporal varied TDS distributions which were obtained by running the 12 simulation cases; 1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B, 3C, 4A, 4B and 4C without the existence of brine water discharges. The field values of TDS were measured by Al-Maliky [35] and the crew of Water Resources Administration. Al-Maliky measured the TDS at station Nos. 1, 2, 3 and 4 and the crew of Water Resources Administration measured the TDS at station Nos. 5, 6, 7 and 8. The locations of these stations along Shatt Al Arab River are shown in Fig. 6.

Table 4
Lateral inflows of brine water discharge points.

Point source no.	Distance from downstream (m)	Section no.	Lateral inflow (m^3/s) at RP	
			50%	85%
1	138,535.7	31.7028*	0.69	0.21
2	127,135.7	31.3088*	0.56	0.17
3	127,035.7	31.3054*	0.22	0.07
4	126,935.7	31.3019*	0.05	0.01
5	118,335.7	31.0048*	0.08	0.02
6	118,196.6	31	0.08	0.03
7	113,058.6	29.1071*	0.14	0.04
8	112,950.4	29	0.14	0.04
9	109,520.4	26.7365*	0.08	0.03
10	109,420.4	26.6706*	0.14	0.04
11	109,320.4	26.6047*	0.06	0.02
12	104,509.4	24.7177*	0.14	0.04
13	104,409.4	24.7094*	0.14	0.04
14	104,309.4	24.7011*	0.03	0.01
15	94,862.39	23.5551*	0.08	0.03
16	94,762.39	23.5106*	0.11	0.03

Table 5
Initial conditions for TDS distribution simulation cases (Without brine water discharges).

Case no.	TDS (mg/l)	
	Upstream	Downstream
1A and 2A	1600	8000
1B and 2B	506	7600
1C and 2C	1890	21,000
3A and 4A	1600	7000
3B and 4B	506	6000
3C and 4C	1890	12,000

For each simulation case, the min and max values of temporal varied TDS where obtained at the location of each measurement station. Then, the range of calculated TDS values at each station was obtained from the min and max values of all the simulation cases. This TDS range was compared with the range of measured TDS at the corresponding station. The comparison results are shown in Table 8. This table shows that the calculated TDS values at station Nos. 2, 5, 6 and 7 are within the measured ranges. While, the min calculated TDS values at station Nos. 1, 3, 4 and 8 are lower than the corresponding measured ones. Also, the max calculated TDS value at station No. 4 is greater than the corresponding measured one. The differences between the measured and calculated TDS values are attributed to; (1) the applied boundary conditions which differ from those actually occurred during the performance of field measurements and (2) the simplifications adopted during the applications of both flow and water quality models, such as neglecting the lateral branches of Shatt Al Arab River. However, for the aim of studying the environmental impact of installing RO units in main WTPs of Basrah city, the water quality model results are thought to be accepted.

6.3. TDS distribution in Shatt Al Arab water

For all the simulation cases (12 cases), the results of TDS distribution in water of Shatt Al Arab River without the existence of BW, with the existence of BW at 50% RP and with the existence of BW at 85% RP during low and high tide times were plotted to study the impact of BW discharges. Herein, examples of these plots are shown for Case-2A at high tide (HT), Case-3C at low tide (LT) and Case-4A at LT in Figs. 7, 8 and 9, respectively. In each of these figures, the TDS longitudinal distribution in the study area is shown for the whole reach and for a reach extends from km 60 to km 140 of the study area. From these figures and when the TDS distribution is plotted for the whole reach of Shatt Al Arab River, the TDS distributions without the existence of BW discharges cannot be distinguished from those with the existence of BW discharges. While, when the TDS distribution is plotted for a reach of the study area extending from km 60 to km 140, the effect of BW discharge on TDS distribution appears. Where it can be noticed that the TDS of Shatt Al Arab water increases when BW is discharged and if the installed RO units are of 85% RP, the increase of TDS values will be greater than that obtained when the installed RO units are of 50% RP. The effect of BW discharge appears in the specified reach of the study area because the locations of all the considered WTPs are distributed between km 97.76 and km 138.54.

Table 6
Comparison of computed and measured flow velocities at the mouth of Umm Al Rasas Island.

Cases no.	Flow velocity (m/s)	
	Min	Max
1	0.23	0.30
2	0.24	0.28
3	0.24	0.34
4	0.26	0.32
Measured [33]	0.25	0.32

Table 7
Comparison of computed and measured flowrates at 3 stations in Shatt Al Arab River.

Station no.	Flowrates range (m^3/s)				
	Computed				Measured
	Case-1	Case-2	Case-3	Case-4	
1	2368.4–3057.8	2415.3–2992.6	2604.6–3256.5	2640–3204.1	1126–3347.9
2	1027–1254.2	1092.4–1194.8	1132.3–1357.2	1200.3–1265.6	413.7–2820.6
3	518.9–598.8	553.4–573.6	481.0–645.2	571.42–577.9	479.3–1061.7

For illustrating the effect of BW discharges on TDS of Shatt Al Arab River water, the results of TDS temporal variation during simulation Cases-4A, 4B and 4C have been plotted at six sections (section Nos. 31, 27, 24, 22, 12 and 4) along this river. These sections are located at distances of 118,199, 110,002, 95,865, 86,174, 73,210 and 61,539 m, respectively, from the downstream boundary of the study area (Section No. 1). The TDS temporal variation results of Cases-4A, 4B and 4C are shown in Figs. 10 through 12, respectively. In these figures, the blue, red and green lines represent the absence of BW discharge, the existence of BW discharge at RP of 50% and the existence of BW discharge at RP of 85%, respectively.

Figs. 10 through 12 show that the BW discharges increase the TDS of Shatt Al Arab water. This impact differs along the study area due to the interactions of; tide effect, location of WTPs and flowrate and TDS of brine water. For example, if Fig. 10 is considered, it can be noticed that the TDS values at any section varies with time due to tide effect; increase during flood period and decrease during ebb period. This variation reduces towards the upstream end of the study area due to the reduction of tidal range. At specific hour, the TDS increases in any section with the existence of BW discharge and the increase at 85% RP is greater than that at 50% RP.

From the results of Figs. 10 through 12 and for each simulation case, the values of max and min TDS with and without the existence of BW discharges were obtained. From these values it was found that during Case-4A, the max TDS value at Section No. 31 increases from 1619.7 to 1646.3 (with BW at 50% RP) and to 1666.5 (with BW at 85% RP). Thus, the percentages of TDS increase are 1.64 and 2.89% for BW at 50 and 85%, respectively. While, the percentages of TDS increase at Section No. 4 are 0.50 and 2.19% for BW at 50 and 85%, respectively. I.e., the TDS increase near the upstream end of the study area is greater than that near the downstream end of the study area. That can be referred to; (1) the flowrate of Shatt Al Arab River increases towards the downstream end, thus, the impact of BW is inhibited by the high dilution of flowing water and (2) all the considered WTPs are distributed between km 97.76 and km 138.54, i.e., near the upstream end of the study area.

6.4. Environmental impact assessment of brine water discharge

The environmental impact of RO units installation in 16 main WTPs of Basrah city is assessed in terms of max percentage of TDS increase due to brine water discharges from the proposed units. This percent was calculated at LT and HT times of each simulation case considering 50 and 85% RP. The obtained max percentages of TDS increase along with their occurrence section numbers are listed in Table 9. In this table, the notation 1A50, as an example, denotes Case-1A with considering the installation of RO units have RP of 50% in all the considered water treatment plants. Table 9 shows the followings:

1. During all the simulation cases, the max percentages of TDS increase occur at sections number distributed between 23.6928* and 31.3088*. This can be attributed to the locations of brine water discharge sources (WTPs location) which are distributed between section No. 23.5106* and section No. 31.7028*, see Table 4. Thus, their combined impact on increasing the TDS of Shatt Al Arab water will be significant in this reach.
2. The highest max percentage of TDS increase in Shatt Al Arab River water is 5.9%. This percent occurs at section No. 26.6047* during simulation Case-3C85 at HT time. That is because Case-3C85 is characterized by;
   a. min flowrate of Tigris River at the upstream boundary of the study area which is 9.0 m^3/s,
   b. max tidal range at the downstream boundary of the study area,
   c. high TDS values at both upstream and downstream boundaries of the study area, and
   d. high TDS values of the discharged brine waters.
3. When the installed RO units have RP of 50%, the results of all simulation cases give max percentages of TDS increase vary over the range (1.6–2.7%). With referring to Table 1, which listed the regulations concerning the allowed limits of brine water TDS, it can be shown that the max allowed salinity increase percentage is 5%. Thus, the max percentages of TDS increase in water of Shatt Al Arab River if RO units are of 50% shall be below the allowed limit.
4. When the installed RO units have RP of 85%, the max percentages of TDS increase during simulation Case Nos. 1A, 1B, 1C, 3A, 3B and 3C (highlighted in yellow color) vary over the range (5.1 to 5.9%). That means, the TDS increase due to the installation of RO units shall exceed the allowed limit (5%). During all these cases, the upstream water inflow from Tigris River to the study area is 9.0 m^3/s. This flowrate value is the min recorded flowrate value during five years period. When the installed RO units have RP of 85%, the max percentages of TDS increase during simulation Case Nos. 2A, 2B, 2C, 4A, 4B and 4C vary over the range (3.9–4.4%). Thus, the max percentages are less than the allowed limit (5%). During these cases, the upstream water inflow from Tigris River to the study area is 97.4 m^3/s. This flowrate value is the max recorded flowrate value during five years period.
5. The results of all the simulation cases indicate that the max TDS increase vary over the range (8.8–226.3 mg/l). With referring to Table 1, some regulations specified the allowed limit of TDS increase to be no more than 1 to 4 ppt. Thus, the TDS increase due to the installation of RO units in the considered WTPs of Basrah city shall be less than the allowed limit.

Table 8
Comparison of calculated and measured TDS values at eight stations along Shatt Al Arab River.

Station no.	Location	Distance from section no. 1 (km)	TDS range (mg/l) Calculated	Measured
1	Al Fao	10	3201.7–23,172.3	3334.4–30,976.0
2	Al Seebh	60	2113.6–3891.8	1452.8–8147.2
3	Mhelah	102	1439.9–2083.0	1465.6–2726.4
4	Al Sindibad	120	1039.2–1917.0	1069.0–1766.4
5	Sehan	65	3107.9–14,174.0	2700.0–13,850.0
6	Labany	96	2652.1–9764.2	1810.0–11,715.0
7	Center of Basrah city	112	2278.1–7028.2	1600.0–9970.0
8	Ktaban	144	618.0–2214.6	960.0–2250.0

7. Conclusions

The environmental impact of installing RO units in 16 main WTPs of Basrah city has been assessed by simulating the TDS distribution in

Table 9
TDS increase due to brine water discharges.

TDS increase due to brine water discharges

Case no.	Sec. no. of max TDS increase	Tide condition	TDS without BW (mg/l)	Max TDS increase (mg/l)	% of max TDS increase
1A50	31.3088*	HT	2309.0	53.6	2.3
1A85	31.3054*	HT	2313.1	120.8	5.2
1B50	31.7028*	HT	836.3	13.6	1.6
1B85	31.3054*	HT	1363.6	69.9	5.1
1C50	31.3088*	HT	4399.2	74.2	1.7
1C85	31.3088*	HT	4399.2	226.3	5.1
2A50	26.6706*	HT	1752.6	34.5	1.9
2A85	24.7094*	LT	1895.0	79.3	4.1
2B50	31.2881*	LT	526.4	8.8	1.7
2B85	24.7094*	HT	797.3	35.2	4.4
2C50	31.2881*	LT	1950.1	32.3	1.7
2C85	24.7094*	HT	2747.2	119.1	4.3
3A50	31.3054*	LT	1993.5	53.7	2.7
3A85	31.3054*	LT	1993.5	106.2	5.3
3B50	31.3054*	HT	886.4	21.3	2.4
3B85	31.3054*	HT	887.4	50.8	5.7
3C50	31.3054*	LT	2626.7	67.9	2.6
3C85	26.6047*	HT	3357.8	197.9	5.9
4A50	24.7094*	LT	1683.6	35.6	2.1
4A85	24.6928*	LT	1685.1	65.9	3.9
4B50	24.7094*	HT	582.9	11.9	2.0
4B85	24.7011*	LT	591.8	25.5	4.3
4C50	24.7094*	LT	2046.6	42.8	2.1
4C85	23.6928*	LT	2049.3	82.8	4.0

Shatt Al Arab River considering 12 different cases. During each case, two RP of RO units were applied; 50 and 85%. From the assessment results, the following conclusions were drawn:

1. The impact of brine water discharge varies along Shatt Al Arab River and it is obvious in a reach extends from km 60 to km 140 measured from the downstream end of the study area (Al Fao city).
2. When the installed RO units have RP of 85%, the max percentages of TDS increase vary over the ranges (5.1 to 5.9%) and (3.9 to 4.4%) during the cases of min and max flowrates of Tigris River, respectively. Thus, during the cases of min Tigris River flowrate, the TDS increase percentages exceed the salinity limit of 5%.
3. When the installed RO units have RP of 50%, the max percentages of TDS increase vary over the range (1.6 to 2.7%) which are lower than the salinity limit specified by all regulation criteria.
4. During all the simulation cases, the TDS increase values vary over the range (8.8–226.3 mg/l) and they are lower than the specified limits by the regulation criteria which is no more than 4 ppt.

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