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ESTIMATION OF TIDAL EXCURSION LENGTH ALONG THE SHATT Al-ARAB ESTUARY, SOUTHERN IRAQ

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Abstract. The tidal excursion length along the Shatt Al-Arab estuary was estimated based on the mathematical relation proposed by Parsa and Shahidi (2010). The field measurements of water level, bathymetry, and discharges were conducted to fulfill the study objective. The results revealed that the tidal excursion length is site-specific and depends on the characteristics of the location which include tidal phases, bathymetry, and geometry of the river. However, the results indicated that there are pronounced differences in tidal excursion lengths between the spring and neap tide phases in all studied stations. The spring tide coincided with the maximum tidal excursion lengths in Shatt Al-Arab estuary with 16.537, 16.187, 11.122, and 9.139 km in the estuary mouth, Faw, Siba, and Abo Flous stations, respectively. While the neap tidal excursion lengths were 12.298, 9.254, and 7.269 km in Faw, Siba, and Abo Flous stations, respectively.

*Keywords***:** tidal phases, tidal excursion length, bathymetry, discharge, Shatt Al-Arab Estuary.

Classification numbers: 3.4.2, 3.7.4, 3.8.2.

1. INTRODUCTION

Estuaries, the transition environments between fresh and saline water are among the most productive places on the earth, hence it required particular management strategies to conserve it. Understanding the physical, chemical and biological characteristics of estuaries come as a high priority for successful management [1, 2].

The water circulation in estuaries is governed by the interaction between two major forces, freshwater inflow, and the oceanic tide, and consequently, the stability of estuaries depends on the balance between these two forces [2, 3]. The estuarine waters are used for many purposes including, drinking, agriculture, and industrial and any deterioration can affect these activities as well as the estuarine ecosystem [4]. The salinization represents the most common problem of water quality deterioration of estuaries as a result of the natural as well as anthropogenic effects [5]. The most popular anthropogenic impacts on estuaries are the construction of upper dams on the river stream, resultant in reducing the amount of freshwater that arrives in estuaries besides the continuous increase of the water demand. Meanwhile, global climate changes represent the most pronounced natural impacts on the estuarine water via many factors such as rainfall reducing, the temperature increasing, and sea level rising [6, 7].

However, the reduction in freshwater inflow resulting from the anthropogenic and natural factors lead to the transfer of salty water from the sea further towards the inland areas, and this phenomenon called a salinity intrusion. The salinity intrusion is a common issue at the tidal river and represent a considerable challenge for those living near these river systems. The salinity intrusion in estuaries is expressed by what is known as the salinity intrusion length, which defined as the distance from the river mouth to the point when the salinity is greater than the salinity of riverine water by 1 ppt [8]. The salinity intrusion length varies according to the tidal phase, it reaches its maximum length at high water slack and then drops to minimum length at low water slack. However, this difference in the distance from the high water slack and low water slack called a tidal excursion length [9]. Consequently, the tidal excursion length represents the net horizontal distance traveled by water parcels between high water slack and low water slack and vice versa [10]. However, the tidal excursion length is one of the most important parameters used to recognize the physical characteristics in estuarine systems. Savenije [11] utilized the tidal excursion as a longitudinal tidal range when he studies the influence of the mixing mechanisms on the longitudinal distribution of salinity along with different types of estuaries and demonstrated that the flood volume can be obtained by multiplying the tidal excursion length and the cross-sectional area at the estuary mouth. There are three types of analytical models for salinity intrusion in estuaries depending on the tidal condition, high water slack model HWS, tidal average model TA, and low water slack model LWS. The salinity intrusion length at HWS can be obtained by adding the tidal excursion length to LWS, and by adding half of the tidal excursion length to TA [12]. Furthermore, this parameter can be utilized as a length scale in the sediment transportation modeling. Schramkowski et al [13] used a two-dimensional morphodynamic model to study the effect of geometry and bottom friction on the bed formation, and indicated that tidal excursion length can be used as a length scale to classify the evolution status of tidal channels beds. Valle-Levinson [10] studied the effects of the basic hydrodynamic parameters on the coastal aquaculture and indicated that the tidal excursion can be used as a reference scale for choosing the optimal sites for aquaculture activities by recognizes the possible locations in the water body that might be influenced by the suspended and dissolved materials associated with these activities.

The Shatt Al-Arab estuary is the main source of freshwater discharged to the northern Arabian Gulf and represents the main resource of surface water that be used for many purposes such as, domestic, agriculture, and fisheries for those people living near the river reaches [14]. However, the Shatt Al-Arab river undergoes many challenges, natural, and anthropogenic, that leading to an obvious deterioration in its water in terms of quality and quantity [5,15]. The salinity intrusion towards the upper reaches of the Shatt Al-Arab river represents the most challenges that occur in a frequent manner in recent years leading to great economic and social problems in Basrah city. Furthermore, the Shatt Al-Arab river suffering from high levels of the pollutant in which an anthropogenic source in origin [16].

There are scarce studies that calculated tidal excursion length in the Shatt Al-Arab estuary. However, according to our knowledge, there are only three studies addressed this parameter when they applied empirical equations to estimate the salinity intrusion in our study area [1, 5, 17]. Nevertheless, and for simplicity, the tidal excursion was used as a constant along the longitudinal axis of Shatt Al-Arab estuary and was estimated by using the traditional formula which based on the tidal velocity amplitude, and ignoring many effective parameters on the tidal excursion. The main objective of this study is the calculation of tidal excursion length at different cross-sections along the Shatt Al-Arab estuary and examine the response of this important parameter to the impacts of the tidal phasing as well as the geometric and bathymetric characteristics.

2. MATERIALS AND METHODS

2.1. Study Area

Shatt Al-Arab river, located in southern Iraq represents the last stage of the Tigris and Euphrates rivers system when they confluence at Qurna, about 70 km north of Basrah city. The length of the Shatt Al-Arab river about 200 km from Qurna to its last section when meeting the Arabian Gulf about 11 km south of Faw city. The last 91 km of the Shatt Al-Arab river represents an international bordering between Iraq and Iran. The width of the Shatt Al-Arab River ranges between about 1000 m at its mouth and 300 m near it originates in Quran. The water depths have an irregular distribution with the maximum reaches to about 18 m. The main tributary of the Shatt Al-Arab river is the Karun river which originates in the Zagros Mountains in Iran.

The hydrological regime of the Shatt Al-Arab river is governed by a status of upstream inflow, the tidal force of the Arabian Gulf, and the influences of climatic conditions [14]. The upstream inflow of the Shatt Al-Arab river is mainly controlled by the water release from the Tigris and Euphatatuse rivers. However, the freshwater inflow from these two rivers historically was higher during wet periods and reaches about 900 m^3/sec, while during the dry periods, the freshwater inflow reduces to about 130 m^3/sec [18]. Furthermore, the Karun river inflow into the Shatt AL-Arab river was greater than both Tigris and Euphrates rivers inflows [19]. The highly freshwater inflow from these rivers into the Shatt Al-Arab river was making it have freshwater along its path with non observed salinity intrusion from the Arabian Gulf. Hence, the area was very fertile with wide palm tree forests on both banks of the river. In the last decades and after a water resources development in the Tigris and Euphrates drainage basins by constructed several dams in Turkey, Syria, and Iraq as well as dams that constructed along the Karun river in Iran, have influenced the flow regime in the Shatt Al-Arab river and resulting in a great reduction in the freshwater inflow towards the river. However, the problem was exacerbated after 2009 when Iraq's Ministry of Water Resources built an embankment on the Euphrates river. The embankment was preventing water from flowing out from the Euphrates river towards the Shatt Al-Arab river. Additionally, the Karun river was completely converted to an Iranian side and linked with Bahminsher river which discharges at the north of the Arabian Gulf. The new estuary of Karun river (Bahminsher estuary) extended in a parallel path to Shatt Al-Arab estuary as shown in Figure (1). Subsequently, and nowadays the Tigris river represents the only source of fresh water in the Shatt Al-Arab river. The Tigris river inflow varies seasonally and reduced in some periods to be in the range that water consumption in the Basra province exceeded its inflow making the Shatt Al-Arab suffering from saltwater from the Arabian Gulf to introduce to the upper reaches of the river [5].

The tidal regime in the Shatt Al-Arab estuary follows up the tidal regime in the northwest of the Arabian Gulf. However, the tidal regime in the northwest of the Arabian Gulf characterized by a mixed predominantly semi-diurnal tide with two high and two low water with diurnal inequality [20 - 22].

The Basrah province characterized by a hot, and dry summer to cold and relatively rainy winter. The average annual precipitation is low in the region and not exceed 100 mm. There are two types of prevailing winds, northwest winds and knew as Al-Shammal and southeast winds mostly during autumn and winter that is relatively warm and moist and brings rainy clouds occasionally [23].

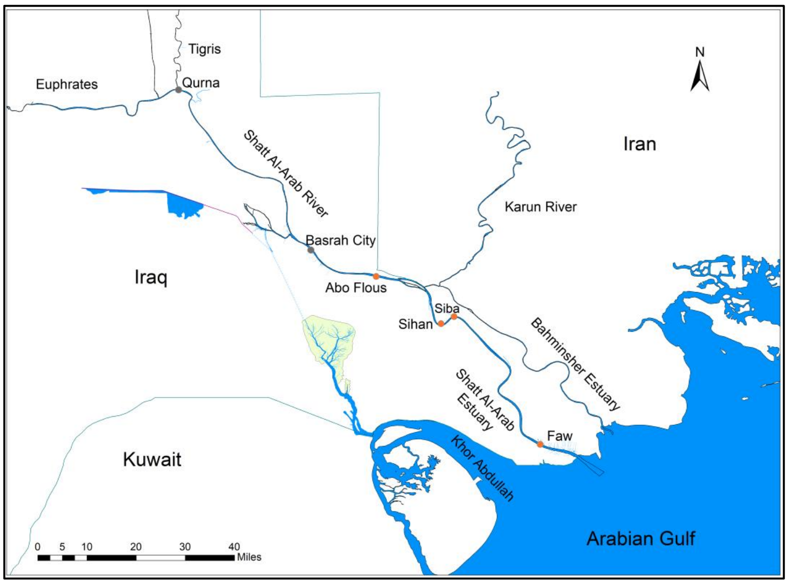

Figure 1. Location map of study area.

2.2. Mathematical formulation

The traditional estimation of tidal excursion length E (km) through the tidal cycle in estuaries was based on the tidal velocity amplitude relative to the tidal frequency and given by [24]:

$$\boldsymbol{E} = \frac{\boldsymbol{v_\circ T}}{\boldsymbol{\pi}} \quad (1)$$

where $v_\circ$ is the tidal velocity amplitude (m/sec) and T is a tidal period (sec). Savenije [25] studied the influence of geometric and bathymetric characteristics on the salinity intrusion in alluvial estuaries and he emphasized the importance of these characteristics on the mixing mechanism and salinity dynamics. However, the tidal excursion length calculation based on Savenije [24] approaches follow the relation,

$$\boldsymbol{E} = \mathbf{1.08}\ \frac{\boldsymbol{v_\circ T}}{\boldsymbol{\pi}} \quad (2)$$

Recently, and by taking into account the importance of the geometric and bathymetric characteristics on the hydrodynamics and salinity distribution of alluvial estuaries introduced by [11, 25], Parsa and Shahidi [9] proposed a comprehensive study to estimate the tidal excursion length in estuaries by examining the responses of this parameter to many geometric and hydraulic factors. The new relation contains several terms that included the effect of the various hydraulic factors on the tidal excursion length and given by:

$$\boldsymbol{E} = \mathbf{7.85} \times \mathbf{10^{-2}}(\boldsymbol{a})\left(\frac{\boldsymbol{L_R}}{\boldsymbol{a}}\right)^{\mathbf{1.11}}\left(\frac{\boldsymbol{g}}{\boldsymbol{C^2}}\right)^{\mathbf{-0.3}}\left(\frac{\boldsymbol{H}}{\boldsymbol{h_0}}\right)^{\mathbf{0.33}}\left(\frac{\boldsymbol{q_r}}{\boldsymbol{h\sqrt{hg}}}\right)^{\mathbf{0.12}} \quad (3)$$

where, a is the cross-sectional area convergence length, L_R (m) represents the tidal resonance length which depends on the tidal period and depths and given by;

$$L_R = \frac{1}{4} T \sqrt{gh}$$

where g is the gravitational acceleration, h (m) the cross-sectional average depth. While the term ($\frac{g}{C^2}$) represents the effect of bottom roughness on the flow, C ($m^{1/2}$/sec) is Chezy roughness coefficient and given by:

$$C = \frac{v}{\sqrt{R_h s}}$$

where v (m/sec) is the flow velocity, R_h(m) is hydraulic radius, and s river slope. Furthermore, H (m) is the tidal range. Lastly, the term $\left(\frac{q_r}{h\sqrt{hg}}\right)$ called by the fround number which represents the velocity to depth ratio, q_r (m^2/sec)is the discharge of river per unit width. This formula was applied in eight estuaries around the world and showed more accurate results in the estimation of tidal excursion length as a function of directly measurable parameters like tidal conditions, bathymetry, and geometry [9].

2.3. Data Sources

Several sorts of data were utilized to fulfill the main objectives of this study. The bathymetric of the estuary was obtained by the several cruises conducted by the Marine Science Center/ University of Basrah along Shatt Al-Arab estuary (estuary mouth, Faw, Siba, and Abo Flous) in 2012. The discharge and cross-sectional measurements of the estuary were conducted by Acoustic Doppler Currents Profiler (ADCP), type RioGrand 600 Hz. Whereas, the water level data were collected by installing a water elevation divers at a specified site (Faw, Sihan, and Abo Flous) as indicated in Figure 1, as the cooperation between Marine Science Center/ University of Basrah and Delft University of Technology in 2014. It's worth mentioning that the water level measurements at Siba station were not available, hence the data of Sihan station which located about 7 km north of the Siba site were used in the tidal excursion estimation.

3. RESULTS AND DISCUSSION

The tidal excursion calculation for Shatt Al-Arab estuary was conducted based on the relation of [9]. However, the application of this relation requires several measurable parameters including, tidal characteristics, bathymetry, geometric properties, and riverine discharge.

In estuaries, the tidal phenomenon plays a significant role in the water exchange with the open sea and consequently, the hydrodynamics regimes are determined based on the tidal characteristics of these estuaries. The tidal characteristics of Shatt Al-Arab estuary are followed by the tidal wave transported towards the northwest of the Arabian Gulf which characterized by a mixed predominantly semi-diurnal nature.

The water level measurements (Figure 2) indicate that the tidal ranges reaches its maximum limit during the spring tide and equal to about 3, 1.3. 0.75 m at Faw, Sihan, and Abo Flous stations respectively. The spring tidal range at estuary mouth was about 3.2 m, while the neap range was 2.65 m as indicated by Shahidi *et al.* [26]. Furthermore, the measurements showed that the neap tidal ranges were 2.4, 1, 0.6 m at Faw, Sihan and Abo Flous stations respectively. The decrease in tidal range towards inland direction can be attributed to the tidal wave attenuation when propagating farther towards the upper reaches of the estuary due to several reasons such as bottom friction effects, irregular estuary shape, and freshwater discharge. However, the high tidal range at Shatt Al-Arab estuary making it a highly dynamic system characterized by strong tidal currents reach to about 1 m/sec [3], which conserves the continuous exchange of water with the Arabian Gulf.

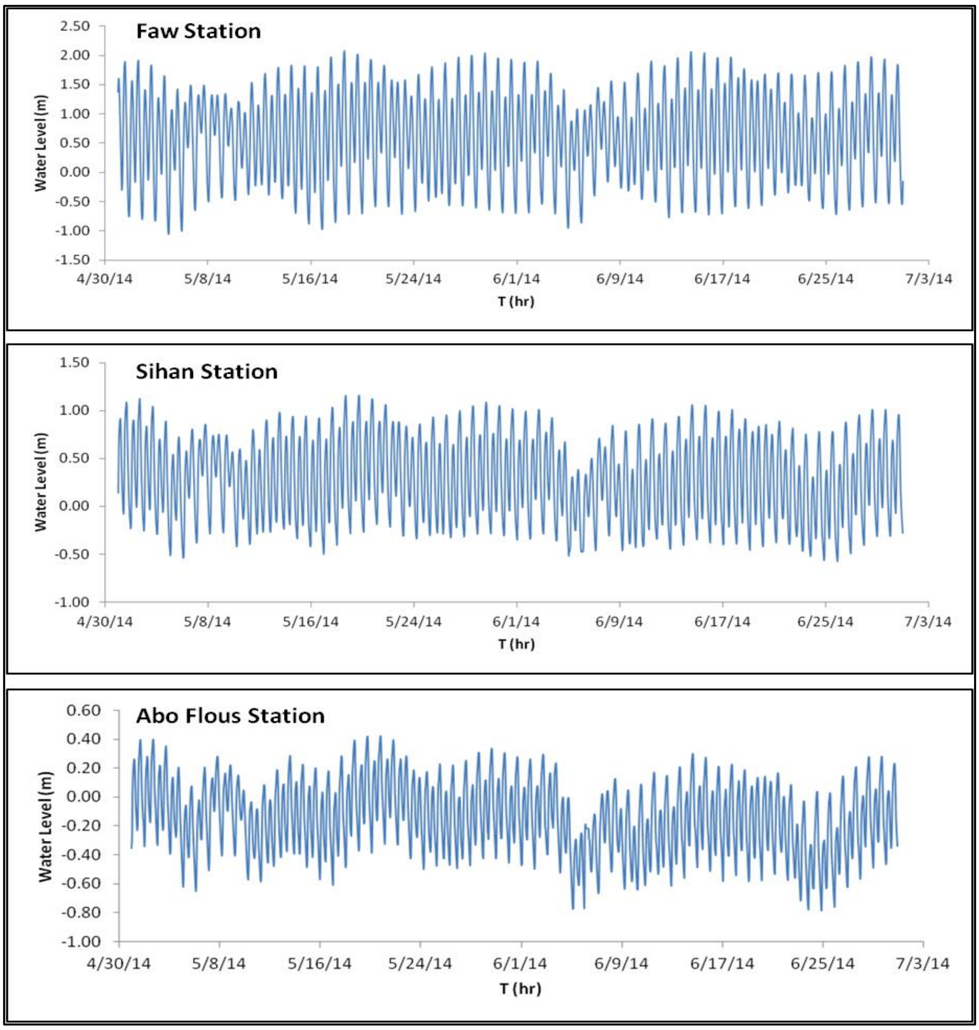

Figure 2. Water level measurements along Shatt Al-Arab Estuary during May and July/ 2014.

The bathymetric measurements revealed that there is a variation in the depths along the estuary. However, the depth in the estuary mouth does not exceed 4.5 m, while it was 9.5, 8.25, and 8 m at Faw, Siba, and Abo Flous stations respectively. The geometry of the estuary follow a convergent shape with a cross-sectional area convergence length (a = 94800 m) [26]. The impacts of the bed friction on the flow were expressed by Chezy roughness coefficient with a value of 50 $m^{1/2}$/sec as used by Hamdan [27]. Moreover, for river discharge, the measurements of the full tidal cycle of discharge (Figure 3) in spring and neap tide conditions, were averaged to get the magnitude of the tidal cycle riverine discharge at the studied stations (estuary mouth, Faw, Siba, and Abo Flous). Table 1 illustrated the parameters used in the tidal excursion calculations.

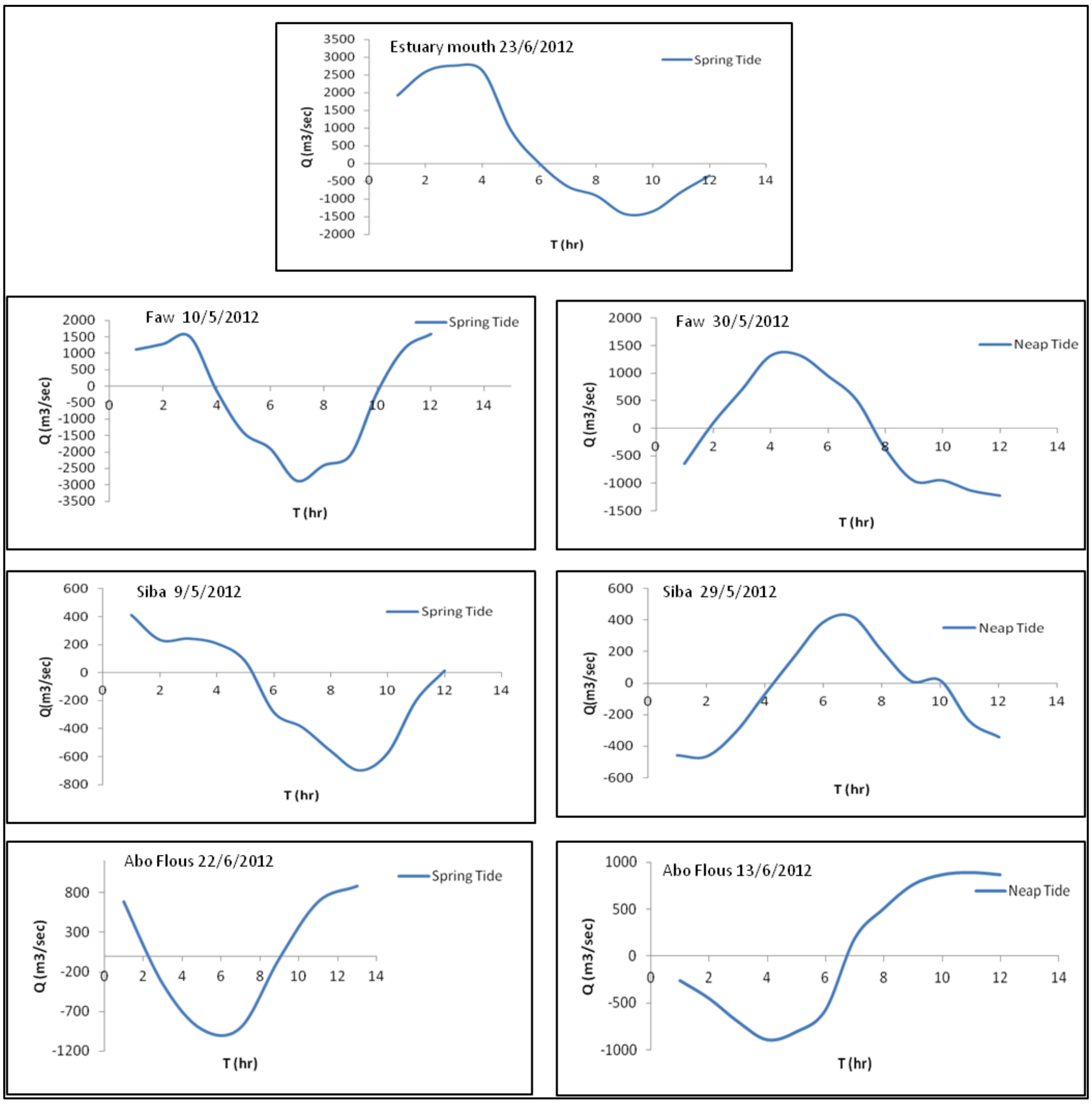

Figure 3. Discharges measurements along Shatt Al-Arab Estuary during May and July/ 2012.

Table 1. The Parameters used in the tidal excursion estimations.

Seq.	Stations	Longitude	Latitude	Depth (m)	Distance to Estuary Mouth (km)	Width (m)	Tidal Range (m)	
							Spring	Neap
1	Estuary mouth	48°36'58.01"E	29°55'46.43"N	4.5	0	1000	3.2	2.65
2	Faw	48°29'2.00"E	29°58'52.01"N	9.5	11.2	630	3	2.4
3	Siba	48°16'29.57"E	30°19'55.80"N	8.25	62.7	480	1.3	1
4	Abo Flous	48° 1'57.25"E	30°27'28.67"N	8	98.4	530	0.75	0.6

The estimated tidal excursion length in the study stations are shown in Table 2. However, it obvious from the table that the tidal excursion is site-specific and varies depending on the location along the estuary. The maximum excursion length in the Shatt Al-Arab estuary coincided with the highest tidal range in the spring tide condition at all studied stations, and this due to the strong tidal currents are associated with spring tide phase and subsequently, the more longitudinal distance will be traveled by the water parcels. The impacts of bottom friction are working on the attenuation of the tidal wave through energy dissipation by bottom friction, hence, estuary depths have an effective infeluence on the tidal wave propagation and tidal currents movements and subsequently on the tidal excursion lengths.

The estimated tidal excursion length at the estuary mouth in the spring tide was 16.537 km, and this represents the maximum tidal excursion length that can be found along the Shatt Al-Arab estuary, due to its dependence on the tidal range, the highest tidal range was observed at the estuary mouth during the spring tide condition. It was worthy to mention here that there are not available measurements of riverine discharge at the neap tide condition in this station, so the estimation was limited for only spring tide conditions. Furthermore, Faw station exhibited a relatively high tidal excursion compared to other stations, particularly in the spring tide with 16.187 km and drops by about 24 % to 12.298 km in the neap tide. The rising in the tidal excursion in the Faw station can be attributed to the high depths in this station as well as their tidal range does not much differ from the maximum tidal range of the estuary due to their nearness to the estuary mouth.

Table 2. The estimated tidal excursion lengths.

Seq.	Stations	Tidal Phase	River Discharge (m^3/sec)	Tidal Excursion Length (km)
1	Estuary mouth	Spring	430	16.537
		Neap	-	-
2	Faw	Spring	358	16.187
		Neap	67	12.298
3	Siba	Spring	126	11.122
		Neap	56	9.254
4	Abo Flous	Spring	124	9.139
		Neap	34	7.269

The results of the estimated tidal excursion length illustrated that this length will be reduced as we move towards the upper reaches of the estuary due to the reduction in the most effective parameters such as tidal range followed by estuary geometry (width, depth, distance from estuary mouth), and this confirmed by the estimated of excursion length at Siba and Abo Flous stations. However, the tidal excursion lengths at Siba station were 11.122 km and 9.254 km in the spring and neap tide respectively, and it can be seen that these values actually less than the neap tidal excursion length of Faw station, and this confirms the hypothesis that tidal excursion is a function of location and vary along the estuary. Moreover, the tidal excursion lengths at Abo Flous station were found to be 9.139 and 7.269 km in the spring and neap tide respectively, and these lengths represent the lowest excursion lengths observed along the Shatt Al-Arab Estuary which can be attributed to the reduction in the tidal range at this station due to its farthest location relative to the estuary mouth.

4. CONCLUSIONS

The estimation of the tidal excursion length along the Shatt Al-Arab estuary was conducted based on the mathematical relation proposed by Parsa and Shahidi [9], which take into account the impact of several factors controlling the longitudinal distance transported by water parcels between high water slack and low water slack and vice versa. The field measurements for many measurable parameters was conducted including water level, bathymetry, and riverin discharges to fulfill the objective of this study. The results revealed that the tidal excursion length is site-specific and vary along the estuary. The results indicated that the most effective parameter controlled the tidal excursion length along the estuary was the tidal range which showen a noticeable changes along the longitudinal axis of estuary as well as between spring and neap tide conditions.. However, the results indicated that there are pronounced differences in tidal excursions lengths between the spring and neap tide phases in all studied stations. The spring tide coincided with the maximum tidal excursion lengths in Shatt Al-Arab estuary with 16.537, 16.187, 11.122, and 9.139 km in the estuary mouth, Faw, Siba, and Abo Flous stations respectively. While the neap tidal excursion lengths were 12.298, 9.254, and 7.269 km in Faw, Siba, and Abo Flous stations respectively.

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