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Tidal Current Behaviors and Remarkable Bathymetric Change in the South-Western Part of Khor Abdullah, Kuwait

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***Abstract*—**A study of the tidal current behavior and bathymetric changes was undertaken in order to establish an information base for future coastal management. The average velocity for tidal current was 0.46 m/s and the maximum velocity was 1.08 m/s during ebb tide. During spring tides, maximum velocities range from 0.90 m/s to 1.08 m/s, whereas maximum velocities vary from 0.40 m/s to 0.60 m/s during neap tides. Despite greater current velocities during flood tide, the bathymetric features enhance the dominance of the ebb tide. This can be related to the abundance of fine sediments from the ebb current approaching the study area, and the relatively coarser sediment from the approaching flood current. Significant bathymetric changes for the period from 1985 to 1998 were found with dominance of erosion process. Approximately 96.5% of depth changes occurred within the depth change classes of -5 m to 5 m. The high erosion processes within the study area will subsequently result in high accretion processes, particularly in the north, the location of the proposed Boubyan Port and its navigation channel.

***Keywords*—**Bathymetric change, Boubyan Island, GIS, Khor Abdullah, tidal current behavior.

I. Introduction

THE Arabian Gulf is a significant water body in the world because of its' role in providing the critical route for oil transportation. Although a noticeable supply of oil is exported from the northern region of the Gulf, there has been little studies done in this area. The reason for this neglect is the fact that it has been a political and military "hot spot" since the early 1980s. This north-western part of the Gulf was subjected to three destructive wars - the First Gulf War (1980-1988), the Second Gulf War (1990-1991), and the Third Gulf War (2003). Peace remains fragile, and the area is still unsafe because of the unstable relations between the USA and Iran. For this reason, there have been few studies into the oceanographic and physical characteristics of the area. These few studies, which were undertaken for a variety of different purposes, were done either before 1980, or during the short periods of peace since 1980 [1].

Despite lack of oceanographic and physical information, regional countries (especially Kuwait) are planning to establish several development projects in the area. For example, the Silk City, Al Subiya New Town, Boubyan Port, and a number of other projects in the western and southern coast of Bubiyab Island (Fig. 1). In such circumstances, oceanographic and physical information on the region has become essential in order to ensure an environmentally sustainable development. This information is required before the development, so unexpected morphodynamic changes can be identified. It is also important because it will help to find early solutions to undesired changes and can avoid long-term environmental impacts. Hence, identifying physical characteristics will decrease serious damages to the physical environment, as well as increase the benefits of the development projects.

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Thorough information on tidal current behavior and bathymetric characteristics is also required to support successful coastal management and scientific community, without which navigation becomes inefficient, or sometimes even dangerous [2]. Moreover, it is essential to harbor structures, sediment transports [3], [4], dispersing pollutants [5]-[8], and bathymetric changes along navigation areas [9]-[12].

In the present study, tidal current behavior in the south-western part of Khor Abdullah is analysed to examine bathymetric changes using a GIS, and to draw a better overall picture of tidal hydrodynamic system and bathymetric evolution in this area. Understanding these features are important for coastal navigation, especially the study area located close to the proposed Boubyan Port (East Boubyan Island). It is also required to predict the movement of any future water pollution that may occur due the human activities. Finally, studying the bathymetric change in the study area will provide a better understanding and prediction of morphologic and morphodynamic trends that are necessary for future coastal management.

II. Study Area

The north-western Arabian Gulf is characterized by an extensive tidal channel network. These tidal channels are locally known as *"Khor"*, such as Khor Abdullah, Khor Boubyan, Khor Al Sabiya, Khor Shitiyanah, Khor Az-Zubair and Khor Al-Mileh. Khor Abdullah, which separates Boubyan Island on the west from the Iraqi mainland (Al-Faw Peninsula) in the east, is one of the more important channels of this area. It is important because it constitutes a broad waterway capable of being navigated by ships of deep draft and is the location of the proposed Boubyan Port. It also links the Iraqi port (Umm Qaser) with the Arabian Gulf.

Physically, Khor Abdullah is a narrow funnel-shaped channel and extends about 40 km NW-SE in length, and averages 10 km in width with an entrance 25 km wide. The depth of the water increases gradually with distance offshore, but increases more rapidly offshore along the western coastline with a relatively deep trough in between. The Khor entrance is characterized by an irregular floor and is interrupted by elongated and linear shoals that align parallel to one another. Wide and muddy intertidal flats are the main feature of the Khor banks that are subject to frequent and extensive inundation during the spring tide.

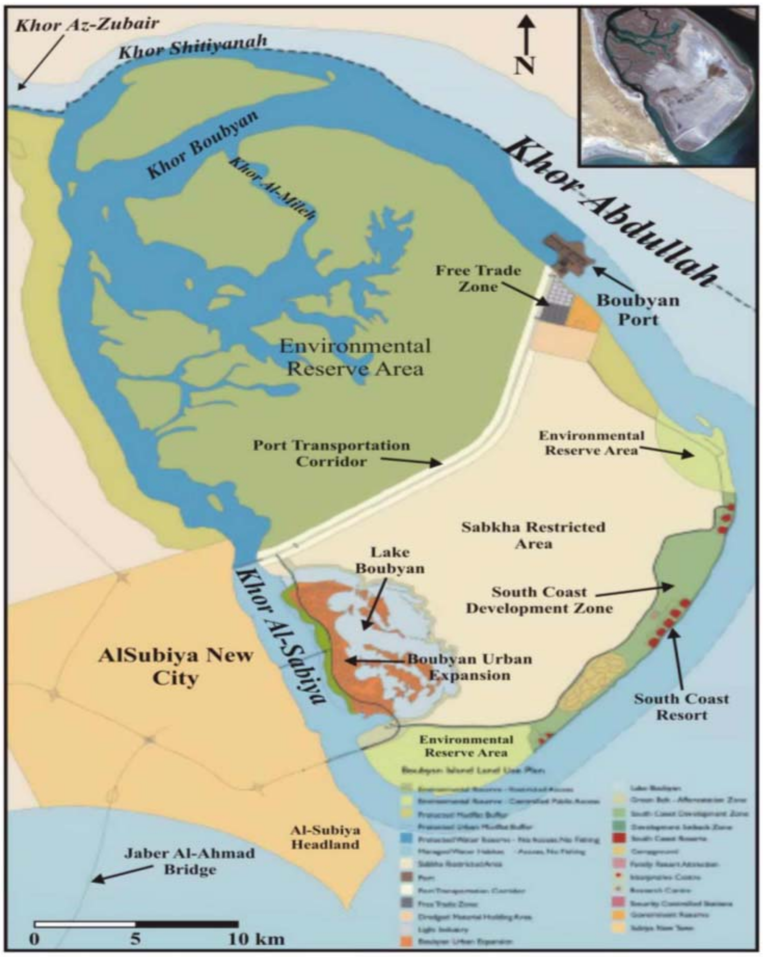

Fig. 1 Land Use Activities for the Northern Coast of Kuwait [3]

The study area of this paper is located in the southwestern part of Khor Abdullah, extending between 29^0 40’ N and 29^0 50’ N latitude, and 48^0 20’ E and 48^0 30’ E longitude (Fig. 2). This area is the only part of northern Kuwait's territorial waters that has been bathymetrically surveyed in 1985 and 1998 by the Kuwait Ministry of Communication. The coastal plain of the study area, which extends inland from the line of mean high spring tide, is the south-western corner of Boubyan Island. This part of the island is a lowland with an extensive wet sabkha flat and extreme concentrations of evaporates with muddy deposits of the upper layer, and low elongated coastal sand berm with shells and nabkhas. Based on the report of [3], the southern coast of Boubyan Island is considered a wave-dominated coast. Waves approach from across the Arabian Gulf, primarily due to easterly and southerly winds, and build up the current southern beach with coarser material and modify to finer bed material in the sub-tidal area. Long-shore coastal processes resulting from wave activity, creates the spit at Ras Al-Qayd. In general, the coastal plain in the study area contains several morphological landforms, such as sabkha, rugged sabkha, salt flats, low lying sabkha, highly vegetated sabkha and tidal channels, rough sabkha, scattered vegetation, smooth hard sabkha, submerged mud flats and tidal salt flats [3].

In the marine portion, wide and muddy intertidal flat (ranges from 400 m to 3000 m) is the most notable morphologic feature in the near-shore area. The offshore area is relatively shallow with an average depth of approximately 4.5 m (counted by GIS). Shoals in the study area, which occur off the shoreline, submerge during high water and expose during low water.

The bottom sediment, in general, is fine-grained. The sources of these sediments are various, but the main two derive from the Shatt Al-Arab deltaic systems and the Aeolian fallout [1]. It is clear that mud fractions (silt & clay) are high as one proceeds from foreshore to offshore, while sand fractions increase as one moves away from the coastline. Mud and sandy mud deposits are the main bottom sediments in the study area, which is bounded by the coastline (Fig. 3). However, textural classes with abundant sand fractions (muddy sand & silty sand) occupy a small area in the deeper water to the east of the study area.

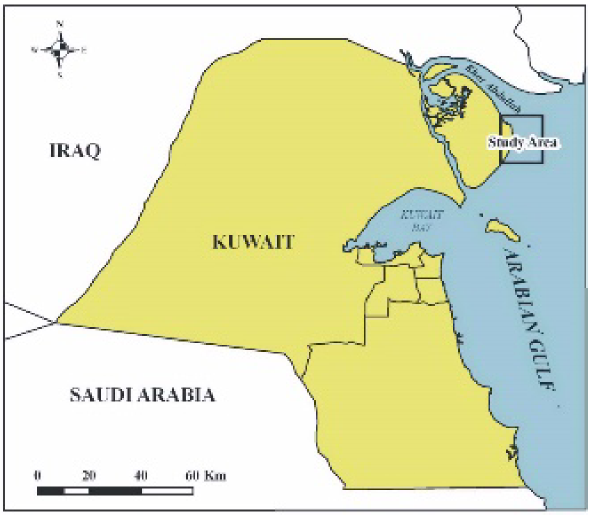

Fig. 2 Location of the study area

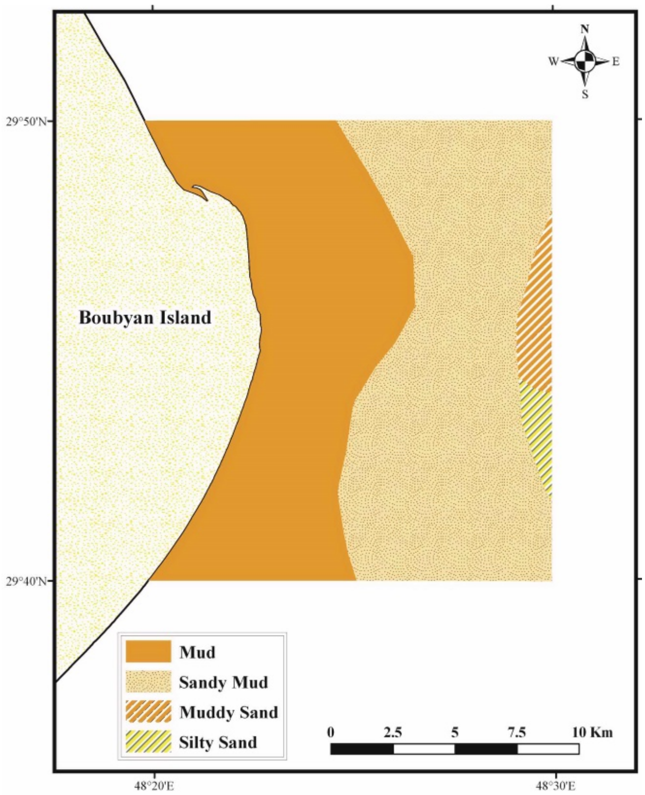

Fig. 3 Spatial distribution of surface sediments in the study area [13], [14]

In terms of hydrodynamic features, the astronomical tide in the study area is a semi-diurnal mixed tide, which consists of two high and two low waters with inequalities in the height and duration of successive tides. It experiences a meso-tidal regime, where the mean tidal range is 2.4 m (Ras Al-Qayd astronomical tidal estimation *"MHHW - MLLW*). However, based on astronomical tide predictions along the eastern coast of Boubyan Island, the highest astronomical tide (*HAT*) may reach 4.3 m and the lowest astronomical tide (*LAT*) is around zero [3]. Tidal currents in the area are important hydrodynamic and sediment processes because they are channelized (convergence effect) in Khors, which are considered as narrow inland marine waters with bi-directional tidal currents in almost opposite directions.

Waves and their effects are noticeable hydrodynamic processes in the study area, but unfortunately wave data and measurements are lacking. Previous studies have depended on either observations or prediction models to explain the wave characteristics in the northern coast of Kuwait. Physically, the secondary prevailing winds (south-easterly winds) create the effective waves because of the longer fetch length. On the other hand, the prevailing north-westerly winds have limited effective waves since the study area is shielded by land resulting in short fetch. Wide intertidal flats also act as a natural protection of lowland coastline because the energy of the waves dissipates as it passes up the intertidal zone. Most effective waves occur during stormy south-easterly wind associated with high spring tide. Overall, wave effects have marked geo-morphological landforms in the study area, such as southern shell sand beach and the spit at Ras Al-Qayd.

Based on prediction model, [15] estimated the wave characteristics for 19 different locations in the Kuwaiti territorial waters. Location 18 and Location 19 are situated in the south and east of the study area (29.6^0 N – 48.4^0 E and 29.7^0 N – 48.5^0 E, respectively). The water depth in both locations is 4 m. The wave data was hind-casted for a total period of 12 years (1st Jan., 1993 to 31st Dec., 2004). The results of the prediction model show that the average wave height at both locations was less than 0.25 m, whereas the maximum significant wave height is about 1.4 m at location 18 m and about 1.7 m at location 19. In general, the study area is characterized by the lowest average and maximum wave heights with other locations in Kuwaiti territorial waters.

III. Material and Analysis Method

Two types of data have been employed on this study. First: data of tidal current velocities and directions, which were obtained from a floating monitoring station. This station was one of eight floating stations that were installed by the Marine Pollution Monitoring Department at Kuwait Environment Public Authority (EPA) [16]. Unfortunately, these stations functioned for a short period of time (two to three months) as they were damaged and spoilt by uninformed people. Hourly data were obtained from station # 1, which is located on the northern end of the study area (29^0 49' N & 48^0 22' E) for the period of 54 days from 6/2/2005 to 31/3/2005. Second data type: two bathymetric maps published by the Kuwait Ministry of Communication Surveys for years 1985 and 1998 (Fig. 4 and Fig. 5).

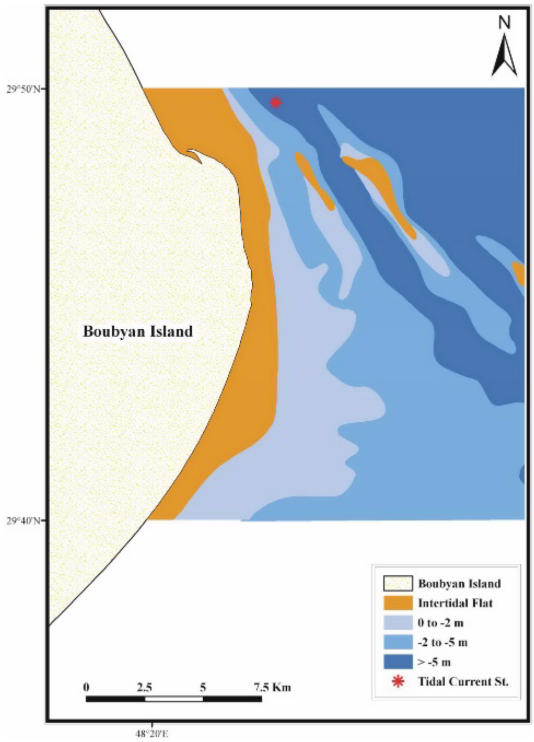

Fig. 4 Bathymetric map 1985 of the study area [17]

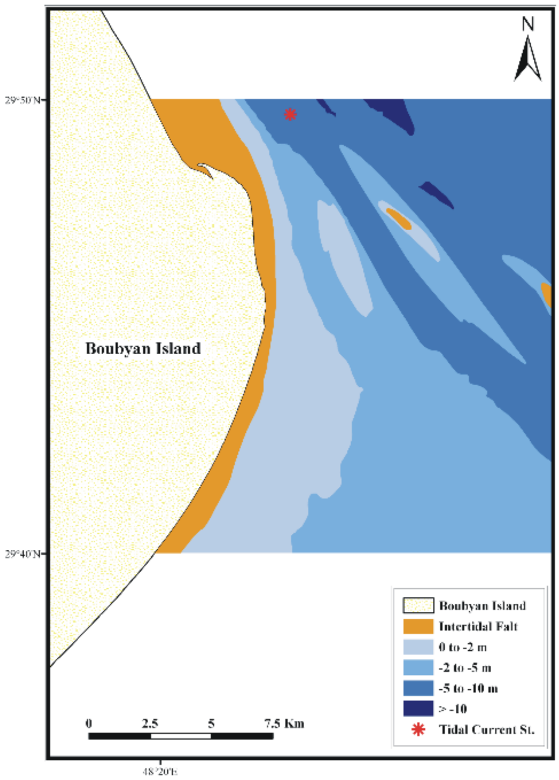

Fig. 5 Bathymetric map 1998 of the study area [18]

The tidal current velocities and directions were represented on rose diagram and were statistically analyzed in order to understand the tidal current behavior in the study area and to compare flood with ebb tides in terms of velocity and asymmetry. The bathymetry data for surveys in 1985 and 1998 were digitized and converted to separate ArcGIS 9.2 shapefiles in order to produce geo-referenced bathymetric maps of the study area. Analyses were done using Spatial Analyst tools in order to quantify and spatial examine the bathymetric changes, either accretion or erosion, for the period of 1985 to 1998 (13 years). In addition, the bathymetric change areas were overlapped with the bottom sediment map to find the percentage of bathymetric changes among various sediment types.

IV. Results and Discussion

A. Tidal Currents Behavior

The main tidal currents of the study area have a bimodal direction associated with the direction of Khor Abdullah – north-west for flood currents and south-east for ebb currents (Fig. 6). Other directions for the tidal current with very limited occurrence were found, but they were all of very weak velocities. These indicate the condition of low and high slack waters when the direction of the tidal current reverses. The average velocity for the measurement period was 0.46 m/s and the maximum velocity was 1.08 m/s during ebb tide. During spring tides, maximum velocities range between 0.90 m/s and 1.08 m/s; whereas, maximum velocities vary from 0.40 m/s to 0.60 m/s during neap tides.

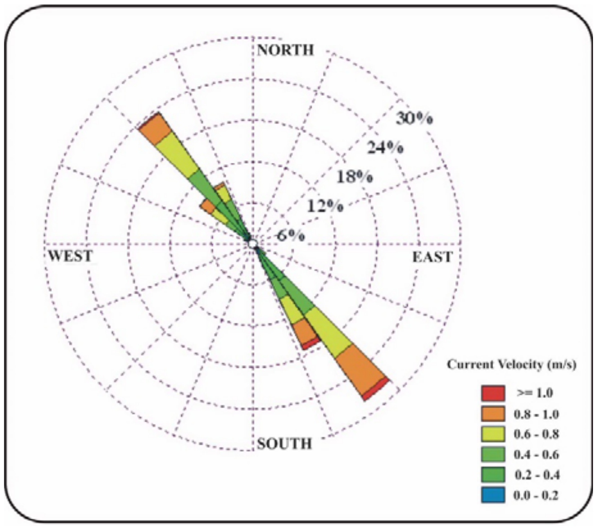

Fig. 6 Rose diagram showing the direction and velocity of tidal current in the measurement station

A detailed comparison of flood and ebb currents is shown in Table I and Fig. 7. The average flood velocity (0.50 m/s) is greater than the average ebb velocity (0.43 m/s). However, the maximum tidal current velocity slightly occurs during the ebb tide (1.08 m/s). Despite the occurrence of maximum velocity during the ebb tide, the overall current velocities during the flood tide are greater. This can be derived from Fig. 11, demonstrating an asymmetry between the flood/ebb velocities for the various velocity classes. The ebb is slightly higher for the lower velocity classes, whilst the flood exceeds the ebb for the higher velocity classes.

Since the bottom sediments in the study area are considered cohesive sediments, erosion usually occurs when the mean depth velocity ranges between 0.51 m/s to 0.58 m/s, and deposition occurs at a mean depth velocity of around 0.25 m/s [1]. Therefore, it can be assumed that deposition processes are similar during both tidal phases because of the similar percentage of flood and ebb for the lower velocity classes. However, the assumption for the higher velocity classes can be different, because the flood currents are clearly higher; particularly for the highest two classes (0.8 – 1.0 m/s and > 1.0 m/s). Hence, it is anticipated that the erosion process is relatively higher during the flood tide. This assumption may have some inaccuracies, because the current measurements were taken at hourly intervals, which gives a general condition rather than detailed result. Moreover, the -2 m and -5 m isodepths around the shoals, as depicted in Fig. 8 and Fig. 9, show an asymmetric pattern where they are longer in the south-east side as compared to the north-west side. These bathymetric features enhance the dominance of the ebb tide. This may be explained by the abundance of fine sediments from the ebb current approaching the study area, in contrast to relatively coarser sediments from the approaching flood currents. In view of the fact that tidal currents have a significant effect on fine sediment dynamics and have limited capacity to re-suspend coarse sediment, it is implied that a net ebbs suspended sediment flux. In other words, the important factor that supports the phenomenon of ebb-domination is the flood current that enters from open waters with low fine sediment, and the ebb current that reaches the study area from another area that has an abundance of fine sediment.

TABLE I
FLOOD AND EBB CURRENTS STATISTICAL CHARACTERISTICS

	Flood	Ebb
Average	0.50	0.43
Max	1.07	1.08
Std. Dev	0.28	0.25

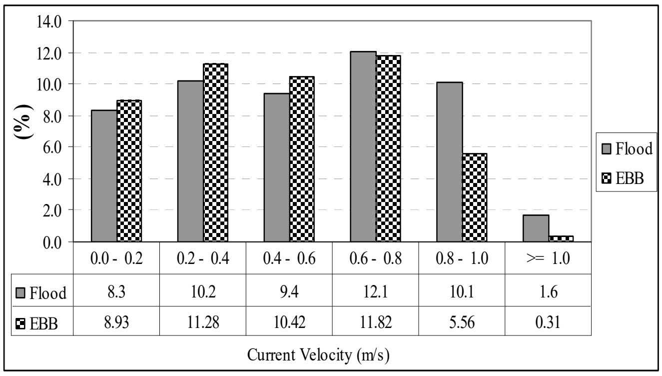

Fig. 7 Percentage of various velocity classes for flood and ebb current

B. Bathymetric Analysis

Bathymetric changes are a common feature in highly dynamic marine systems, such as the study area. Change analyses were carried out by comparing depth areas of 1998 bathymetric map with the 1985 bathymetric map (Fig. 8). It was noticed that during the 13 years (1985-1998), bathymetry had considerably changed. Intertidal flat and area with depth less than -2 m had decreased, particularly the intertidal flat, which was reduced by 45% (approximately 17 km^2). However, areas with depth greater than -2 m had increased. This indicates a high process of erosion and accretion within the study area.

Fig. 9 illustrates the overall amount and distribution of erosion and accretion areas. Only 23% (approx. 56.8 km^2) of the study area showed depth differences for the period 1985 to 1998. The general pattern of bathymetric change indicates the dominance of erosion process. The areas affected by erosion were approximately 49.85 km^2 (20.2% of the total study area), however they decreased to approximately 7.03 km^2 (2.8% of the total study area) for the accretional area. Spatially, erosional areas are widely distributed and occupy the deeper waters as well as the shallow waters. In contrast, limited distribution of accretional areas was found at the middle of the study area.

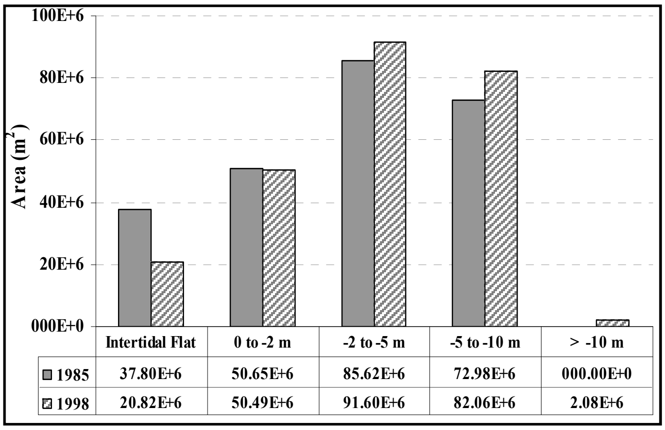

Fig. 8 Depth areas (m^2) between 1985 and 1998

Subtracting depth areas of the 1998 bathymetric map from the 1985 bathymetric map effectively highlighted the amount of erosion and accretion in the study area (Table II and Fig. 10). It is clear that most of depth change was for erosion range of -2 and -5 m (86.1% of the total depth change). On the other hand, major accretion was 3 m to 5 m (10.4% of the total depth change). This means that active depth changes (96.5%) occurred within depth change class of -5 m to 5 m. Fig. 14 shows evidence of the relationship between the depth differences and the distance offshore. The depth differences increase with the distance offshore for both erosion and accretion. Moreover, the width of intertidal flat had been decreased, particularly in the southern part. Offshore shoals in the study area had either disappeared, or had noticeably shrunk.

In terms of relationship between depth differences and bottom sediment types, erosion occurred in all sediment types while accretion took place only in mud and sandy mud types (Table III and Fig. 11). Because of the dominance of finer bed sediment in the study area (see Fig. 6), most of depth differences concentrated on the finer sediment types (mud and sandy mud). Despite the sandy mud area being larger than the mud area, depth differences were higher in the mud area (37.8 km2 or 66.4% of the total depth differences), as compared to the sandy mud area (17.3 km2 or 30.3% of the total depth differences). In the same manner, erosion in silty mud (1.8%) was greater than in muddy sand (1.5%), despite the larger area covered by muddy sand.

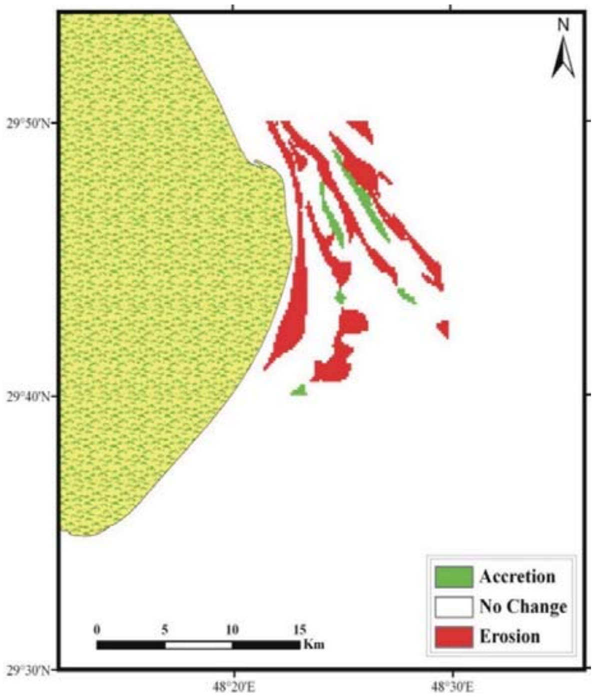

Fig. 9 Spatial distribution of erosional and accretional areas

TABLE II
THE AMOUNT OF DEPTH CHANGES FROM 1985-1998

Bathymetry Change from 1985-1998	Area (m^2)	%
-10	668,259	1.2
-8	206,859	0.4
-5	17,105,590	30.1
-3	17,260,462	30.3
-2	14,606,867	25.7
2	421,200	0.7
3	3,075,347	5.4
5	3,408,393	6.0
8	129,600	0.2
Total	56,882,577	100.0

TABLE III
DEPTH DIFFERENCES VS. BOTTOM SEDIMENT TYPES

Sediment	Accretion / Erosion	Area (m^2)	% of Accretion / Erosion
Mud	Erosion	32,194,475	56.6
	Accretion	5,561,713	9.8
Sandy Mud	Erosion	15,780,529	27.7
	Accretion	1,472,827	2.6
Muddy Sand	Erosion	863,267	1.5
Silty Sand	Erosion	1,009,766	1.8
Total		56,882,577	100.0

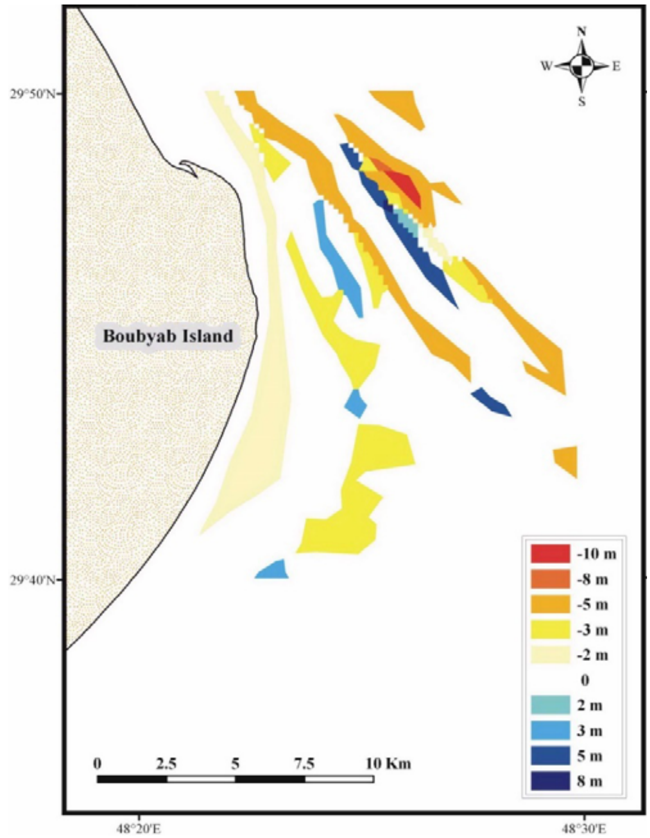

Fig. 10 Spatial distributions for the amount of depth differences from 1985 to 1998

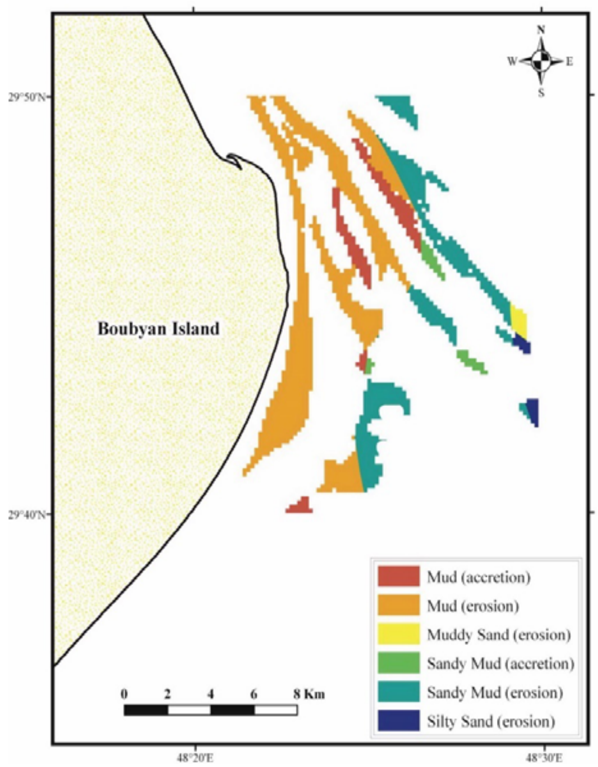

Fig. 11 The relationship between differences depth and bottom sediment types during the 13-years interval between surveys

It is, therefore, clear that depth differences in the mud area occur near the shoreline and around the parallel offshore shoals (shallow water). This condition can be explained by the effect of convergence (channelize) between the Boubyan shoreline and the offshore shoals. As the tidal currents flow either between Boubyan Island and offshore shoal, or between different offshore shoals, the cross-sections of these areas rapidly begin to narrow and the tidal current velocities accelerate again due to the convergence effects. Consequently, the sides of offshore shoals suffer from severe erosion when the tidal currents pass the narrow waterways between shoals. Moreover, the effect of long-shore processes resulting from southern wave activity along the spit at Ras Al-Qayd, lead to a serious erosion along the Boubyan intertidal flat.

The high erosion processes will generate high accretion processes, especially in the north of the study area (due to flood tide and southern long-shore current). Hence, the future viability of a proposed Boubyan Port could largely depend on routine dredging of the navigation channels. This is consistent with the statement of [19] who cited, "Most fluid muds occur as intertidal flats and subtidal mudbanks or mudshoals. Shoals composed of fluid mud range in size from a few hundred meters to large-scale shore-attached banks of soft mud… Migrating mudshoals with values up to 3 km/yr are unique in that they provide both benefits and problems to the coastal zone. …the primary problem is that soft masses of mud can cause severe shoaling in harbours, turning basins and shipping channels" [19, p.6.1].

Overall, [1] concluded that the coast is a multi-scale and non-linear dynamic system. Evolution of coastal morphology is inherently non-linear and time dependent as a consequence of the effect of morphodynamic feedback. Hence, details of coastal evolution are unpredictable and irreversible, when subject to stochastic boundary conditions over the long term, the Large-Scale Coastal Behaviour - LSCB [20]. The LSCB concept is governed by unpredictable input fed into a non-linear system, producing a highly unpredictable outcome. Therefore, it is difficult to determine how relatively short-term processes lead to long-term coastal behaviour.

Based on the LSCB concept, [21] state that many coastal areas have shifted from positive to negative sediment budgets over the Holocene time scale, therefore areas that were formerly accumulating are now eroding. For example, at Moruya on the southeast coast of Australia, erosion dominated during a stormy period in the 1970s, but in the 1980s the beach recovered to its pre-storm volume during this accretion-dominated period [22]. In inland marine waters, [23] hypothesized that in some lagoon inlets, systems may change their sediment transport tendency from flood-dominated when the lagoon is open, to ebb-dominated after lagoon infilling becomes advanced. Similarly, [24] explained how the Colne estuary in eastern England, evolved from flood- to ebb-dominated due to its changing morphology. It shifted from flood-dominated in 1918, with a shallow channel, to ebb-dominated in 1949 with a deeper channel.

V. Conclusions

The results obtained in this study allow the following conclusions to be drawn:

1. The future development projects in the northern coast of Kuwait need oceanographic and physical information in order to ensure environmentally sustainable development.
2. The recent lack of this information could lead to unsustainable planning decisions.
3. A better understanding of the tidal hydrodynamic system and bathymetric evolution in this area is necessary for future coastal management.
4. The coastal plain in the study area is characterized by very lowland with an extensive wet sabkha flat, while the offshore area is described by an irregular floor and is interrupted by muddy shoals.
5. The shoreline shape and orientation in the study area give a significant signature of wave effects that result from southeasterly wind.
6. The tidal currents have a bimodal direction (NW & SE) with average velocity of 0.46 m/s, and maximum velocity of 1.08 m/s. Comparison of flood and ebb currents reveals that the ebb is slightly higher for the lower velocity classes, whilst the flood exceeds the ebb for the higher velocity classes.
7. Because flood current enters from open water with low fine sediment, while the ebb current reaches the study area from an area with an abundance of fine sediment, the bathymetric features in the study area enhance the dominance of the ebb tide.
8. There are morphological developments and significant bathymetric changes for the period from 1985 to 1998 with dominance of erosion process as revealed by the analysis of historical bathymetric maps of the study area.
9. The active depth changes (96.5%) occurred within depth change classes from -5 m to 5 m.
10. Offshore mud shoals in the study area had either disappeared or noticeably shrunk over the 13 years.
11. The subtidal morphology affects depth changes, particularly in the convergence between the Boubyan shoreline and the offshore shoals.

Finally, for future coastal management in the study area and the northern coast of Kuwait, a great consideration should be given to the high sediment dynamics in order to ensure that development in such areas does not disturb the natural operation of coastal processes and to establish effective management plans that complement natural processes rather than disrupting them. An example of such management problem within the area, the rapid accumulation of mud occurs within the intake structure of the existing Subiya Power Station and Desalinisation Plan, which leads to frequent maintenance dredging and extra cost.

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