



Detection of shoreline changes along the coast of Jeddah and its impact on the geomorphological system using GIS techniques and remote sensing data (1951–2018)

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Abstract

The focus of this research was to monitor the spatiotemporal evolution of the Jeddah shoreline and its impact on geomorphological features. The Digital Shoreline Analysis System application (DSAS) was used for the statistical analysis of shoreline changes from 1951 to 2018. Two techniques were utilized to understand the general trend of shoreline movement (linear regression rate–LRR) and the changes between two successive periods (end point rate–EPR). The results show that trends generally shifted from the shoreline to the sea (accretion), particularly in the central part of the city around the port area where the maximum accretion rate reached 47.6 ± 0.2 m/year (an average of 17.8 m/year). These quite high rates are very limited in time and are linked to land reclamation works which have been very frequent in this part of the coast. The boom and bust of Jeddah resulted in human activities on the coast as well as the continued expansion of its port during the monitored period. An area of about 23 km² of sea and islets was backfilled for port facilities and various geomorphological units have undergone morphodynamic changes. Human intervention thus modified the configuration of the littoral leading to multiple consequences.

Keywords Shoreline change · DSAS · Accretion · Erosion EPR · LRR · Remote sensing · GIS · Jeddah · Saudi Arabia

Introduction

Coastal areas are dynamic interfaces of land and water that provide economic and social security to coastal habitations. In this context, they face multiple threats due to both natural and anthropogenic processes. These spaces are challenged by unprecedented populations and urban growth, which contribute to the exacerbation of coastal vulnerability and the development of island shore areas (Bukvic et al. 2020; Yasir et al. 2020; Matin and Hasan 2021). Thus, the evolution of the shoreline is strongly linked to climate change, anthropogenic pressures,

and coastal geomorphology (Le Cozannet et al. 2020). These zones are subject to intense land use and land cover changes. Moreover, they are being turned into residential and tourist areas or are occupied by socioeconomic and industrial infrastructures, with all of the risks entailed therein (El-Raey 2009; Al-Sheikh 2011; Nassar et al. 2018; Abdullah et al. 2019; Niang and Ascoura 2020). Monitoring spatial and temporal changes is becoming necessary for better management of these environments in the global context marked by rising sea levels and coastal erosion both of which pose serious threat to most coastal areas (Pajak and Leatherman 2002; Mayerle et al. 2016; Dedekorkut-Howes et al. 2020; Zhang and Hou 2020). The position of the shoreline and its historical movements are relevant geomorphological indicators for coastal resource development and for planning policies. The analysis of long-term and shoreline change trends also provides a better understanding of the morphological evolution of the coastal environment. (Niang and Ascoura 2020; Matin and Hasan 2021).

In the context of coastal vulnerability, accreting shorelines are considered less vulnerable as land results from their movement toward the sea. Eroding shorelines in contrast are considered highly vulnerable because of the resulting loss of

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associated natural and man-made resources. Thus, healthy beaches and shorelines are considered essential for the quality of life along coasts. Moreover they provide buffers for storms and critical habitats for many species of plants and animals. In addition, monitoring shoreline changes makes it possible to identify the nature and processes that cause these changes in a particular area, assess the anthropogenic impacts, and suggest management measures accordingly. Shoreline delineation is a pertinent exercise for coastal zone management, watershed definition, and flood prediction. This can be analyzed in a geographic information system environment by measuring differences in past and present shoreline locations.

While several studies have addressed shoreline movement in various countries at the global level (Hapke et al. 2011), very few have been performed in the context of Saudi Arabia (Niang, 2020). Little research has been conducted on coastal erosion or shoreline changes in the study area with studies concerned with these being limited to only certain parts of the coast. Al-Sheikh (2011), compared Landsat images, based on the north coast of Jeddah (i.e., Sharm Abhur and Salman Bay). Al-Dubai Talha et al. (2017), published a study focused on the southern Jeddah Corniche that relied on the visual interpretation of digitalized shorelines, mainly involving Landsat imagery. Aboulela et al. (2020) were interested in monitoring and predicting changes occurring in some sites on the Jeddah shoreline. These three studies did not use the Digital Shoreline Analysis System (DSAS) technique for statistical analysis of the rate of shoreline changes. Furthermore, the studies did not cover a long period with high-resolution images. Most of the studies that have used the DSAS application relied on shoreline extraction from remote sensing data, which can provide valuable information with reasonable accuracy by virtue of spatial and temporal scales.

Jeddah is the largest port city on the Red Sea (Spalding et al. 2001). Its coveted coast is a fully artificial space, partly because of the city's urban and demographic growth and partly because of its geomorphological setting being wedged between the Hijaz Mountains in the east and the Red Sea in the west (Abu-Ouf and El-Shater 1991; Al-Sheikh 2011; Youssef et al. 2016). The coastal geomorphology of the study area is characterized by the presence of numerous landforms including small bays, rocky coral reefs, submerged reefs, coral islands, etc. These geomorphic units are subject to continuous changes (Bruckner et al. 2012; Nofal and Abboud 2016). Under these circumstances, it is important to evaluate historical trends related to shoreline changes through remote sensing data and GIS techniques (e.g., DSAS) that allow for a statistical study of coastal dynamics, especially as measurements are rare and often limited to port areas (Rasul and Stewart 2015). Thus, any changes affecting the shoreline have an environmental and morphological impact on the city (Mayerle et al. 2016). This study focuses on the evolution and dynamics of the shoreline in different periods between

1951 and 2018. The preliminary analysis of the factors of change in these Jeddah shores highlights the human role in shaping the shoreline during different periods. Human intervention resulting from the city's rapid development and the port's extension been the major factor controlling the spatial and temporal dynamics of shoreline changes and their implications.

The rapidly growing economic importance and urban development of shore areas will lead to the city encroaching on the marine environment resulting in a series of problems related to shoreline dynamic trends and shore geomorphological changes with anthropogenic and natural driving factors. Detection and analysis of retracted shorelines from remote sensing data will be important for gaining a better understanding of morphological dynamics of coastal areas.

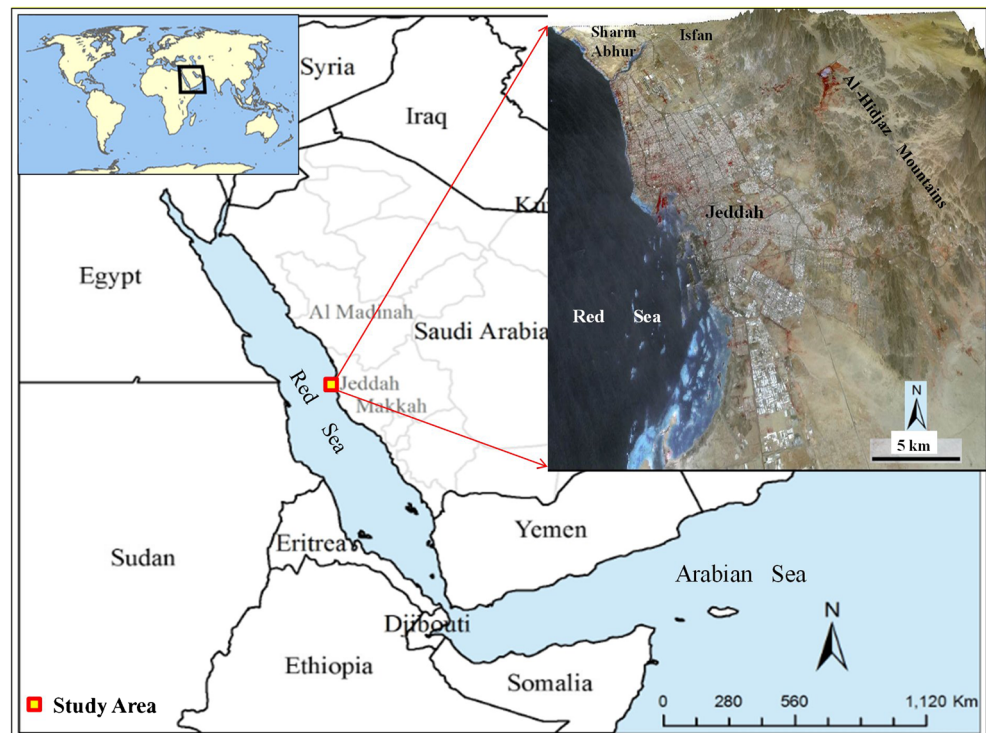
However, shoreline changes assessment in Jeddah are relatively rare if not nonexistent. In particular, there is an absence of detailed studies that calculate changes rates of change using the DSAS technique (which is used for the first time, to the best of our knowledge, by the present study) to assess shoreline changes in Jeddah. Moreover, there is a lack of research on the evolution of geomorphological features morphodynamic in the study area despite numerous scientific studies being conducted in this context.

The main aim of this study is to analyze the shoreline changes from 1951 to 2018 and detect their impact on the geomorphological system along Jeddah's city coast, using GIS techniques through DSAS application and multi-source and multi-temporal remote sensing data. The statistical methods included in the DSAS are one of the most parameters used to compute the short and long-term spatiotemporal erosion and accretion rates along the shoreline. This is useful for examining the costal morphodynamics and landforms of Jeddah's shore with emphasis on the main driving factors.

Study area

Jeddah is located in the western region of Saudi Arabia on the coastal plain of Tihamah between the Red Sea and the mountains of Hijaz (Fig. 1). This cosmopolitan city is the most important urban center of the Red Sea, being home to the largest and most dynamic commercial port. Jeddah is the nerve center of the Red Sea and the second-largest city in the kingdom. Its geographical location on the ancient trade routes and its status as a seaport and airport through which the vast majority of pilgrims travel to the two holy cities of Mecca and Medina have made it one of the cities that has experienced the largest growth in Saudi Arabia. While the population was estimated at nearly 1 million at the end of the 1970s, it increased to 1.4 million in 1986, and exceeded three million in 2010 (Ewea 2010). It now stands at nearly 3.5 million, according to the municipality of Jeddah, representing

Fig. 1 Study area



14% of the population of Saudi Arabia, and have a growth rate of 3.5%.

The morphological setting is characterized by the Tihamah littoral plain (maximum width of 40 km), located at the foot of the highly dissected Precambrian granitic mountains of Alhijaz, whose peaks reach up to several hundred meters (Monnier and Guilcher 1993). Hydrologically, there are 24 watersheds in the context of the flooded area. Sixteen watersheds are directed to the city of Jeddah to the west, while the rest flow in a southwesterly direction toward the great valley of Wadi Fatimah (Al Saud 2010). The presence of volcanic tongues and quaternary sediments plays an important role in locating the population and human activities following the presence of springs as well as loose and fertile lands. The deltas of coastal wadis are affected by human activities along the Red Sea coastal plain (Fig. 2). The study area includes various morphological features, such as flat-lying sandy beaches, lagoons, sabkhas, sea islands, bars, spits, and mountainous landforms. The geomorphologic unit areas are controlled by the structures are aligned with the Red Sea shore (Qari 2009).

Materials and methods

Data used

Multi-source and multi-temporal remote sensing data with high spatial resolution were used in this study to cover the

Jeddah coast in 1951, 1966, 1972, 1986, 2003, 2010, and 2018.

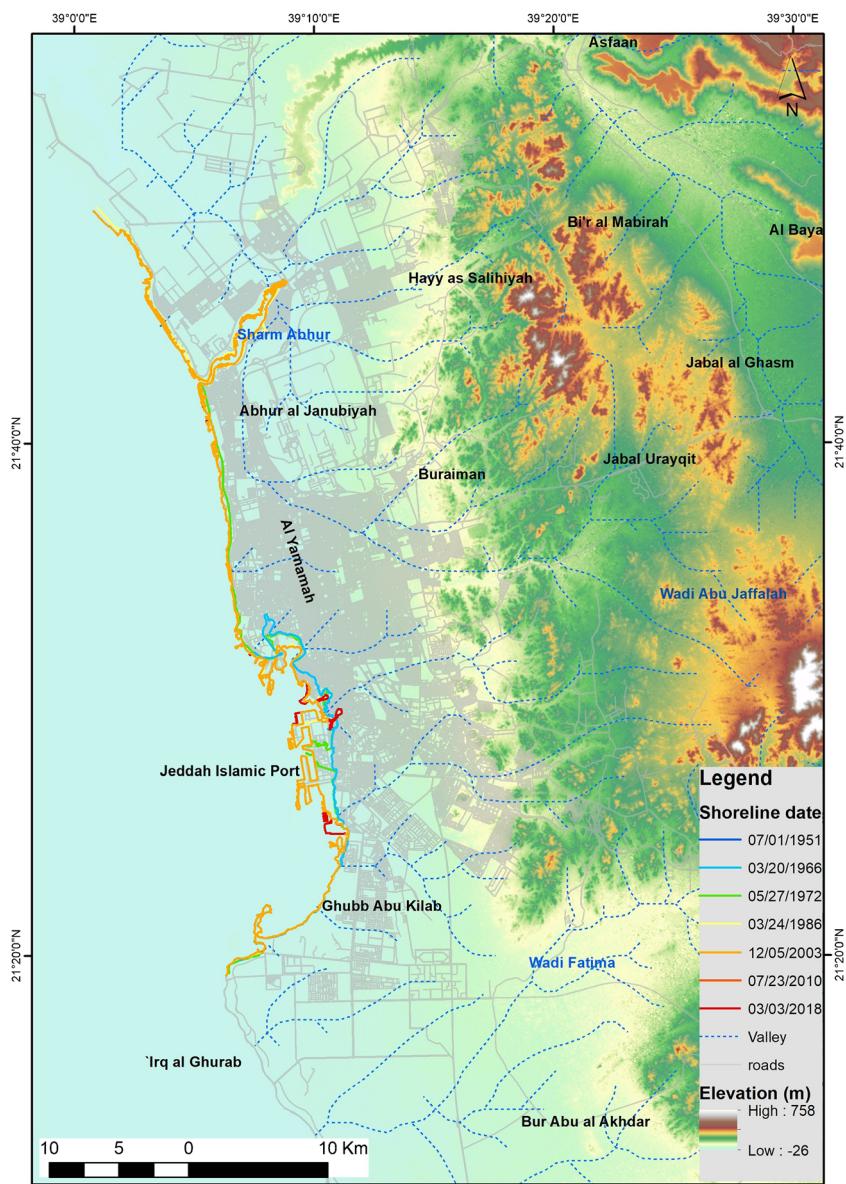
- The first 3 years were covered by aerial and satellite photographs taken by CORONA, a U.S. reconnaissance satellite that provided fine resolution, panchromatic data from 1960 to 1980 (McDonald 1995). These data were declassified in 1995. The acquisition of CORONA images with fine spatial resolutions and wide spatial coverage qualified them for use in a wide range of scientific and mapping applications.
- The 1951 aerial photographs were taken and mosaicked by Aero Service Corp. Photogrammetric Engineers, Philadelphia; these photographs covered the south and center of the coast.
- The other periods were covered by optical satellite images: SPOT in 1986 and 2010, OrbView3 in 2003, and Sentinel-2 in 2018.

All these data can be downloaded from the USGS website (<https://earthexplorer.usgs.gov>) except 1951 aerial photographs. The characteristics of the data are detailed in Table 1.

Image processing

The geometric correction process was performed from control points on the orthorectified reference image, from which all others were rectified using the ERDAS IMAGINE software.

Fig. 2 DEM SRTM and topographic context of the study area



The next step was to project the images in Universal Transverse Mercator (UTM) format with reference to the WGS-84 datum of the orthorectified reference image (sentinel in 2018). After rectification, it was found that the root mean

square error (RMSE did not exceed one pixel, revealing a high geometric match between the images. All rectified images were exported to the ArcGIS software to digitize the shoreline (Fig. 3).

Table 1 Details of the image dataset

Data set	Acquisition dates	Resolution (m)	Coverage zone
Aerial photograph	07/01/1951	4	South-center
CORONA/Satellite photo	03/20/1966	0.6	South-center
CORONA/Satellite photo	05/27/1972	2	South-center North
SPOT CIB 10	03/24/1986	10	South-center North
Orbview-3	12/05/2003	1	South-center North
SPOT 5	07/23/2010	2.5	South-center North
Sentinel 2	03/03/2018	10	South-center North

Shoreline extraction and indicators

The high water line (HWL) shoreline was chosen; as this land-water interface was clearly visible in the images through the contrast of the dry beach with the darker wet beach. The HWL can easily be interpreted visually from aerial photography and high resolution satellite imagery (Kelly and Gontz 2020). It is considered by many researchers to be the best indicator of shoreline position for historical studies of shoreline kinematics, especially in non-tidal areas (Crowell et al. 1991; Pajak and Leatherman 2002; Wernette et al. 2017). According to Sanlaville and Prieur (2004) and Bruckner et al. (2012), the tidal range around Jeddah is insignificant, and there is no difference in tidal heights over 24 h. The HWL is also known to be easily localizable in the field and by photographic interpretation with a variable margin of error (Pajak and Leatherman 2002). Given that the area studied is highly artificialized and urbanized, the shoreline corresponds in the central part of the study area to the limit of the harbor facilities, including the section jetties greater than 20 m (Zhang et al. 2014).

In this study, the Jeddah shorelines were extracted from remote sensing data using ArcGIS 10.6 .The manual method (digitizing) was favored for shoreline extraction because it promotes the judgment and interpretation skills of the operator (Matin and Hasan 2021) Visual interpretation is regarded as the most common and reliable shoreline detection technique

(Boak and Turner 2005; Tian et al. 2020) while automatic algorithms are not adapted for multisource remote sensing data and need many adjustments to get accurate results (Toure et al. 2019; Tian et al. 2020). Thus, shoreline delineation was based on visual interpretation from remote sensing data in a digital format. It was easy to delineate the shoreline because the spatial resolution of the images helped in distinguishing the shoreline that was developed and urbanized over a large part of the coast. The dynamics of the shoreline were measured from the superposition of multiple shorelines digitizations for the different years. Figure 4 shows a portion of the shorelines extracted for the different dates.

Estimation of shoreline position uncertainty

Several sources of uncertainty can affect the accuracy of the reference line positioning and, hence, the reliability of measurements of the historical shoreline evolution. They can be divided into two categories: errors introduced by data sources and errors related to methods of measuring and interpreting the shoreline (Moore 2000; Wernette et al. 2017). Errors in relation to the shoreline position in historical images, georeferencing, choice interpretation and shoreline digitization, geometry, and image resolution were all taken into consideration. Several types of uncertainties are often identified by researchers (Hapke et al. 2011; Chenthamil Selvan et al., 2014). In this study, the uncertainties related to georeferencing

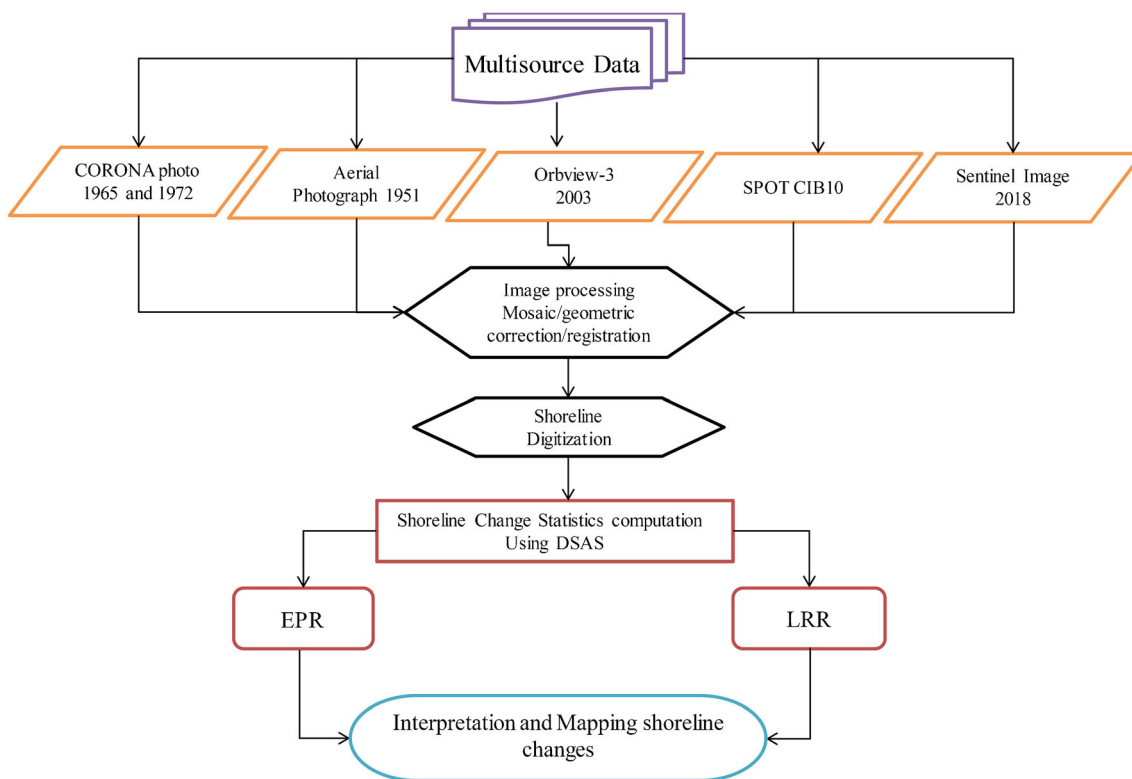


Fig. 3 Flowchart of the methodology for shoreline change analysis

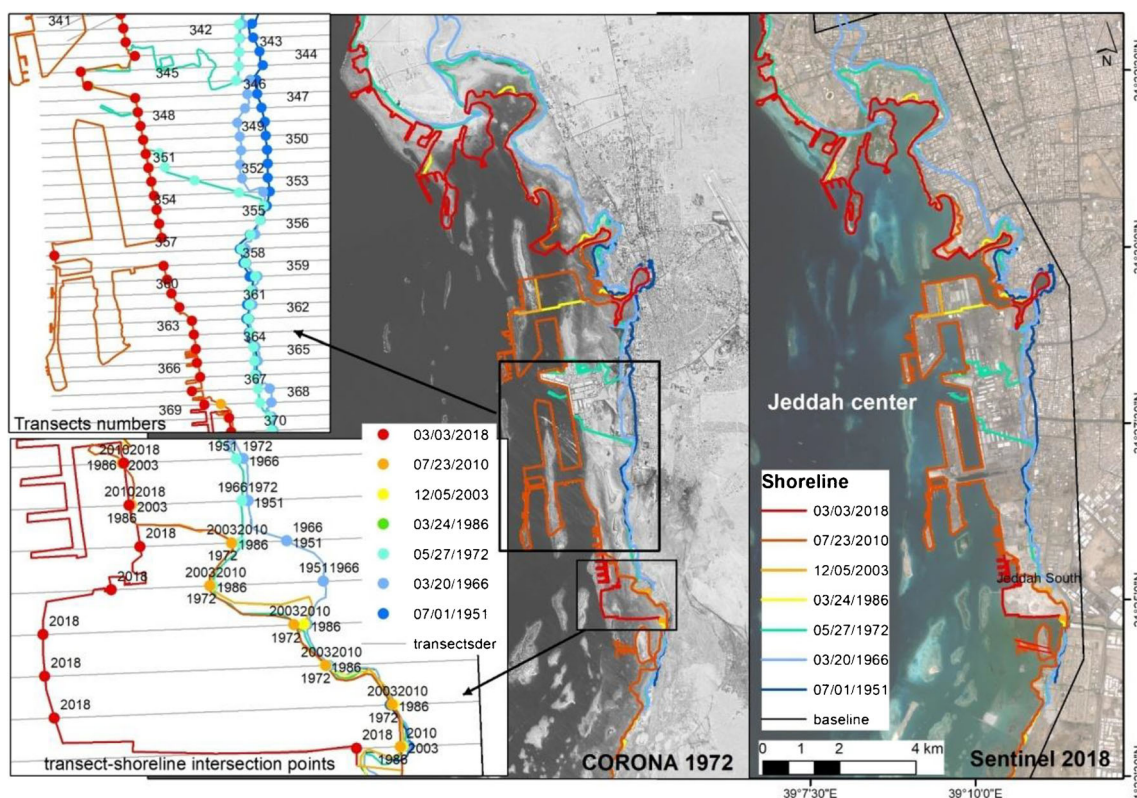


Fig. 4 Multi-temporal extracted shoreline positions (Jeddah center seaport) and the transect-shoreline intersection points used in rate-change calculations

(Eg) and associated with the digitalization of the shoreline (Ed) and pixel errors (Ep) were calculated. Ed was calculated as the standard deviation of the shoreline position from repeated digitizations of the same section of coast by a single operator. Eg is the value of RMSE. This error measures the accuracy of control points between the true and transformed locations of the control points. Ep is the pixel size of the image. The tidal change was negligible (Sanlaville and Prieur 2004; Zubier 2010; Bruckner et al. 2012; Rasul and Stewart 2015; Antony et al. 2021) meaning, its impact on the shoreline change due to tide variation was very small (Elnabwy et al. 2020) so it was not counted as a source of uncertainty due to the resolution of the imagery used. The uncertainty (U) associated with the determination of shoreline position was calculated for all periods using the Eq. 1 (Hapke et al. 2006, 2011; Baig et al. 2020):

$$U = \sqrt{E_g^2 + E_d^2 + E_p^2} \tag{1}$$

The different sources of uncertainty were calculated according to the quality of the diachronic data used. The georeferencing uncertainty that represented the maximum acceptable RMSE varied from one source to another (between 0.3 m and 8 m). It was higher for the photographs in the north and south zones because of the scarcity of fixed markers on the ground before the massive urbanization of the coast in the early 1980s. The digitization error specified in this study was

between 0.3 m and 5 m. The pixel error varied between 0.6 m and 10 m, influenced the shoreline determination. The total error was higher for CORONA data due to distortions related to image geometry.

Uncertainty was also estimated for the rate of shoreline change. For each transect, the uncertainty associated with the rate of change of the end point (Ur) was the square root of the sum of the uncertainties of the shoreline position for each year divided by the number of years between the two shoreline survey dates (Hapke et al. 2011; Himmelstoss et al. 2018; Baig et al. 2020), using the Eq. 2.

$$U_r = \sqrt{\frac{U_1^2 + U_2^2}{\text{year2} - \text{year1}}} \tag{2}$$

U1 and U2 were the total shoreline uncertainties for the first date (year1) and the last date (year2), respectively. Tables 2 and 3 provide the averages of the shoreline position errors and those associated with the change rate calculations (EPR).

Calculation and interpretation of shoreline change rates

The rates of change of the baseline were calculated using two approaches. A short-term analysis (EPR) was applied using successive shoreline pairs, namely 1951–1996, 1966–1972,

Table 2 Estimated accuracy of the shorelines derived from various sources and average uncertainty for extracted shorelines

Measurement uncertainty	1951	1966	1972	1986	2003	2010	2018
Georeferencing error (E_g)	6 m	2.4 m	4.12	2 m	1 m	1 m	2 m
Digitizing error (E_d)	2 m	0.6 m	1.03	5 m	0.5 m	1.25 m	5 m
Pixel error (E_p)	4 m	0.6 m	2.06	10 m	1 m	2.5 m	10 m
Total shoreline uncertainty (U)	7.4 m	2.5 m	4.7 m	11.35 m	1.5 m	2.9 m	11.35 m

1972–1986, 1986–2003, 2003–2010, and 2010–2018. A long-term analysis (LRR) exploited all shorelines and was used to calculate shoreline changes over 67 years, from 1951 to 2018. The LRR determines a rate-of-change statistic by fitting a least squares regression to all shorelines at specific transects (Thieler et al. 2017).

The short- and long-term change rates for each transect were generated using the DSAS version 4.4, which was developed by the USGS (Thieler et al. 2017). This tool is a freely available application designed to work with ESRI ArcGIS software. DSAS was used in this study to generate orthogonal transects spaced 100 m apart along the coast and calculate change statistics, accordingly, using distinct approaches, including end point rate (EPR), linear regression rate (LRR), net shoreline movement (NSM), shoreline change envelope (SCE), and weighted linear regression (WLR).

Note that while linear regression is the most commonly used statistical technique for expressing shoreline movement and estimating rates of change (Crowell and Leatherman 1999), it does not take into account shifts between intervening periods that may slow down or accelerate trends (Himmelstoss et al. 2017; Santos et al. 2021) in response to various factors. Average short-term change rates (EPR) filled this gap and highlighted all trends for each transect between the different periods. The calculated rates represented the shore position differences between 2 years, divided by the time elapsed between the two shorelines. In this study, the time that elapsed between the oldest and most recent shoreline varied between 6 and 15 years throughout the observed period. This allowed us to reconstruct the main stages of the occupation of the Jeddah shoreline.

Table 3 Estimated error for shoreline change rates

Period	Annualized error (m/year)
1951–1966	0.52
1966–1972	0.88
1972–1986	0.87
1986–2003	0.67
2003–2010	0.46
2010–2018	1.46
1951–2018	0.2
1972–2018	0.26

An analysis of the kinematics of the shoreline was then performed at 100 m intervals along a 120-km section of the coast (from 1972), covering the south of the city to its north.

Results and discussion

Erosion and accretion were calculated using two techniques. The EPR statistic can be used to compute changes in terms of rates or areas between two successive shoreline pairs. The major disadvantage of the EPR is that only two shorelines (the newest and the oldest) are taken into account in the computation. With The LRR, all of the data are used, regardless of changes in trends or accuracy. By comparing erosion and accretion in the study area, it was found that accretion was dominant in the Jeddah port and Sharm Abhur areas. Furthermore, it was associated with human activities on the coast even if natural causes cannot be excluded in some cases. The stabilized shoreline was also linked to human intervention (coastal engineering, land use changes) following urban extension on the coast. Natural and anthropogenic factors were the cause of erosion,

Long-term analysis

The long-term evolution of the shoreline was calculated over two periods: 1951–2018 (67 years) and 1972–2018 (46 years). The first period was the longest, but the 1951 shoreline only covered the southern part of Jeddah. The entire study area drew from the 1972 data. The long-term analysis focused on both periods. Figure 5 shows the overall shoreline changes calculated from the analysis. The first period exclusively covered the center of Jeddah (a distance of 18 km), corresponding globally to the port area, there was mainly accretion, reflecting the shoreline advancing to the sea following the extension of port facilities. The maximum rate reached 47.6 m/year \pm 0.2 m and was recorded during the boom period of the 1970s and 1980s when the port experienced its greatest spatial extension different, terminals were built. The average for this period was 17.8 m/year. The second period, which covered the entire coast, showed what were essentially the same trends, (accretion or stability over most of the 120 km of the studied area). The maximum rate was 49.27 m/year, while the average was 5.5 m/year.

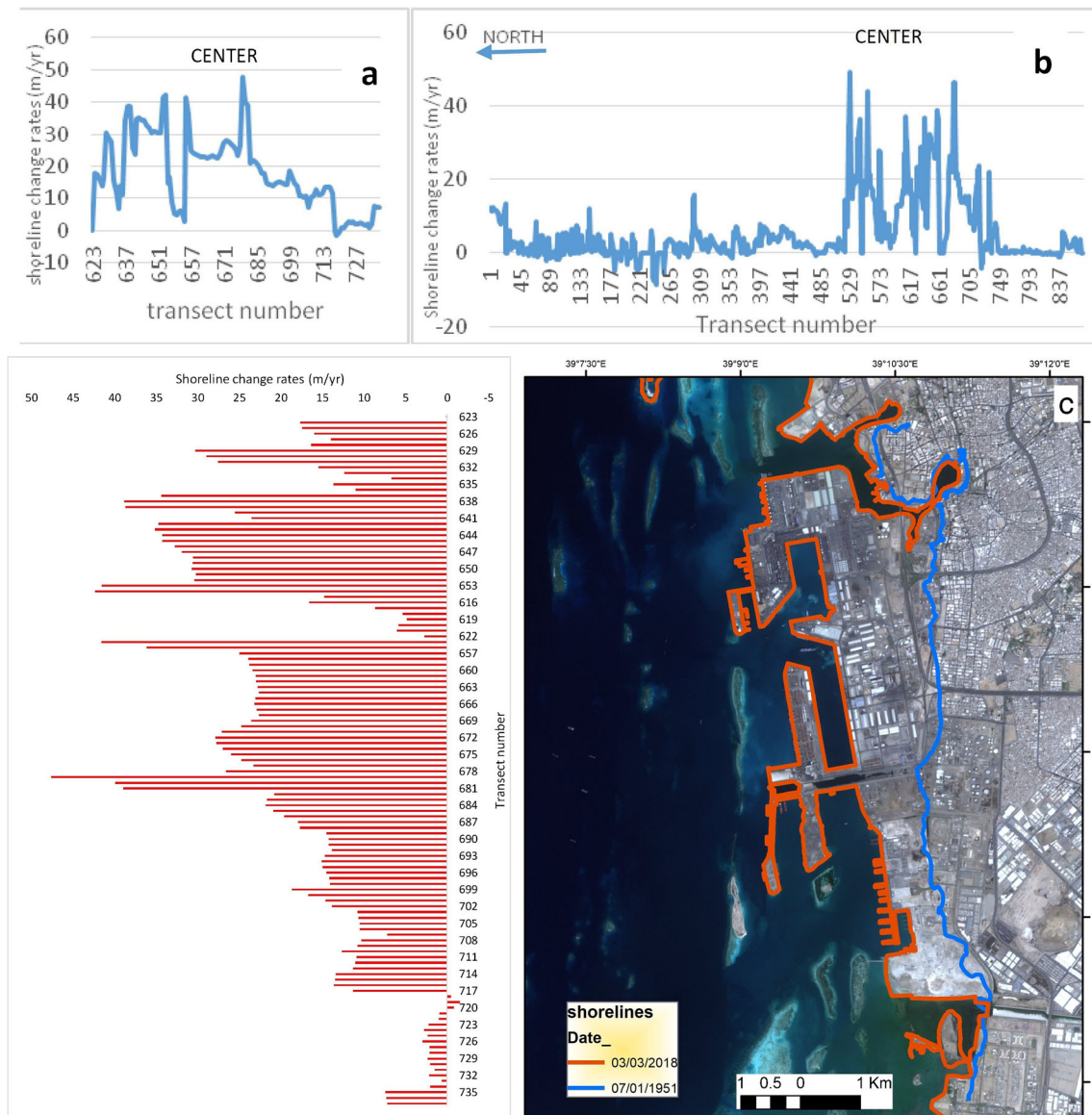


Fig. 5 Average long-term shoreline change rates. **a**, **c** Jeddah center 1951–2018, the seaport area. **b** All the study area 1972–2018

Note that during these two periods, the shoreline recorded very strong accretion and insignificant erosion. The part that experienced the highest rate of change was the center, the port area, hence the variation in averages. These results also show that the main factor in shoreline change was mainly anthropogenic. The shoreline was affected by the city's urban extension and occupation by tourist and recreational infrastructures (as shown in Fig. 6). The rapid urban growing and sea reclamation for industrial zones and ports explain the high rates of shoreline changes in this part of the study area. In general, these accelerated changes occur over very short periods of time.

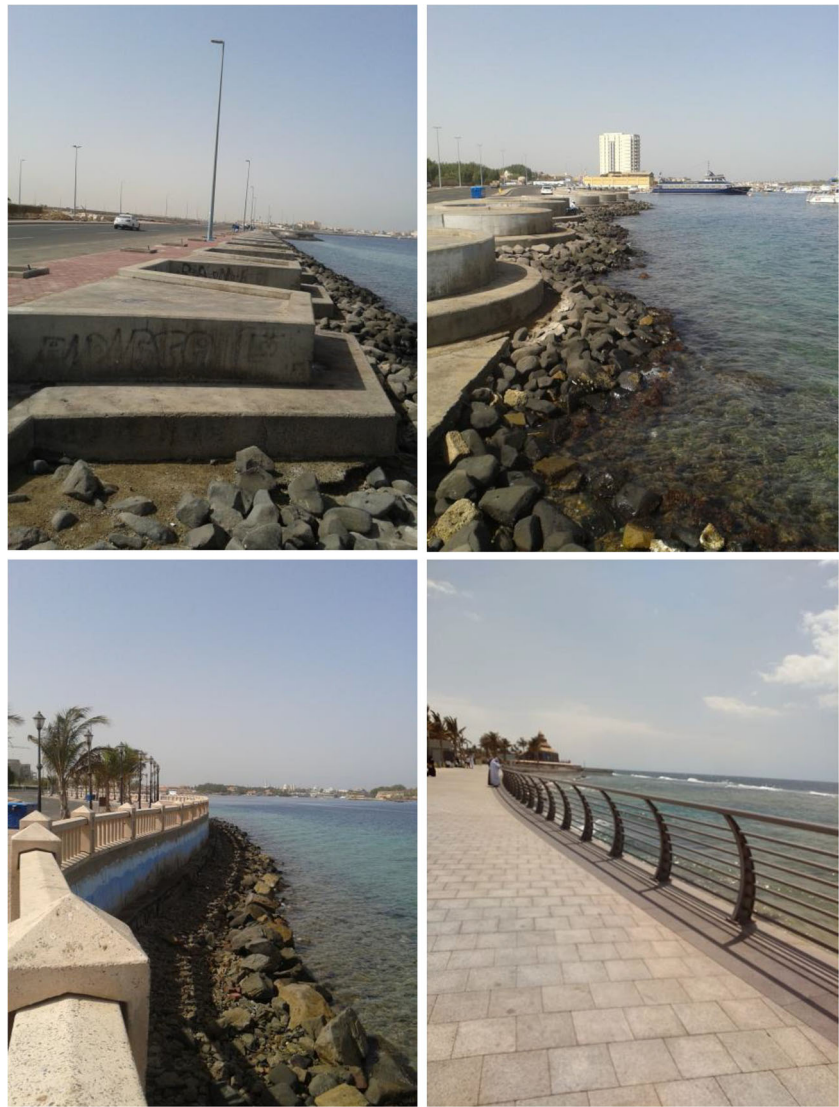
The various infrastructures stabilized certain sections of the shoreline and played a role in protecting against erosion, which can be observed with the small portions of the shoreline

that lacked infrastructures. Erosion rates were, however, very low.

Short-term analysis

Short-term analysis of shoreline changes highlights short-term trends that may be related to an acceleration and a temporary slowdown or even reversal of shoreline movement. It also allows for the case of a shoreline subjected to intense human activity, such as that of the area studied, to follow the different stages of infrastructure development along the coast. Thus, assessment of the speed and cartography of the evolution rates of the littoral relied on analysis and the interpretation of data contained in the attribute tables generated by the DSAS application. The indices proposed by this application reflect the

Fig. 6 Different aspects of human occupation of Jeddah coast (Sharm Abhur area)—Source: Authors, 2019



temporal evolution of the shoreline. The EPR index made it possible to evaluate the evolution between two successive shorelines. The results of the EPR between the different pairs of years are shown in Fig. 7a, b. The variation shown in Fig. 7b identifies areas with strong accretion, with the center reaching up to 200 m/year. This area corresponds to the port of Jeddah, which has experienced significant extension since the 1970s (Baesse 2012; Mayerle et al. 2016).

Shoreline changes during the period 1951–1966

The 1951 aerial photographs essentially covered the central part of the area (124 transects). The results of this period generally indicate an average rate of 5.72 m/year with a maximum of 44 ± 0.52 m/year and a minimum of -7 m/year. Erosion affected 20% of the sections, while accretion reached 66% of the segments. This period was particularly marked by weak human activity on the shoreline.

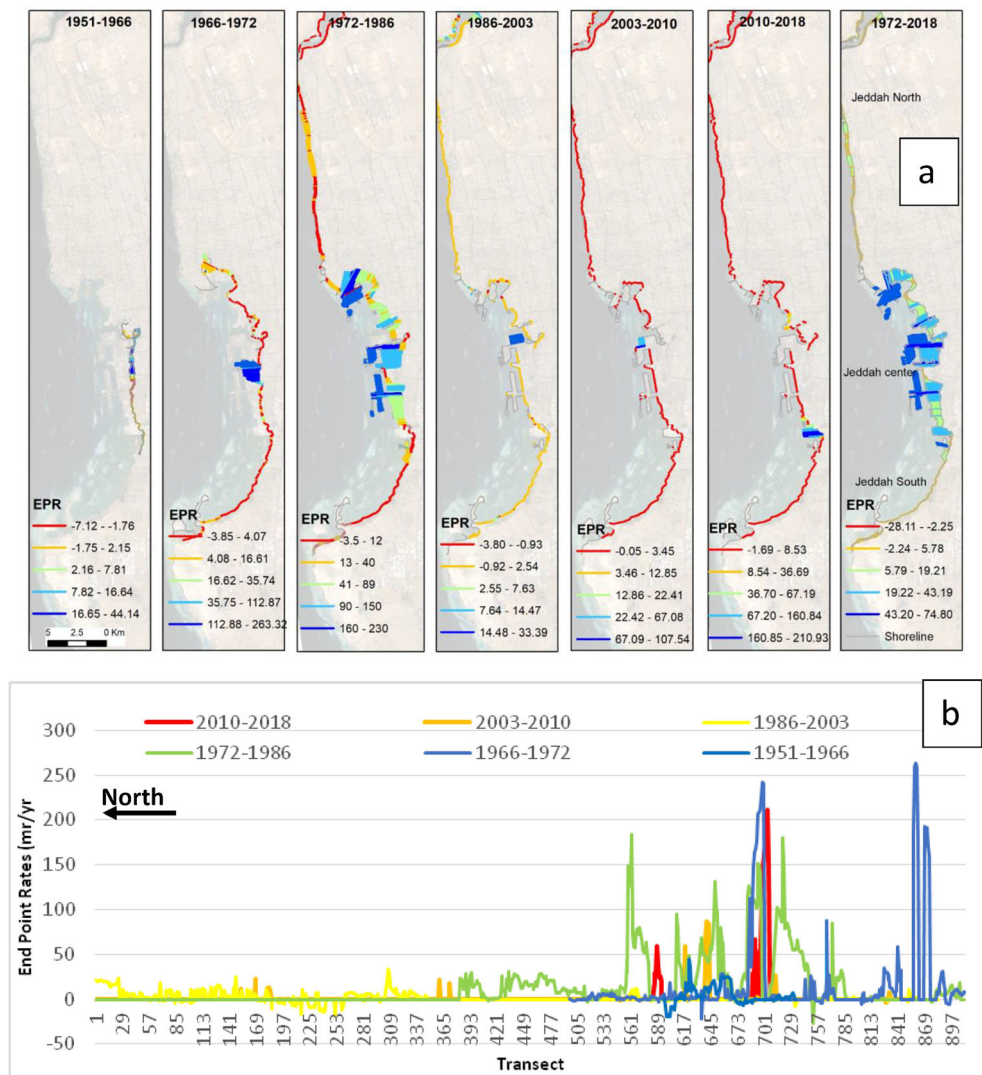
Shoreline changes during the period 1966–1972

This period covered the southern and central parts of the studied area (381 transects). It was marked by the first large extension of the port, which is visible on the 1972 CORONA photographs and was materialized by the encroachment of the shoreline. The maximum accretion reached 263 ± 0.88 m/year. The average rate was 16.9 ± 0.88 m/year, while the minimum was -3.8 ± 0.88 m/year. Furthermore 70% of the beach was by way of accretion, whereas erosion accounted for 14%.

Shoreline changes during the period 1972–1986

This period was distinguished by a total coverage of the area studied by the two images. The 1986 image is distinguished by greater human pressure on the coast. The port recorded its largest spatial extension, materialized by the unprecedented

Fig. 7 a, b End point change rates for transects in m/year for periods 1961–1966, 1966–1972, 1972–1986, 1986–2003, 2003–2010, 2010–2018, and 1972–2018. The transects with negative values (red color) indicate erosion and positive value (blue) show accretion rates that fall within the uncertainty of the data at the 95% confidence interval



development of infrastructures and port facilities. Urban growth also led to a great advance of the urban fabric toward the sea, occupying large areas of the shoreline in the central part. In the southern part, there were roadside developments on the seaside, while the north had the establishment of infrastructures on the coast. The urban growth of this period can be explained by the launch of the second Saudi national plan and the 1973–1983 consolidation of the oil boom. According to Abdu et al. (2002), this period marked the economic and diplomatic boom of Jeddah. Several development projects and programs were adopted, with a focus on the urban sector. The population of the city increased from 381,000 in 1971 to 1,000,000 in 1983. This context is reflected in the evolution of the shoreline, with the maximum change rate (accretion) reaching 180.8 ± 0.87 m/year and the minimum (erosion) reaching -3.4 ± 0.87 m/year. More than 20% of the transects showed accretion rates above 20 m/year, particularly in the central part. Littoral erosion represented only 3% of the transects. The average rate (accretion) in the central part was 39.8

± 0.87 m/year, while the rate for the whole shoreline was 13.4 ± 0.87 m/year.

Shoreline changes during the period 1986–2003

The evolution of the shoreline in this period did not follow the same trends as the others. The stable zones dominated most of the shoreline, (46.7%). Although the period was the longest, the maximum change rate (accretion) recorded was the lowest, reaching only 33.39 ± 0.67 m/year. Moreover, this rate was for the first survey outside the central part (located to the north, in the area of Sharm Abhur). This period also marked the beginning of an extension of the anthropic pressure on the entire shoreline. The weak of the maximum rate can be attributed to the fact that the port area had only experienced a very limited extension. The changes mainly affected the northern part of the study area, where the shoreline became almost entirely artificial with the installation of various recreational or tourist infrastructures along the beach.

Shoreline changes during the period 2003–2010

During this period, the shoreline was characterized by stability, which covered more than 95% of the transects. This situation was due to the stabilization of much of the beach area by different land management schemes. The maximum change rate (accretion) reached 107.5 ± 0.46 m/year, located in the port area, which had undergone a small extension. The minimum rate (erosion) was -0.05 ± 0.46 m/year, while the average was 0.8 ± 0.46 m/year.

Shoreline changes during the period 2010–2018

The same global tendencies noted during the preceding periods were outlined in this one, with stable transects representing 96.7%. The maximum change rate recorded was 210.93 ± 1.46 m/year, in an accreting consecutive to the last extension of the port towards the sea. This high rate can also be explained by the fact that the period is very short. Another accretion zone was located north of the central part. These two accretion zones located on either side of the port corresponded to extensions of the port area. Elsewhere, there were no noticeable changes in the shoreline. The minimum rate was -1.69 ± 1.46 m/year, while the average rate was 2.27 ± 1.46 m/year.

Note that the most significant changes recorded during these different periods are mostly linked to spontaneous and localized human interventions which do not take place over the entire period. Thus, the interpretation of the results may be biased, especially in the central part of the area where port extensions have been very frequent. Changes in area may be another indicator of changes in the littoral zone.

Impact and drivers for spatiotemporal variability of shoreline changes

The evolution of the shoreline measured over different periods from 1951 to 2018 shows that the dynamics of the shoreline are mainly controlled by human actions. While there are certainly natural factors, linked in particular to climate change and hydrodynamic conditions, their impacts are weaker than those of anthropogenic factors. Furthermore, it is more difficult to measure them in the study area in the long term. Many studies conducted in different geographic areas have concluded that human activities are the main driving force behind shoreline changes (Amrouni et al. 2019; Tian et al. 2020) .

Part of the urban expansion has come at the expense of the coast and the sea. The most significant changes have occurred in the port of Jeddah which has undergone continuous expansion following successive backfilling. Thus, aggradations were recorded for this zone across all periods. To the north of the port area is a stable area linked to the development of this part for recreational purposes such as road embankment,

promenade, and urban beach (see Fig. 6). The lagoons have also been partly backfilled on account of urban expansion in the coastal area.

Drivers of coastal shoreline changes

Natural drivers Various natural driving forces should also be considered here such as sea level rise; however, it is not easy to identify their influence apart from anthropogenic activities on shoreline changes. Among the natural drivers that played a role in shoreline change, we can note waves, precipitations or water, and sediment discharges of rivers at outlets, even if most of the wadis no longer end in the sea because of the urban sprawl on their tracks. Mangroves, reefs, and the numerous islands in the study area can be considered as protective barriers against erosion

Jeddah coastal area will be affected by global sea level changes. The Intergovernmental Panel on Climate Change (IPCC, 2019) predicts that the impacts of climate change will result in sea level rise, between 0.29 m and 1.1 m. With the increase in sea level, on the one hand, and given the topography of the shore, on the other hand, Jeddah are considerably vulnerable to the risks of coastal erosion, and floods as well as to extreme climatic events (Aljoufie and Tiwari, 2015; Khusaifan, 2020; Alothman and Bos, 2020). (Khusaifan, 2020). Khusaifan (2020) has identified that 24 coastal districts within Jeddah city will be impacted by sea level rise of 1 m. Moreover, the climate adaptation policies are still insufficient (Aljoufie and Tiwari, 2015 ; Khusaifan, 2020).

Hydrodynamic conditions indicate that multi-directional swells are present in the Jeddah nearshore with a persistent diurnal variability in the wave spectra throughout the year and seasonal fluctuations according to the prevailing wind conditions. In this zone, dominant waves arrive from the northwest and their average height is around 0.6 m (Fery et al. 2015; Mayerle et al. 2016). According to Albarakati and Aboobacker (2018), a very significant mitigation in wave heights occurs in central Jeddah coast. This is due to geomorphology and topography of the Jeddah bay where the coral reefs and islands reduce considerably the impact of wave spread towards the coast.

Near the city of Jeddah winds from north and northwest predominate throughout the year (Mayerle et al. 2016 ; Shanass et al. 2018)

Studies on coastal sediments in the study area reveal that they are mainly composed of terrigenous materials derived from fluvial and aeolian deposits as well as erosion of coral reefs. Several processes promote their distribution including wave regime and wind action (Sagga, 1992; Al-Dubai Talha et al., 2017).

The sedimentation rates is estimated to approximately 0.6 cm/year and its increase would be linked to anthropogenic activities, according to Al-Mur et al. (2017).

Anthropogenic drivers Human actions (which can be direct or indirect drivers) played the main role in the spatiotemporal variability of the shoreline change in the studied area, due to the oil boom and massive urban expansion in the coastal plain since the 1970s. Anthropogenic direct drivers had a direct incidence on the shoreline (e.g., costal facilities) and their impact could be directly observed and monitored.

Anthropogenic direct drivers include:

Port facilities: Jeddah Islamic Port can be considered the most important driver of spatiotemporal littoral change. It has been the driving force behind the economic development of the city of Jeddah and is the largest commercial port in the Red Sea. Its construction has been the subject of successive spatial expansion to the detriment of the sea by backfilling and dredging (see Fig. 8).

Embankment for roads and urban promenade beach: several kilometers of road (including the 30 km long corniche road) and recreative facilities have been built on the beach (see Figs. 6 and 10).

Urban sprawl on coastal area: the waterfront of the city land use has been deeply modified. Residential, tourist industrial, and public services or infrastructures have been installed on the beach (see Fig. 10).

Anthropogenic indirect drivers include all human actions that can modify the sediment flow ending in the sea and offshore or flood control works as well as urbanization and changes in land use/land cover. Along the Jeddah coast, we

noted modifications in the layout of the wadis, including the reclamation of vast areas of swamps and shallow depths of the coral reef, and the removal of significant amounts of beach sediments. Destruction of plants mangrove has been also noted in some parts of the coast (Aljrah and Daoudi 2021).

The impacts and spatiotemporal variability of shoreline changes

Accretion, stability, or erosion The most important changes resulted in accretion, which implies a progression of the land toward the sea and an advance of the shoreline. The EPR varied along the coast; some sections have eroded (see Fig. 9), but this is not significant because the average rate indicates positive values for all periods.

It should be noted that the few studies that have dealt with the issue of quotient dynamics (Al-Sheikh 2011; Al-Dubai Talha et al., 2017) have focused on the northern and southern Jeddah Corniche. The study of coastal erosion has been based on the comparison and detection of changes between different images, which makes it impossible to evaluate real trends with much precision.

The detailed analysis of the rates over time shows an increasingly anthropized range, first in the central part, then for the whole shoreline from the 2000s. The pivotal period in the modification was 1972–1986 (the boom period), corresponding to an unprecedented extension of the

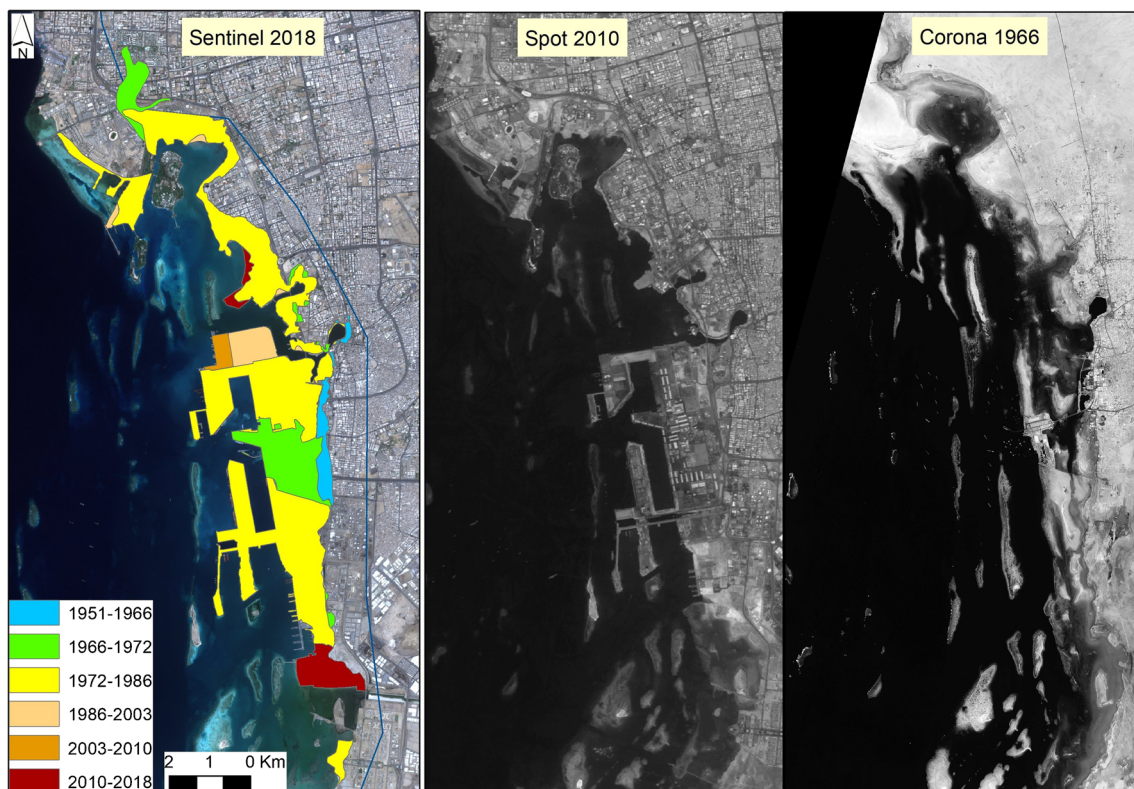


Fig. 8 Land reclamation in Jeddah for different periods between 1951 and 2018



Fig. 9 Manifestations of erosion in northern part of the coast: photos 1 and 2 were taken in 2015, photos 3 and 5 in 2019, photo 4 shows some measures taken against erosion. Source: Authors

port of Jeddah and the city toward the Red Sea. This analysis also indicates that the port of Jeddah experienced successive extensions, during all periods, as can be seen in Table 4. The maximum rate reached 210 m/year, but it can be a jetty, a dock, or an artificial promontory. The areas give a clearer idea of the successive extensions. They were obtained by extracting extensions of coastal zones from the superposition of the multi-temporal shorelines in the form of a polygon under the ArcGIS software. The coastal zone in this part of the coast increased by about 23 km² (Fig. 8). This massive expansion was

associated with the expansion of the port of Jeddah, which involved large amounts of salvage and backfilling as well as construction work (Spalding et al. 2001; Tortel 2004; Al-Dubai Talha et al., 2017).

Outside the port area and areas of human occupation on the beach, the shoreline was generally stabilized by the various tourist infrastructures and amenities along the beach. Sectors lacking these developments were subject to erosion in some places. While the long-term rates of erosion in these areas do not appear to be very significant, they may be locally significant.

Table 4 The EPR* and increased coastal area of Jeddah center during different periods

Center Jeddah				
Shoreline dates	EPR max (m/year)	EPR min (m/year)	EPR mean (m/year)	Accretion area km ²
1951–1966	44.14	– 7.12	5.79	0.88
1966–1972	241.93	– 3.85	18.23	3.52
1972–1986	229.01	– 1.22	52.95	15.68
1986–2003	11.69	– 3.75	0.23	1.05
2003–2010	107.54	– 0.05	3.25	0.37
2010–2018	210.93	– 1.69	24.14	1.41

*For uncertainties of EPR for each period, see Table 2

Impact on the coastal environment Changes in shoreline dynamics have also affected the coastal environment. The ecosystems and marine habitats of the near-shore area have been affected.

Urbanization on coral reefs and tidal flats has modified the environmental conditions in these areas. The transformation of old lagoons into urban areas destroys lagoon ecosystems. The planting of mangroves in several places along the coast has helped stabilize these areas and improve the ecological conditions there (see Fig. 11). The evolution of these plantations has varied: in some places, there has been an extension of plants while in other places human pressure has led to degradation.

Geomorphological implications

The geomorphological configuration of the shoreline has also been modified. The various geomorphological features considered in this part area their experienced morphodynamic change during the observation period. The various port extensions highlight an enlargement of the coastal plain, implying the creation of semi-closed lagoons and the disappearance of several reefs and islets. Coastal urbanization, extraction, dredging, and shifting of coastal sands have also resulted in the morphology of the shoreline (Luijendijk et al. 2018). Although accretion is more common, in some places, the beach has eroded. The photos that were taken in 2015 and 2019 (Fig. 9) along the northern part of the shoreline at Sharm Abhur bear witness to this. These eroded portions have also contributed to the modification of the shoreline morphology.

Depositional features dynamic

Tombolos The formation of tombolos is often linked to anthropogenic influences Tombolos were formed following the construction of roads to connect the islands to the mainland such as the one that linking the island of Ghurab to Jeddah see Fig. 12a. This tombolo shown many stages of accretion before its connection to the mainland that appeared on the 2003 image.

Spits The formation of spits (elongated sandy barriers that prograde in the direction of net sediment transport) are controlled by the movement of sediments. These forms are very dynamic; in our study area, they experienced spatial and temporal morphodynamic changes likely due to human intervention and sediment transport processes (see Fig. 12b). Most of them appeared after 1986 and were highly dynamic.

Barrier islands Several barrier islands were present in the central part of the study area. These elongated forms were parallel to the coast and separated from the mainland by bays and

lagoons. They were formed on coasts with a low tidal range and played an important role in shoreline protection. Many of the barrier islands have been destroyed and integrated into the extension of the port area (Fig. 13a).

Coral reefs and artificial islands Several coral islands and islets were formed in the bay of Jeddah. Some of them were reshaped or integrated into the mainland under the pressure of urban expansion on the coast while others were completely artificial and urbanized which illustrates the anthropic impact on the geomorphological changes of the coast (see Fig. 13b).

Beaches Despite being the most widespread marine dispositional feature on land, sandy beaches have become rare in the study area. The human occupation of the coast has led to the disappearance of beaches which only appeared in the northern part of the studied area. We also noted the existence of artificial beaches north of the port (see Fig. 13c).

Anthropogenic structures Various others anthropogenic structures have been erected parallel to the shoreline such as sea-walls or breakwaters to prevent erosion or protect the coast (see Figs. 6 and 13c).

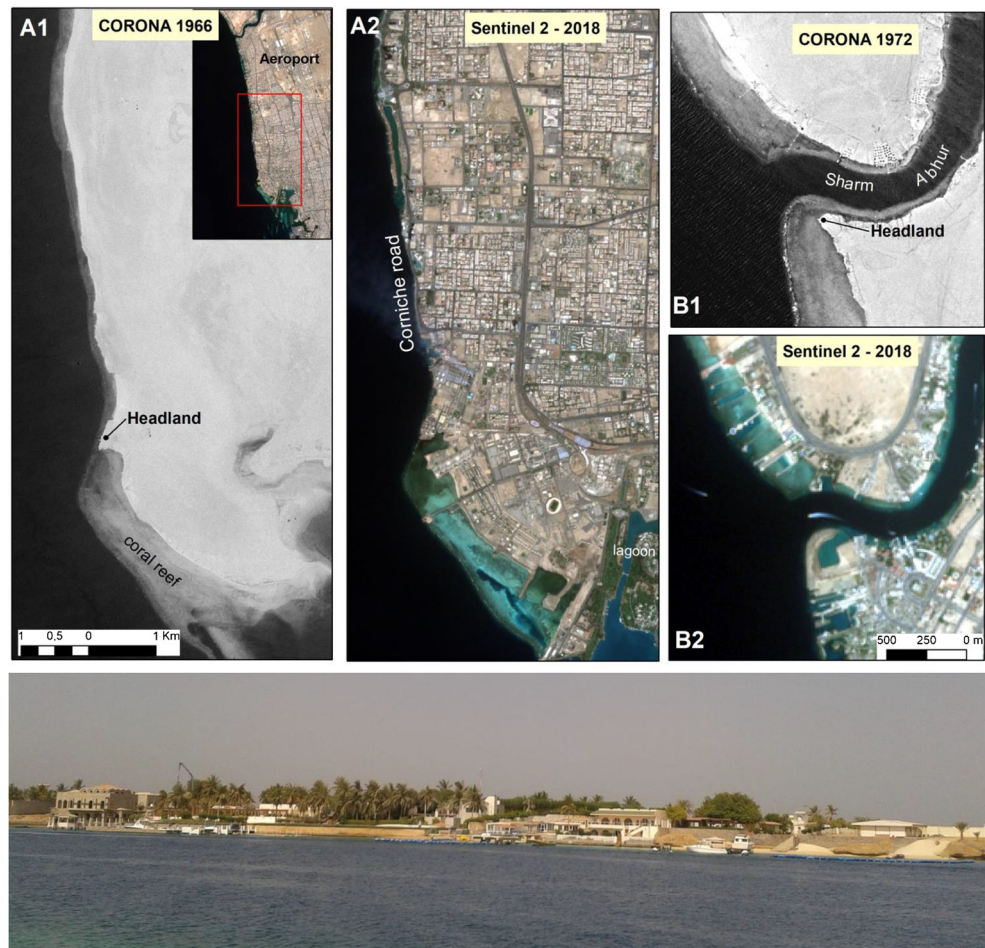
Anthropogenic activity (such as sea reclamation, urbanization and industrialization) has been identified as the most influential factor, on the morphology and dynamism of these forms even if the modification of climatic and hydrodynamic conditions can play a significant role in some cases.

Erosional features dynamic

Despite the dominance of accretional changes in the shoreline, numerous erosional features have been noted in the study. We noted the presence of natural forms of erosion, prior to human occupation of the coast, including headlands (a narrow strip of land that projects out into a body of water), bays, and lagoons. Most of the headland was remodeled and reconfigured as a result of urbanization of the coast as can be seen in Fig. 10.

Sharm, bays, and lagoons The evolution of Sharm Abhur, bays, and lagoons in Jeddah illustrates human influence on marine areas. Various geomorphic modifications were caused by anthropogenic activities in the coastal zones. The coastal lagoons experienced modifications regarding their shapes and their connections with the Red Sea. Moreover, the morphology and characteristic features of bays and lagoons have been affected by human intervention, including their depth, surface area inlets, and barrier islands. The forms of some of them appear restricted while others have disappeared or been transformed into urban areas. We also noted the appearance of new artificial lagoons in the new residential areas on the coast (see Figs. 10 and 13b)

Fig. 10 Illustration of different changes in the morphology of coastal area and shoreline in the north part of Jeddah (A1 and A2) and Sharm Abhur (B1 and B2) between 1966 and 2018



Other erosional features The phenomenon of erosion appeared prominently in several sites and led to the cracking and collapse of sidewalks and structures built on the edge of coral reefs, including in the northern and southern corniches and the seashore of Abhur. It also led to the removal of huge quantities of beach sediments and the destruction of coral reefs.

Morphological changes

Figure 10 illustrates some of the many coastal zone changes between 1966 and 2018, including the disappearance or appearance of islands and islets, the disappearance of coral reefs, and the dredging or filling of the sea for urban extension needs. The various land use and land cover changes in the coastal zone highlight a widening of the littoral plain, implying the creation of semi-closed lagoons along the coast (Fig. 10, A2 and B2) and the disappearance of several reefs and islets, particularly in the port area (Fig. 8). Coastal urbanization and the extraction, dredging, and displacement of coastal sands also resulted in a change in the shoreline morphology (Luijendijk et al. 2018). Figure 10 A2 and B2 shows this change in some sites of the northern part of Jeddah around

Sharm Abhur between 1966 and 2018. The shore, which had a more or less rectilinear shape in 1966 (Fig. 10, A1) presented several sinuosities after the various installations on the beach (Fig. 10, A2).

Geomorphologic hazards

Risks related to the modification of the morphology of the littoral are numerous. Coastal erosion is a hazard to structures built on cliffs and bluffs near the shoreline. The extension of low-lying areas on the coastal fringe is a major source of flood risk. Some urban areas of Jeddah are built on the sites of ancient lagoons or sabkhas. El-Raey (2009) also identified Jeddah as one of the most vulnerable coastal areas along the west coast of the Red Sea. The risks of flooding are also exacerbated by changes in wadi outlets. In the studied area, the extension of the coastal plain modified the equilibrium of the wadis and changed their course a situation that can increase the risks of floods. Changes in the topography of the shoreline can affect the entire coastal strip: subsidence, the constitution of sabkhas, and the rise of saltwater tables.

Coastal erosion is a hazard for structures built on the shore such as dwellings or roads. We can see through diachronic

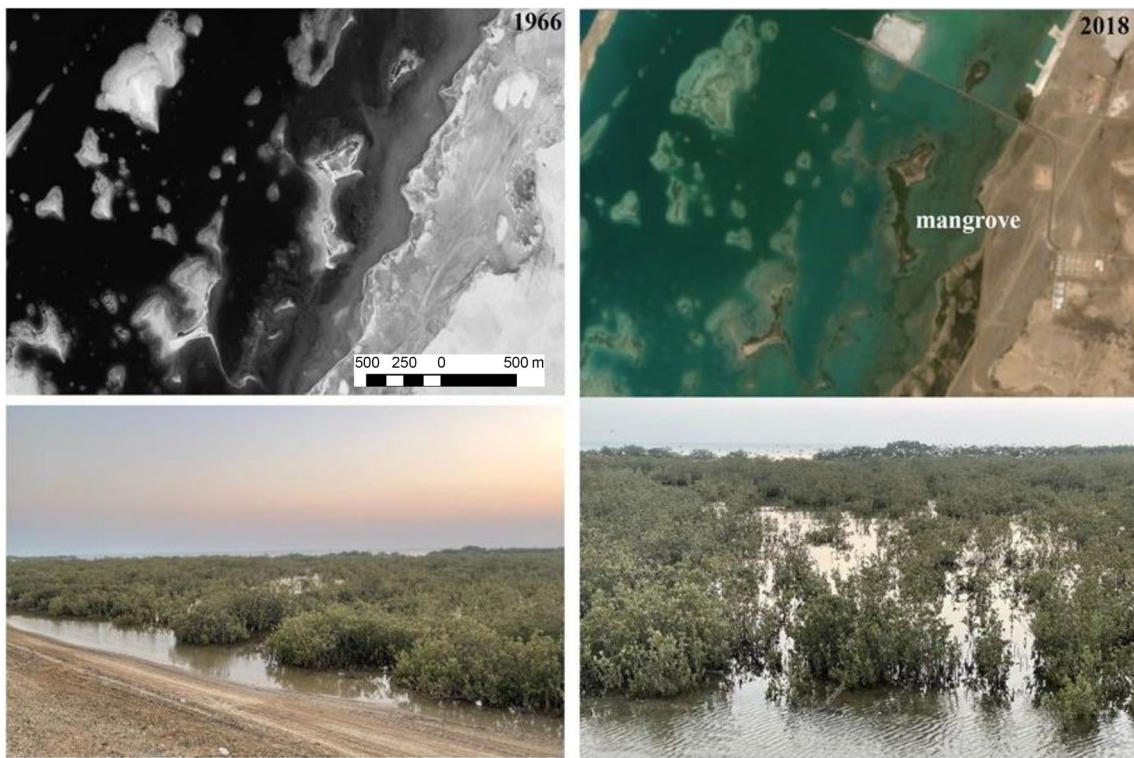


Fig. 11 Dynamic mangrove plantations between 1966 and 2018. Photos: Authors, 2019

satellite images that most of the major ports and tourist sites along the Jeddah coast are built on coral reefs (see Fig. 10). The coastal corniche asphaltic road that runs along the coast of Jeddah from north to south is built on reef flats and coral reefs,

meaning a serious loss of coastal habitat and damage for structures (Mansour and Madkour 2015).

Anthropogenic (particularly anthropic) actions play the main role in the dynamics and the spatiotemporal variability

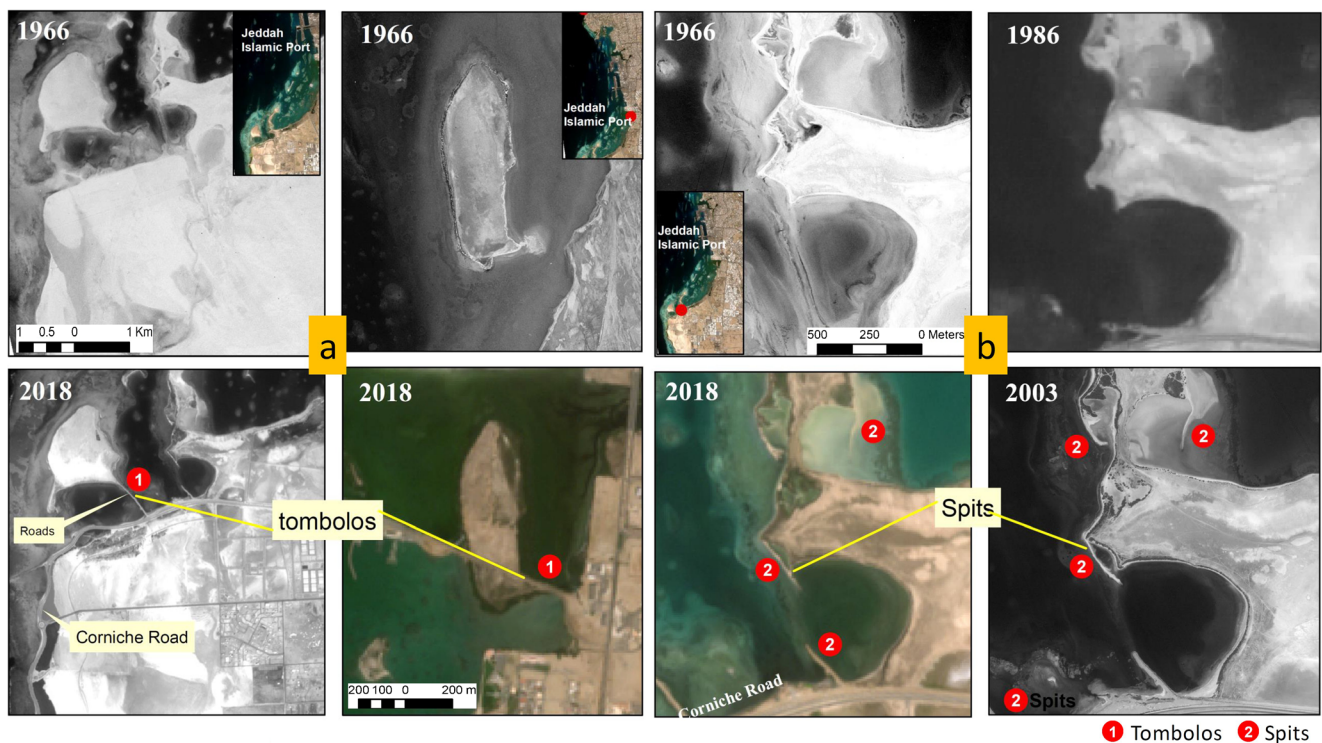


Fig. 12 Dynamic tombolos (a) and spits (b) between 1966 and 2018

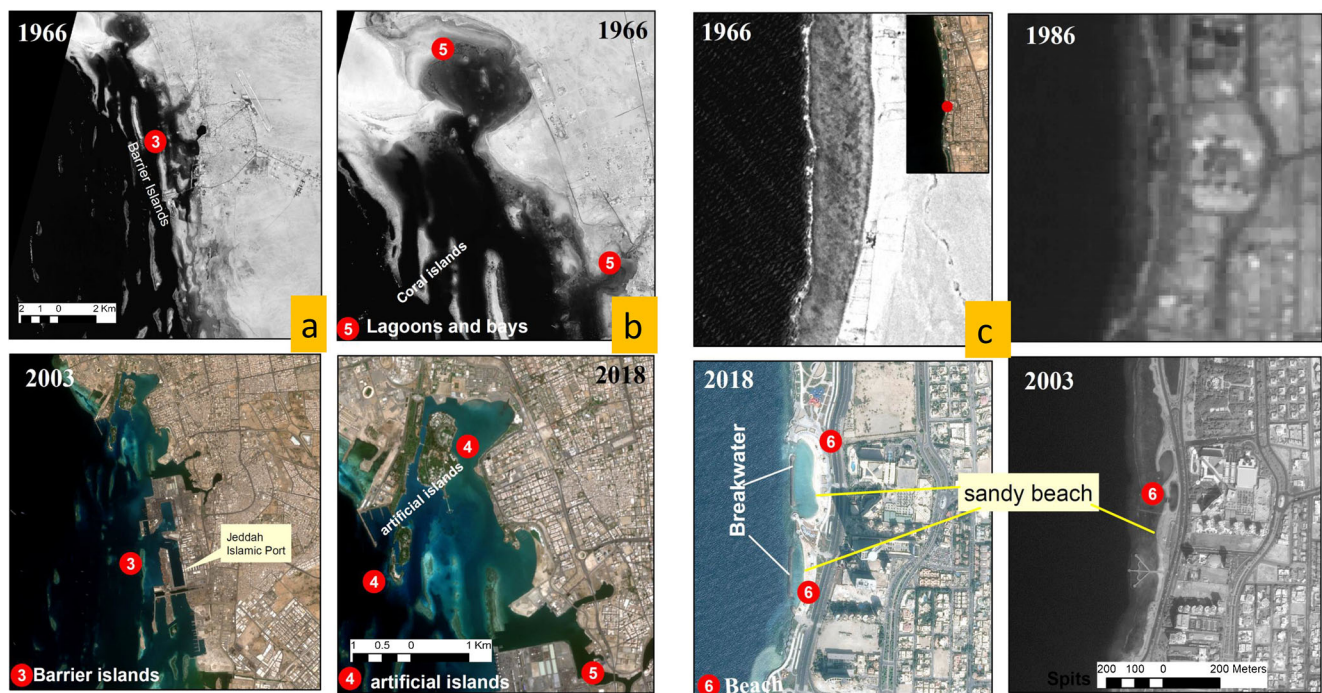


Fig. 13 Dynamic of barrier islands (a), coral islands, lagoons, and bays (b), and sandy beaches between 1966 and 2018

of shoreline and geomorphological changes. Moreover, they influence the dynamics of the shoreline along the Jeddah coast even if natural forces have also contributed.

The highest shoreline change rates were in the form of accretions recorded at the port of Jeddah which experienced successive extensions in all periods. These significant high rates are very limited in time and are linked to land reclamation works. For the other sections, the massive urbanization of the coast led to different dynamics depending on the period. This reclamation of coastal land for residential, industrial, or public tourist uses led to significant geomorphological and environmental changes that exacerbate the vulnerability of the coastal area, particularly in the context of the rising sea level and climate change.

Monitoring and identifying of coastal vulnerability and linked hazards resulting from shoreline dynamics can be useful as a decision-making tool for urban management and planning.

Conclusion

The rapidly growing economic importance and urban development of shore areas will lead to encroachment of the city on the marine environment, resulting in a series of problems related to shoreline dynamic trends and shore geomorphological changes with anthropogenic and natural driving factors. Detection and analysis of extracted shorelines from remote sensing data will be important for gaining a better understanding of morphological dynamics of coastal areas. In this

shoreline, change rates were analyzed from 1951 to 2018 through the use of the DSAS application. The rates of change were calculated according to two rate-of-change statistics: one in the short term between two successive observation years (using EPR) and the other in the long term between the oldest and the most recent periods (LRR function). This long period that included the economic boom and urban expansion of Jeddah was marked by progressive human occupation of the coast.

The statistical results obtained highlight the predominance of the accretion phenomena, particularly in the central part, where the highest rates were recorded. This trend is explained by the expansion of the city on the coast and, in particular by the construction and extension of the port of Jeddah in which large sea areas have been backfilled, leading to the disappearance of some islands and reefs. The maximum rates for certain periods exceeded 210 m/year (accretion) for EPR and 44 m/year for LRR. Note that these fairly high rates are punctual and limited in space and time and must be considered as exceptional, not reflecting perpetual or lasting trends. Erosion affecting some transects was mainly recorded north and south of the littoral, with low rates. The EPR rates of 2003–2010 and 2010–2018 indicated an increase in stable zones, related to the stabilization of the beach by recreational or tourist facilities in several places. The disagreement between the long- and short-term rates indicates that there were trend changes and slow movements of the shoreline between different dates. The kinematics of the coastline and the encroachment of the continent on the sea imply changes in the geomorphology of the littoral, which contributes to the exacerbation of risks related

to floods with the extension of the low altitude zones on the littoral fringe. The geomorphological configuration of the coastline shoreline has been modified. The various geomorphological features (e.g., spits, tombolos, lagoons, bays, barriers islands) experienced morphodynamic change during the observation period. The various port extensions highlight an enlargement of the coastal plain, implying the creation of semi-closed lagoons and the disappearance of several reefs and islets. Anthropogenic actions play the main role in the dynamics and the spatiotemporal variability of shoreline changes. Moreover, they influence the dynamics of the shoreline along the Jeddah coast. Monitoring coastal changes and identifying vulnerability and linked hazards resulting from shoreline morphodynamics is useful as a decision-making tool for urban management and planning.

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