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Short-term Geoinformatics Evaluation in the Shatt Al-Arab Delta (Northwestern Arabian/Persian Gulf)

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ABSTRACT

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Riverine deltas are records of past hydrosedimentary conditions, in conjunction with nearshore tidal and wave dynamics. Within recent human developments, these variables have been affected by increased global warming as well as anthropogenic modifications on the feeder catchment, the delta itself, and the active/discharge channel. This paper investigates the recent (1971–2016) changes at the mouth of the Shatt Al-Arab delta, which includes migration of the navigation channel to inside the Iraqi border. Farther upstream, the channel is migrating toward the Iranian side. A mapping study was conducted with new data obtained from bathymetric surveys as used in the digital shoreline analysis system in GIS applications. The results highlight significant changes regarding the shoreline positions and rates of erosion and sediment accumulation. Additionally, mapping the coastal dynamics has revealed significant shoreline migration with differences between the left and right sides of the river mouth and an increased salinity intrusion up the channel. The effect of these findings could potentially affect the classification of the river mouth, changing it from delta to estuary and affect the international demarcation border.

ADDITIONAL INDEX WORDS: *Delta dynamism, human impacts, geomorphic stressors, geoinformatics modelling.*

INTRODUCTION

Understanding the composition of deltas can be complicated by the interactions between the morphological features and hydrodynamic conditions. These interactions complicate the understanding of transformations in the zone between a river and the ocean and affect the geomorphological setting of the river mouth. Consequently, the classification of deltas and estuaries can be influenced by the amount of sediment supply that is controlled by river dynamics, tidal forces, or wave action (Orton and Reading, 1993). In any case, riverine and tidal energies play essential roles in modifying the form of an estuary or delta (Dalrymple and Choi, 2007; Nichols, 2009; Rossi and Steel, 2016). The sediment systems in estuarine areas reflect the inhomogeneity of natural river and marine interactions that play a significant role in changing the spatial and temporal morphology of the estuary as a response to major allogenic causes, including climate change and relative sea level (Knight and Fitzgerald, 2005). Al-Nasrawi *et al*. (2016) demonstrated that modifications to the catchment area, including river dams and increased urbanisation, play important roles that affect the runoff characteristics, which, in turn, multiply the downstream problems of water quality and quantity that affect eco-geomorphic systems. Any decreases in water supply enhance the dominance of tidal processes that continue to influence the morphology of the estuary. Deltas and estuaries form where river discharge energy is reduced and where waves and tidal forces dominate, complicating the sedimentary environment, which varies depending on the relative importance of these factors.

Study Site Specifications

The Shatt Al-Arab estuary is basically delta transitioning into an estuary. The delta's location and composition mean that it forms a significant geopolitical and economic zone (Figure 1). It is located at the head of the Arabian/Persian Gulf and is the main freshwater source that supplies this gulf (Heyvaert and Baeteman, 2007). The thalweg (which is the lowest path of the river/delta) defines the national border between Iraq and Iran (Cukwurah, 1967). Accordingly, understanding erosion and deposition within this estuary is of national importance because the thalweg position can change through time. Furthermore, the Shatt Al-Arab channel has been an important site regarding controlling navigation and transport, especially for the ports of Almaaql and Abu Flus. However, the development of the Shatt Al-Arab estuary has been affected by factors such as tectonic movements, sea-level rise, and sedimentation.

However, a number of previous and recent local studies have investigated different sediment phenomena in the delta of the Shatt Al-Arab. These studies have contributed in different ways to the current understanding of this specific delta. For example, Darmoian and Lindqvist (1988) investigated the sedimentology of Khor Abdullah and the delta area, and Albadran (1995) and Albadran, Al-Beyati, and Khalaf (1995) provided details about the sediments and sedimentation mechanisms within the delta. Galloway (1975) quantified the sediment supply to the delta of the Shatt Al-Arab, showing that

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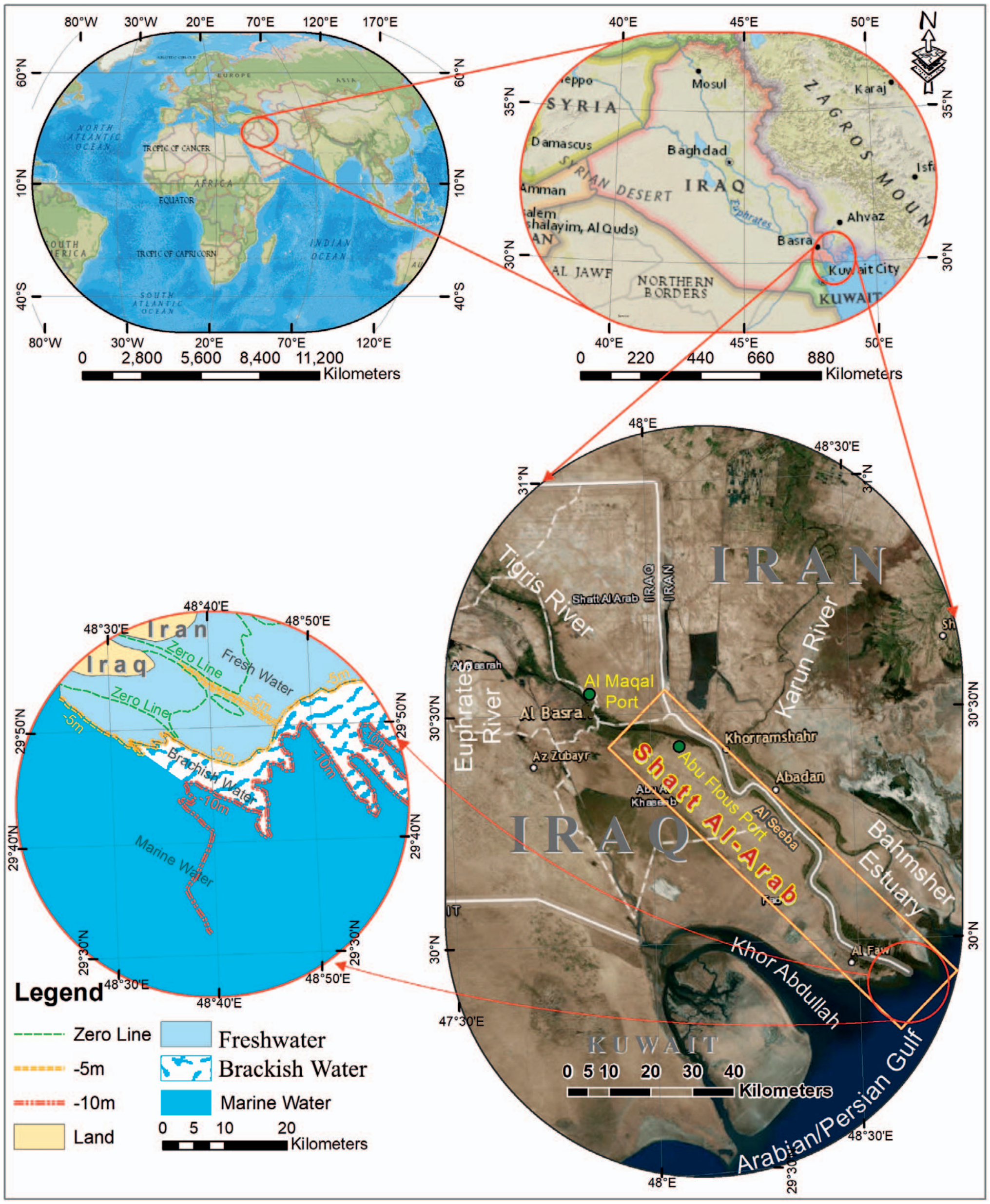

Figure 1. Map of the Shatt Al-Arab mouth (modified after Al-Saadi *et al*. [1977]) showing the effect of freshwater discharge on surface salinity of the estuary.

this delta receives around 9,500,000 and 85,000 tons of sediment as suspended load and bedload, respectively, and that most of this sediment is deposited in the navigation channel. Moreover, it was found that the semidiurnal tidal system in the Shatt Al-Arab characterizes the channel as a tidal delta, but it also has a high wave-dynamic component. The hydrodynamic properties and the intrusion of marine water into the estuary were investigated by Al-Ramadhan and Pastour (1987), Al-Mahdi (2001), and Albadran (2004). The current situation in the Shatt Al-Arab is that the Tigris River provides the only freshwater supply, but by 2040 it is unlikely to be enough to prevent large upstream intrusions of marine water from Arabian/Persian Gulf. This is because of the construction and development of hydraulic structure projects in the headwater countries (Al-Asadi, 2017). Consequently, the delta of Shatt Al-Arab and the interplay between the factors that have affected this delta need to be reinterpreted.

The present study is based on the assertion that the delta of Shatt Al-Arab is undergoing significant changes, which contribute to transforming it from a delta to an estuary by altering the morphological features. This study employs combined hydrodynamic and remote sensing (RS) methods to investigate the recent composition and development of the Shatt Al-Arab mouth to provide a proper understanding of its

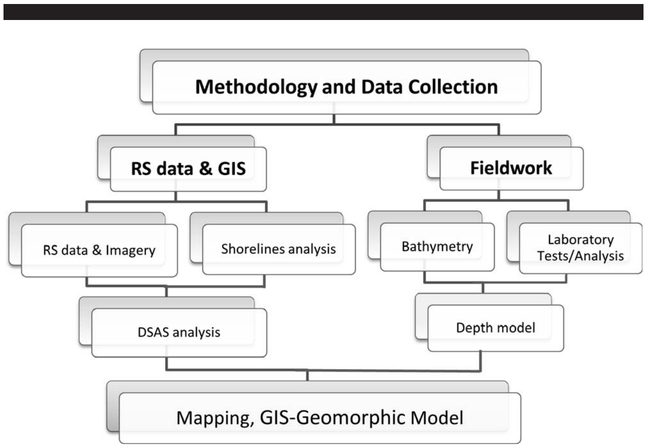

Figure 2. Methodology: data collection and analysis sequences.

shape and sedimentary situation by focusing on recent shoreline changes and their geopolitical implications. The principal objectives of this study are to monitor and measure the Shatt Al-Arab estuarine dynamics and to provide a spatial-temporal evaluation of changes in shoreline position and the depth and location of the navigation channel.

METHODS

This study has used multitemporal RS data from Landsat MSS, TM, and ETM+ between 1971 and 2016 (with 10-y gaps). Digital mapping of the coastline and sedimentation patterns enabled the detection of morphological changes and sedimentation status (Chu *et al*., 2006). The mouth of the Shatt Al-Arab channel can be presented at a landscape scale by using image processing techniques in GIS (ArcGIS 10.2, 2019).

This research is based on a continuous estimate of multi-temporal differences of shoreline positions and channel stability at the study site. The active areas of the Shatt Al-Arab estuary have been evaluated by mapping shoreline movements on RS and Admiralty maps over time, thus providing changes in erosion or accretion rates around the estuary. Changes to the shoreline position (from the 1971 zero line) and the channel location illustrate the morphological instability especially in the delta mouth zone. This project entails the assessment of threats caused by shoreline erosion and channel movement. Also, the effects of climate change and artificial modification in the catchment area are addressed. Achieving the project aims was performed on several levels. It started with GIS and RS-based analyses to identify and to classify the land cover and shoreline changes at the specific study sites, depending on recent and historical records of aerial photography, satellite, and LIDAR data. The methodology was divided into two parts, as shown in Figure 2, to achieve the aims.

Investigating and monitoring the development of the Shatt Al-Arab estuary is complicated because of difficulties in sampling, setting up field instruments, security obstacles, continuous cross-section changes in the subtidal areas, and the high cost of water surveys in this area (Fitzgerald and Knight, 2005).

Data Collection

The following multitude of datasets have been compiled to achieve the study targets.

Three Admiralty maps (from 1971, 1984, and 2016) were digitised to obtain the 1971 zero shoreline, followed by analysis and mapping in GIS.

A bathymetric survey was conducted along the active channel of the estuary and adjacent river using an echo sounder in combination with an RTK-antenna GPS linked to the nearest ground-control stations. This survey was performed by the Marine Science Centre at the University of Basra during 2014–15.

The changing delta morphology has been investigated using RS data from 1949, 1972, 1998, and 2014 together with the digital shoreline analysis system (DSAS) to quantify the amount and rate of shoreline changes over 65 years. The study has used several RS datasets for the analysis, as shown in Table 1. It has utilised ERDAS IMAGINE 2014 analytic tools during the preprocessing stage, including geometric and radiometric corrections using an image-to-image orthorectification and edges enhancement for better isolating and detecting the shoreline. The study applied unsupervised and supervised classifications as coastline extraction tools to extract the shoreline positions from the Landsat imagery. Meanwhile, to validate the results, this paper used the Classify Raster (ArcGIS Spatial Analyst Tool), which is a classifying tool for raster datasets based on an Esri Classifier Definition (.ecd) file and raster dataset inputs. The DSAS test used 772 transects, sampled along the left and right sides of the active

Table 1. *The remotely sensed datasets used for analysis in this study.*

Satellite	Sensor	Orbit Frequency	Recording Time	Spectral Resolution	Spatial Resolution
Landsat 1, 3	MSS/RBV	18	May 1975	Band: 4 (0.5–0.6 μm), G Band: 5 (0.6–0.7 μm), R Band: 6 (0.7–0.8 μm), NIR	79 m
Landsat 4, 5	MSS/TM	16	May 1985	B: 2 (0.52–0.60 μm), G B: 3 (0.63–0.69 μm), R B: 4 (0.76–0.90 μm), NIR	30 m
Landsat 7	ETM+	16	April, May 1995, 2005	B: 2 (0.519–0.601 μm), G B: 3 (0.631–0.692 μm), R B: 4 (0.772–0.898 μm), NIR	30 m
Landsat 8	OLI	16	April 2015	Bands: 1 (0.433–0.453 μm), coastal/aerosol 2 (0.450–0.515 μm), B	30 m

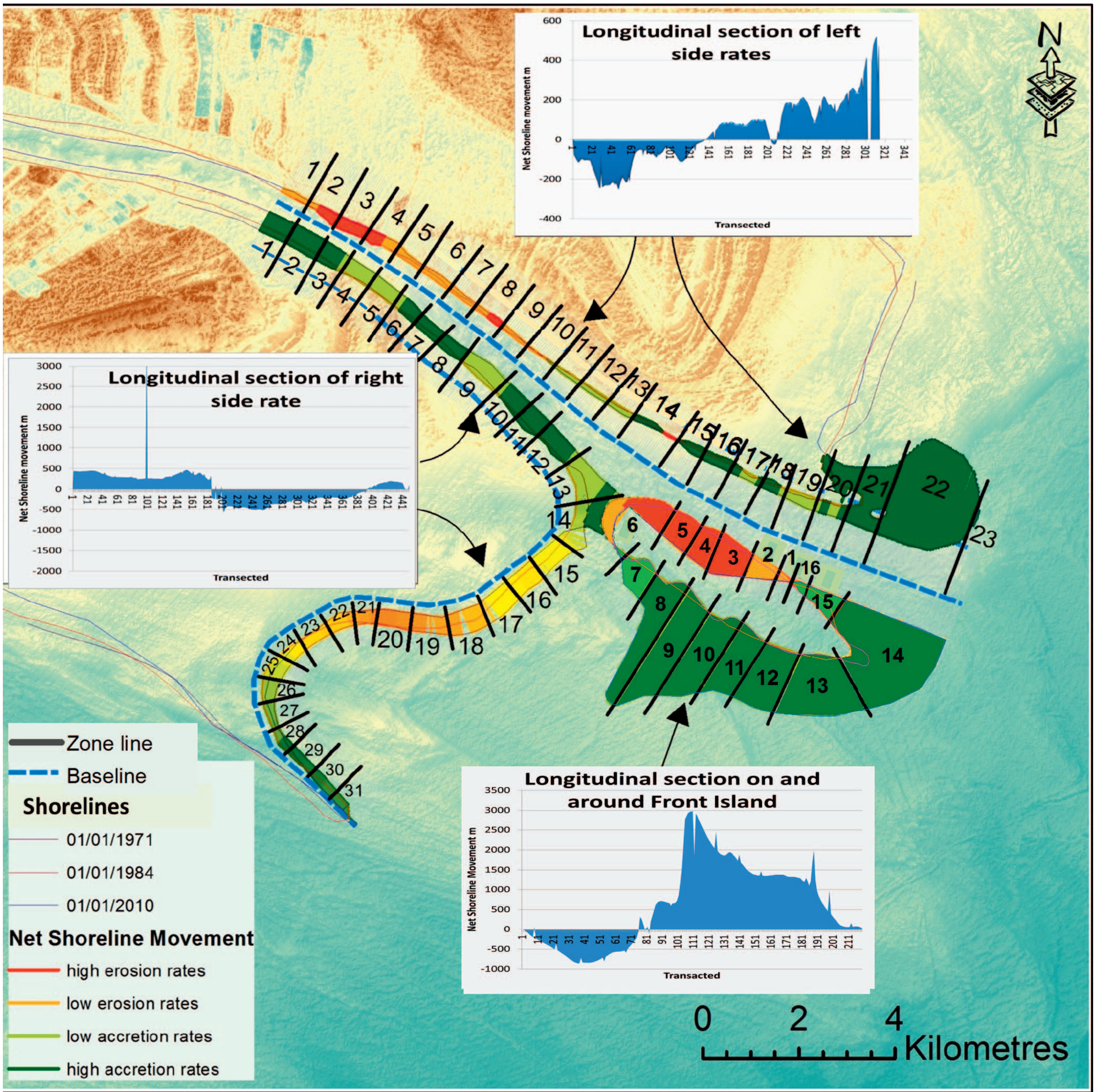

Figure 3. The digital shoreline analysis system (DSAS) has been used to investigate the changes in the Shatt Al-Arab estuarine shoreline over time. Displayed are the DSAS transect/baselines, the numbered zones containing similar transects, and the net shoreline movement between the 1971, 1984, and 2010 shorelines. The longitudinal sections illustrate the erosion and deposition on the (a) left bank, (b) right bank, and (c) around Front Island (red to yellow = erosion; green = accretion).

channel (336 each) at 50 m intervals, as well as a circle of 204 transects around the recent Front Island that appeared on the right bank end of the estuary mouth. The DSAS sampling was conducted along the channel shorelines, using a centred baseline in the middle of the channel and a baseline on the southern shore around the right bank (Figure 3). These transects were then grouped into a smaller number of zones with internally consistent patterns of erosion or deposition (Figure 3). The Iranian side of the estuary (left bank) is divided into 23 zones whereas the Iraqi side (right bank) is divided into 31 zones. Sixteen zones have been recognised around Front Island. Two statistical methods have been used to calculate the

Table 2. *Net shoreline movement in each zone of the Shatt Al-Arab's channel on the left and right banks of the active channel and around Front Island, as shown in Figure 3. Negative values indicate erosion and positive values indicate accretion. (Source: DSAS analysis attribute database).*

DSAS Transect Location	Summation of Negative and Positive Zones (m)	Average Shoreline Movement per Zone (m)	Average Movement Rate per Zone (m/y)	Maximum Shoreline Movement (zone no.) (m)	Maximum Movement Rate per Zone (m/y)	Minimum Shoreline Movement (zone no.) (m)	Minimum Movement Rate per Zone (m/y)
Left bank (Iran)	–1050	–116	–2.47	–227 (3)	–4.83	–52 (7)	–1.11
	+2967	+228	4.85	1250 (22)	26.60	2 (10)	0.04
Right bank (Iraq)	–4356	–311	–6.62	–494 (17)	–10.51	–83 (27)	–1.77
	+7647	+449	9.55	3243 (7)	69.00	43 (28)	0.91
Front Island (Iraq)	–2624	–437	–9.30	–806 (1)	–17.15	–21 (13)	–0.45
	+12,030	+1336	28.43	2446 (6)	52.04	159 (12)	3.38

rate of shoreline change in each zone over the study period: (1) the net shoreline movement (NSM) and (2) a linear regression rate (LRR).

RESULTS

The results show significant geomorphological shoreline position shifts, caused by spatial changes in erosion and deposition between 1971 and 2016. This paper confirms the relocation of the geomorphological units as presented by Abd-Alqader (2010). It also supports the concept that the delta is transforming to become an estuarine system in the future.

Tracing Temporal Shoreline Dynamics

Specific statistical details have been derived from the modelling approach adopted in this paper, leading to an estimation of the shoreline changes at the mouth of the Shatt Al-Arab estuary between 1971 and 2016 (Table 2). For simplification within this study, Front Island refers to the tidal flat area that became established near the Iraqi Shatt Al-Arab river-mouth shoreline in 1971 and has remained exposed above the lowest low-water level since.

Figure 3a shows that significant accretion has occurred on the Iranian side of the outer Shatt Al-Arab estuary, with an average shoreline movement of 228 m at an average accretion rate of 4.85 m/y (range 26.60–0.04 m/y; Table 2). Deposition is greatest at the seaward margin of the channel, and it progressively decreases from zone 23 until zone 10, where erosion becomes more prominent farther up the channel to zone 1. The average amount of shoreline erosion in the upper part of the channel is 116 m at an average erosion rate of 2.47 m/y (range 4.83–1.11 m/y).

In contrast, the Iraqi side of the channel shows a dominance of deposition in zones 1–14 (Figure 3b) with an average accretion distance of 449 m at an average rate of 9.55 m/y (range 69.00–0.91 m/y; Table 2). Evident erosion occurs along the outer SE-facing flank on the Iraqi side of the Shatt Al-Arab estuary (zones 15–24 where the average erosion distance is 311 m at a rate of 6.62 m/y with a range of 10.51–1.77 m/y). Because this area is away from the main Shatt Al-Arab channel, the erosion is probably caused by wave action rather than tidal currents. The southern spit on the margin of Khor Abdullah (zones 25–31) represents an additional area with minor accretion.

The northern side of Front Island, adjacent to the main Shatt Al-Arab channel represents a major area of erosion (zones 1–6; Figure 3c) that shows an average shoreline erosion of about 437 m from the 1971 zero shoreline during the past 45 years at a mean erosion rate of 9.30 m/y (range 17.15–0.45 m/y; Table 2). In contrast, a large amount of sediment has accreted on the eastern and southern margins of Front Island (zones 7–16), causing an average shoreline extension of 1336 m at an average rate of 28.43 m/y (range 52.04–3.38 m/y).

Shoreline Analysis Statistics and Validation

The statistics for the NSM along the Shatt Al-Arab estuary are shown in Figure 4a–c. Statistics include the transect line count and the minimum, maximum, and mean NSM for combined transects in each zone (Table 2). For instance, the left bank (Figure 4a, 336 transects) shows a nearly normal distribution centred around no movement with a tail of large accretion amounts and a slight increase in frequency toward the maximum erosion. In contrast, the right bank (Figure 4b, 336 transects) has a peak at no movement and a broader peak at 200–500 m of accretion that mainly occurs along the inner southern margin of the channel. Front Island (Figure 4c) has been investigated using 204 transects and shows the maximum shoreline retreat of about 860 m representing erosion on the northern side of the island, whereas the island's southern and eastern sides show a maximum accretion of 2974 m. This results in a mean NSM of 617 m of accretion as an overall island dynamic state.

The LRR of shoreline movements has validated the confidence of the results derived from the analytical tools used in this study. The LRRs for both the left and right banks have shown more than 95% coefficient levels (mean p values of 0.005 and 0.03, respectively) in the calculated movement vectors. However, for Front Island the mean p value of 0.17 reflects the opposing movement directions around the island. This can be rectified if both sides of the island are analysed separately. As a result, the occurrence of the shoreline movement is clearly distingushed when you see the frequency of movements on each side of the island and as seen on the sides of the main Shatt Al-Arab channel (see Figures 3 and 4).

Channel Movement

Temporal satellite imagery (Figure 5) closely matches the results of the statistical analyses (Figures 3 and 4). Variations in the location of the navigation channel are shown on the Landsat satellite images in Figure 5 between 1972 and 2016, which support the findings of Albadran, Al-Mulla, and Abd-Alqader (2016). Changes include shoreline movement toward the NE (Iran) in the upper part of the channel and to the SW on

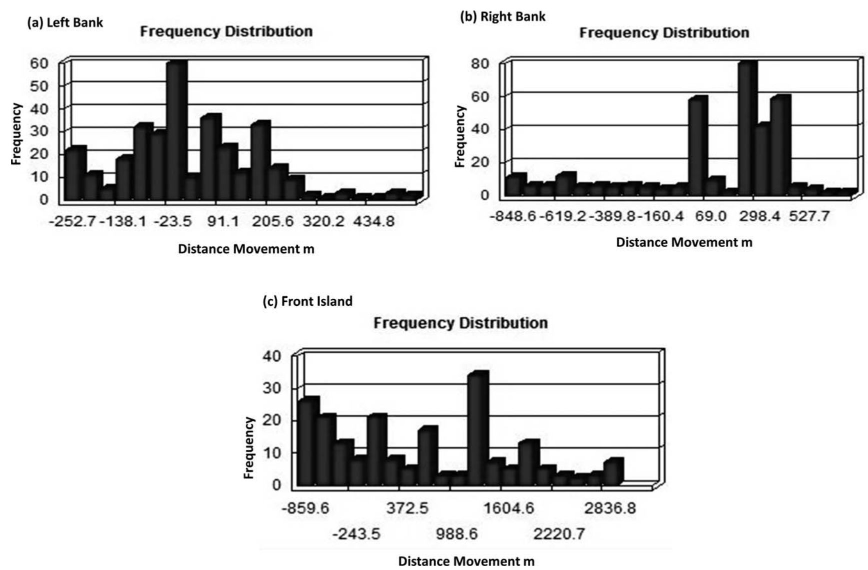

Figure 4. Results of statistical evaluation of the movement from the 1971 zero line at (a) left-bank, (b) right-bank, and (c) Front Island.

the NE part of Front Island along the Iraqi side of the Shatt Al-Arab estuary. The results of the statistical analysis support this movement, which displays the highly eroded channel margin areas with the channel and thalweg movement toward these eroded areas. In the outer part of the estuary/delta, the movement of the active channel between 1972 and 2016 is shown by the dynamic changes in red when compared to the 1972 base location of the deep channel in blue (Figure 5).

DISCUSSION

The results show significant geomorphological shoreline position shifts, caused by spatial changes in erosion and deposition between 1971 and 2016. The results confirm the relocation of the geomorphological units (Figure 3), and this finding is consistent with the previous research presented by Abd-Alqader (2010). It also supports the concept that the delta is transforming to become an estuarine system in the future.

This study highlights that the current morphology of the Shatt Al-Arab estuary is a direct result of the shoreline movement and the navigation channel dynamics over the last decades. The analysis of shoreline changes at the mouth of the Shatt Al-Arab estuary between 1971 and 2016 indicate moderate wave dynamics, which have significantly affected the whole geomorphic system and the associated ecosystem habitats. The shorelines, bars, and their vegetation canopies have clearly been eroded and retreated from the SE landward side of the delta in Iraq (Figure 3). In contrast, it becomes clear through the results that accretion has occurred at the mouth of the delta on the Iranian side (Figure 3). Significant accretion has also occurred on the southern and eastern sides Front Island, and in this part of the estuary the Shatt Al-Arab is still too active and too dynamic for the island to become stabilised (Figure 3, Table 2).

The study shows that within the main Shatt Al-Arab channel, natural hydrodynamic processes play an essential role in increasing the sinuosity of the channel with erosion into Iran in the NW and erosion toward Iraq on the NE portion of Front Island. It has resulted in equivalent migration of the

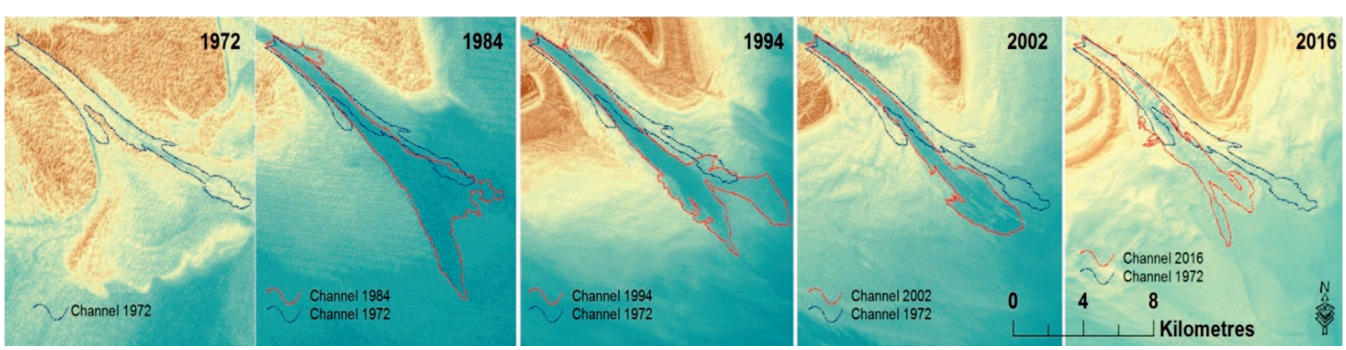

Figure 5. Progressive shifting of the navigation channel and estuary between 1972 (blue) and 2016 (red) shown in Landsat satellite imagery.

channel and thalweg that could have implications for the position of the Iran-Iraq border. The change in channel position is even more marked in the offshore part of the delta where the channel has migrated 2–4 km farther south from its 1972 position.

As illustrated earlier, the Karun River (on the Iranian side; see Figure 1) is an important river/tributary in the region. Diverting its flow within Iran has had an important effect on the Shatt Al-Arab discharge volume because its discharge originally contributed ~23% of the total Shatt Al-Arab discharge (Al-Asadi, 2017). The discharge reduction resulted in a lower supply of sediment load to the Shatt Al-Arab channel, which in turn caused channel bank erosion. This artificial discharge fluctuation also led to increased deposition in the main channel of the Shatt Al-Arab because of the lower discharge velocities and caused a southward shift of the river mouth. In contrast, before the flow of the Karun River was regulated, the higher discharge from the Shatt Al-Arab resulted in a significantly higher stream power, which was capable of flushing most sediment seaward toward the Arabian Gulf or the Khor Abdullah.

Understanding the effect of the decreased discharge of Karun River into the Shatt Al-Arab is critically important when considering the significant accretion that occurred on the Iranian side of the outer Shatt Al-Arab estuary. The erosion and deposition along the Shatt Al-Arab channel means that the channel (and thalweg) have migrated northward toward Iran in the upstream part of the channel resulting from scour along the outer margin of the slightly curved channel. This erosion has probably been enhanced by the reduced sediment load from the upstream catchments in both Iran and Iraq. In the outer part of the estuary channel erosion has been concentrated along the northern margin of Front Island with deposition along the seaward and southern Iranian coast. This has caused the thalweg of the main channel to shift toward the SW across the Iraqi political border.

CONCLUSIONS

Decreasing the upstream freshwater discharge into the Shatt Al-Arab and the consequent drop in sediment supply from the catchment area has caused the tidal power to become the primary controlling factor of erosion in the estuary. Reclassification of the water body could be in favour of an estuary instead of a delta. The shallowing of the navigation channel at the mouth of the Shatt Al-Arab and the shift of its location southward across the Iraqi border could be of significant concern regarding the location of the political border and the naval and merchant transport to Iraqi ports in the upstream part of the estuary. The reorganisation of the river mouth has also shifted ecosystems and the classification of the area as a water body. The loss of large areas on the Iraqi side at the mouth of the channel and delta as it migrated southward and the equivalent accretion on the Iranian side have been influenced by human activities. These include the added hydraulic structures on the Iranian tributaries and the anthropogenic catchment modifications that control the supply and amount of freshwater and sediment. Climate change, sea-level rise, and the impact of humans have all contributed to the morphological changes in the delta/estuary. Understanding the behaviour and effect of these changes requires further research on hydrodynamic and sediment transport modelling to study all the parameters over different time periods.

The broad-scale methodology in this paper is applicable worldwide for evaluating the changes to estuaries and helps provide more understanding of the factors responsible for these changes. These factors can then be considered when estimating responses to future riverine dynamism in such coastal-politically sensitive systems and can be used as sustainable and useful management tools for peacefully deciding the national borders when faced with dynamically active geomorphic changes. Valuable information on historical and current changes in precipitation and river discharge can be employed to predict future trends by considering how these changes will control the amount of sediment derived from the catchment. Also, future direct human modification might increase significantly in the Shat Al-Arab mouth, as well as in the catchment area, which could have severe effects on the shoreline's movement and all of the relatively natural processes. Thus, future research should consider these factors in the preparation of applicable preservation and restoration plans.

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