Monitoring long-term shoreline changes along Yanbu, Kingdom of Saudi Arabia using remote sensing and GIS techniques

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ABSTRACT
This study presents the shoreline position changes of Yanbu coastal zone from 1965 to 2109, using multitemporal satellite data and the Digital Shoreline Analysis System (DSAS) application. The shoreline change rates were calculated based on End Point Rate (EPR), Linear Regression Rate (LRR), Weighted Linear regression (WLR) and Net Shoreline Movement (NSM) statistical methods to assess the short- and long-term trends. The maximum accretion reached was 1655.9 m (30.66, 32.32 and 36.9 m/year based on EPR, LRR and WLR methods respectively) while the maximum erosion was −1484.8 m (−37.9 m/year, −32.7 m/year and −33.5 m/year based on EPR, LRR and WLR methods respectively). An area of about 20 sq. km of sea and islets has been backfilled or dug in for various facilities. Thus, major changes in the configuration of the coastline are linked to human activities. This study provides a synoptic outlook of the degree of potential threat to the coastal system and their potential consequences.

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1. Introduction
The often greatly dynamic nature of coastal zones and changes in the structure of their shorelines may be affected by a wide range of environmental factors, as described by a number of authors [1–4]. These factors include the direction of the wind and height of the waves [3,5]. However, [6,7] explain that some such variation may only be transient, such that any alterations in the morphology of the coastline may be reversed after any influencing factors have eased.

According to [8] an increasing dependence on the regions around the coast often results from a growth in the density of people living in that region who use limited resources or take away vegetation that is well established. The susceptible areas caused by this population growth (which is often the result of economic or social demands) requires urbanization of the coastal regions, which, along with other human activities and demands on resources increases exposure to risk and ecological deterioration. The coastline areas are then subjected to significant anthropogenic pressures. These impacts tend to be more permanent changes [9–11]. As a result, evaluating the possible and real risks to the coastline requires monitoring and mapping the spatial and temporal changes of the shoreline for better management.

Long-term studies have tended to concentrate on using one or more of several methods for approximating the speed of change in coastlines. These methods include the evaluation of numerous topographic survey techniques, historic maps and aerial images [3,7,12–17]. More recently, high-resolution satellite data has become more widely available, enabling satellite remote sensing methods and geographic information systems (GIS) to be widely used for identifying variations in shorelines, their mapping and analysis. Also, remote sensing methods in conjunction with geomorphological and sedimentary information could be used to evaluate changes in coastlines [18–20].

However, many authors indicate that the shoreline indicator is a basic aspect to be considered in mapping variations in the coastline, and identification of a perfect indicator is not simplistic, either in images or on the ground [3,5,13,21–24]. The position of the shoreline is often defined as the mean high-water line (MHWL). However, in practice the vegetation line is used, as it is more easily discernible both on aerial photographs and on historical maps [3,5,13,25]. The change in the coastline resulting from variations in environmental factors is not widely studied in international investigations.

At the local level, there are few and rare detailed studies specific to Saudi Arabia using remote sensing

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and GIS techniques for surveying the shoreline kinematics. To our knowledge only some studies have been conducted on coastal erosion in the Saudi Arabian red sea coast [26–29]. For Yanbu city only one study was published by [30] focused on the impacts of the sea level changes on the Sharm Yanbu coast between 1990 and 2016.

None of these studies used the DSAS technique for a statistical analysis shoreline change rate. The main objective of this study is to assess the long-term change rates of the Yanbu shoreline from 1965 to 2019. The southern part of Yanbu is mainly an industrial city that has become the third largest oil refinery centre in the world. Its coastline is a very coveted and fully artificial space, partly because of the urban growth and the high speed industrialization, and secondly because of the geomorphological setting of the city located in the western region of Saudi Arabia characterized by low altitude-flat coastal plain bounded from the east with a chain of the high rugged mountains of Hijaz [26,31–33]. In this context it is timely to evaluate historical trends related to shoreline change using remote sensed data and tools such as DSAS (Digital Shoreline Analysis System) which allow for a statistical study of the kinematics of the coastline, especially when there is a lack of measurements which are often limited to port areas [34]. This study focuses on the impact of the greatly developmental projects and urban growth, as well as industrial installations on evolution and dynamics of Yanbu shoreline at different periods between 1965 and 2019, using GIS techniques. Thus, any changes affecting the coastline will surely have an environmental and morphological impact on the beach evolution and the city.

2. The study area

Yanbu is an important port city (one of the largest and oldest marine ports in the Kingdom) located on the eastern Red Sea littoral at about 160 km west of Al Madinah and 300 km northwest of Jeddah (Figure 1). This region, largely a level plain, is nearly 80 km long and incorporates both Yanbu Al-Balad or Al-Bahr (Old Yanbu) and Yanbu Al-Sinaiyah (Industrial Yanbu – Figure 1). The implication of this is that the region has a sharply rising population, resulting in rapid urbanization and land of a high monetary value. The resident population of the city in 2016 was about 76 000 [35]. A growing destination for tourists, the city is mainly known for its industrial activities. The industrial city was established in the south of the old city of Yanbu in 1975. Recently, the city attracted several development and urban expansion projects [36]. This young city became a Centre for modern industries and plays a major role in the kingdom’s gross national income [35]. Yanbu Industrial City represents the last station for the raw oil and liquid natural gas pipelines.

Sabkha soil covers large parts of Yanbu and causes several geotechnical problems, according to the Saudi Geological Survey. So the site of the city is subjected to seismic activity. Yanbu was affected in the past and recently by earthquakes [36,37].

The coastal morphology of the red sea is characterized by an extension of various open bays on its shores referred to as “Sharm”. In the northern part of the city the Sharm Yanbu stretches for about 2 km. The coastal zone of Yanbu is a dynamic and morphologically unstable area [30]. The natural harbour is sheltered by the mainland to the north and has coral reefs blocking much of its entrance [38]. The industrial port which has different terminals and long channels has profoundly modified the morphology of the coastline.

3. Physical background setting of the Yanbu area

According to [36], the surface geology of the city is covered by Tertiary and Quaternary deposits where these sediments crop out along a narrow coastal plain of the Red Sea.

The development over time of the beach morphology is controlled by sub-environments including sand dunes, wadis, sabkhas, lagoons and intertidal flats, as reported by [39]. Changes in such structure may vary over timescales from the very short (in the order of seconds) to a number of years [40].

The lowest topographic zone between 0 and 7 m extends inland from the coastline to various distances (see Figure 2). The morphological setting is characterized by the “Tihamah” littoral plain (Figure 2) with a maximum width of 40 km, located at the foot of the highly dissected Precambrian granitic mountains of Alhijaz whose peaks reach several hundred metres. The plain is surrounded by a basalt ridge forming part of a set of so-called Harrats (lava flows today in inversion of relief), coming from mouths located at a hundred kilometres inside, and going back to the old Pleistocene [41]. Flash floods from close-lying coastal escarpments have resulted in a large number of ancient wadis depositing terrigenous material, with the majority of the sediments close to the shore originating from such material.

Further terrigenous sediments that originate from the metamorphic and igneous mountains adjacent to the area were carried by other wadis’ paleo-channels. In addition to the terrigenous sediments, biogenous and calcareous components resulting from the Red Sea’s erosive action on coral reef flats are present. Particularly to both the north and the south of Yanbu, for around 1 km in each direction, sabkhas develop.

The variety of topography and physiogeography in the study area is associated with a contrasting range of
Figure 1. Study area.

Figure 2. Topographic setting of study area (DEM SRTM).
conditions. In the mountains, winters are cooler than close to the Red Sea. Around Harrat, summer is very hot and mostly arid, while closer to the sea the same period is semi-arid and, while still hot, less so than at Harrat. Across the entire area, seasonal air temperatures are moderate to high; radiation is high, as are the wind speeds that, according to [42], frequently result in dust storms (particularly close to the sea). Effectively semidiurnal and microtidal, the Red Sea’s tidal range varies along its length [43]. According to [30] the marine factors of waves and tides have a weak impact on Yanbu Coast and the average rise in sea level during tide reaches 60 cm (based on a study of tidal data recorded at the Yanbu Environmental Protection Station in the last ten years).

4. Materials and methods

4.1. Data sources

Multisensor and diachronic remote sensed data with high spatial resolution were used in this study to cover the Yanbu coast in 1965, 1980, 1988, 2000, 2010 and 2019. The first two periods are covered by panchromatic satellite imagery (CORONA). The satellite photographs of 1965 and 1980 are taken by the CORONA spy satellite mission (USGS) declassified in 1995; they encompass the entire coast of Yanbu. The other periods are covered by optical satellite images; SPOT-CIB 1988 ASTER 2000, and 2010 and Sentinel-2 in 2019. These optical images encompass the entire area studied. All images are downloadable from the USGS website (https://earthexplorer.usgs.gov). All data used has a spatial resolution between 3 and 15 m. Note also that the three first periods are covered by panchromatic images and the others by multispectral images. The details of the images are noted in Table 1.

4.2. Data processing

The CORONA satellite photographic images were acquired for reconnaissance and mapping were captured as parallel strips. The different stripes were firstly mosaicked by collecting tie points in the slightly overlapping parts. These images are not digital and result from a high-resolution scan of a negative film, so radiometric correction can’t be applied to them. Secondly the mosaics were geo-referenced, using many ground controls points (GCP) identified across the CORONA image for co-registration with the ortho-rectified reference image. Then all other images were geometrically corrected from control points on the reference image projected, using the UTM and WGS Datum, Zone 37 N (the number depends on the images to be corrected, the largest number of points was selected on the CORONA photographs because of the distortions to which they are subject). The geometric correction was performed in the ERDAS IMAGINE software using the polynomial method, to eliminate distortions related to the scale variation, tilt and distortion of the lens. After rectification, it was found that the Root mean squared error (RMSE) did not exceed 1 pixel, revealing thus a high geometric match of the images. After the geometric correction, we proceeded for the CORONA photographs were the contrast enhanced to better identify the reference line. The radiometric correction was only applied to Aster imagery. Spectral index was also performed on some satellite images (ASTER and Sentinel) to perform Land-Water Classification such as calculation of NDWI (Normalized Difference Water Index) for classifying the images in water and non-water classes. The next step was to display the images in the ArcGIS Desktop software in order to digitize the coastline. The flowchart of the methodology is illustrated in Figure 3.

4.3. Shoreline indicator and reference line extraction

The High-Water Line (HWL) was chosen as the shoreline. This land-water interface is clearly visible on the images through the contrast between the wet beach that appears darker than the dry beach. HWL, which can be interpreted visually, is considered by many researchers to be the best indicator of shoreline position for historical studies of shoreline kinematics, especially in non-tidal areas [22,44,45]. The High-Water Line is also known to be easily located in the field and by photo-interpretation with a variable margin of error [22]. Given that the area studied is highly artificialized and urbanized, the reference line corresponds in the central part to the limit of the harbour facilities, including the section jetties greater than 20 m [46].

The shoreline of Yanbu was extracted from multi-source remote sensed data for the years 1965, 1980, 1988, 2000, 2010, and 2019, listed in Table 1. The manual method was favoured for the extraction of the shorelines. The positioning of the coastline is based on visual interpretation from satellite images and satellite photographs in digital format. The defined reference line is determined by assessment according to the contrasts observed in the images, but over a very large part of the coastline it is reduced to the limit of the harbour and / or coastal infrastructure existing along the beach. It was

| Source no | Data set type           | Acquisition date | Resolution (m) |
|-----------|-------------------------|------------------|----------------|
| 1         | CORONA/Satellite photo. | 10/06/1965       | 3.11           |
| 2         | CORONA/Satellite photo. | 08/27/1980       | 6              |
| 3         | SPOT CIB 10/Satellite image | 08/24/1988 | 10             |
| 4         | ASTER /satellite image | 08/27/2000       | 15             |
| 5         | ASTER /satellite image | 10/19/2010       | 15             |
| 6         | SENTINEL 2/satellite image | 10/12/2019 | 10             |
screen digitized manually (using ArcGIS 10.7 GIS software) as a vector layer in linear shapefile. A coastline is thus obtained for each year. This method is simple, but its accuracy is related to the resolution of images and photographs as well as their quality, in addition to the assessment of the photo interpreter.

The dynamics of the coastline was calculated from the superposition of multiple shorelines for the different years. Figure 4 shows a portion of shorelines extracted for the different dates.

4.4. Estimation of shoreline position uncertainty

Various types of uncertainties are often identified by researchers [47,48], but the uncertainty related to georeferencing (\(E_g\)) and that associated with the digitalization of the coastline (\(E_d\)) and pixel error (\(E_p\)) are calculated in this study. The uncertainty (\(U\)) associated with the determination of shoreline position was calculated for all periods using the following equation:

\[
U = \sqrt{E_g^2 + E_d^2 + E_p^2}
\]

where \(U\), \(E_g\), \(E_d\), and \(E_p\) represent the total shoreline uncertainties for the first date \(\text{year1}\) and the other dates, respectively.

The many sources of uncertainty are calculated according to the spatial and spectral resolution of the diachronic images used. The georeferencing uncertainty (that represents the maximum acceptable RMS error) differs from one image to another (between 3 and 6 m); it is higher for CORONA satellite photographs because of the scarcity of fixed markers on the ground before the massive urbanization of the coast in the early 80s. The digitization error specified in this study is between 2 and 7.5 m. The digitizing involves the interpretation of geographic features via the human hand, there are several types of positional errors that can occur during the course of capturing the data. The pixel error a function of pixel size varies between 3.1 and 15 m; it influences the determination of the reference line. The total error is higher for CORONA data due to distortions related to image geometry.

Uncertainty is also estimated for the rate of shoreline change. For each transect the uncertainty associated with the rate of change of the End Point Rate (\(U_r\)) is the square root of the sum of the uncertainties of the position of the coastline of each year divided by the number of years between the two shoreline survey dates [47], using the following equation:

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

where \(U1\) and \(U2\) are, respectively, the total shoreline uncertainties for the first date \(\text{year1}\) and the last date \(\text{year2}\).

Table 2 shows the uncertainty associated to the shoreline extracted for each year taken individually (\(U\)) and the Table 3 give the average of the position errors associated with the calculation of the change rates for the EPR statistics between two dates (\(U_r\)). The annualized error indicates the annual average uncertainty for each short time period.
4.5. Calculation and interpretation of shoreline change rates

The change rates of the shoreline were calculated from two methods among those available in the DSAS application. This tool is a freely available application designed to work with ESRI ArcGIS software. For this study, the DSAS software version 5 developed by the USGS [49] was used to generate orthogonal transects spaced 100 m apart along the 80 km covering the Yanbu city coast and calculate change statistics accordingly, using six distinct approaches including EPR, LRR and WLR. Note that according to [50] when rate of shoreline change calculated at different segments the LRR method performed better than the EPR and WLR.

The EPR (short time period) method was conducted to monitor changes between successive shoreline pairs, namely: 1965–1980, 1980–1988, 1988–2000, 2000–2010, 2010–2019. The LRR and WLR statistics (which exploits all shorelines) was used to calculate shoreline changes for the entire period considered of 54 years from 1965 to 2019. The total distance between two periods are reported as Net Shoreline Movement (NSM).

Note that while linear regression is the most commonly used statistical technique for expressing shoreline movement and estimating rates of change [44], it does not consider shifts between intervening periods that may slow down or show acceleration trends in response to various factors [51]. Average EPR changes fill this gap and highlight all trends for all transects between the different time periods. The calculated rate represents the difference in shore positions between two years, divided by the time elapsed between the two
5. Results

5.1. Evolution over the entire period considered (long time period analysis)

The dynamics of the shorelines over the period 1965–2019 (54 years) was calculated using the Linear Regression Rate (LRR) and the Weighted Linear Regression (WLR). This tool determines the rate of change statistics by fitting the least square regression to all the shorelines positions from the oldest to newest at each of the transects. For the WLR tool greater emphasis is placed on data points for which the position uncertainty is smaller [49]. The results illustrated in Figure 5 show the overall shoreline change rates calculated from the analysis. The positive values indicate a progradation of the shoreline while the negative values are related to coastal erosion. This Figure illustrates also the location of accretion and erosion areas.

Over the period of 54 years, the LRR and WLR overall average rate indicates an accretional trend of the shoreline of 1.14 and 1.41 m/year (± 2.27) respectively. Overall averages show that the Yanbu coastline is mainly subject to an accretion: 54.92% of all transects are accretional but only 0.08% of them are statistically significant, while 45.08% of all transects are erosional with the same significant value. The maximum accretion distance is 1360.6 m (32.72 and 36.9 m/yr based on LRR and WLR methods respectively), situated with an average rate of 3.87 m/yr (LRR), and 4.13 (WLR) located in the King Fahd Industrial Port (KFIP). The maximum erosion distance is −1549.4 m (−32.7 m/yr (LRR) and −33.5 m/yr (WLR) with an average of −2.2 m/year and −1.91 m/yr based on LRR and WLR methods respectively), situated in the waterfront area.

The results of the End Point Rate analysis for this period confirm the predominance of the accretion process: 56.1% of all transects are erosional with 33.51% that have statistically significant erosion, while 43.9% of all transects are accretional, and 24.4% of them have statistically significant accretion. The maximum accretion distance is 1655.9 m (30.6 ± 0.23 m/yr) located at the KFIP, and the average of all accretional rates is 4.23 ± 0.23 m/yr, whereas the maximum erosion distance is −1484.8 m (−37.9 ± 0.23 m/yr – in the Waterfront area) with an average rate of −2.02 ± 0.23 m/year. Note that during this period, the coastline recorded some isolated strong accretion and/or erosion. The parts that have experienced this rate are occupied by socio economic activities.

These results also show that the main factor in high shoreline change is anthropogenic (as we can see in Figure 6). Many sections of this coast are affected by urban expansion. In this period the total area directly affected by these modifications reached around 20 sq. km. The accretion zones which represent approximately 17 sq. km are almost entirely recovered from the sea by backfilling, while the erosion zones with an area of 3 sq. km are amenities on the coast for industrial, recreational and port facilities. Figure 6 reveals that the essential changes are linked to the port activities and located in the industrial part of Yanbu Al Sinayyah.

5.2. End Point rate (short time period) analysis

This short time period analysis of shoreline changes highlights spatiotemporal and short trends of two timescales that may be related to acceleration and a temporary slowdown, or even reversal of shoreline kinematics. It also allows for the case of a coastline subjected to intense human activity 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 coastal dynamics relies on analysis and the interpretation of data contained in the attribute tables generated by the DSAS application. The methods proposed by this application reflect the temporal evolution of the coastline: the EPR (End Point Rate) is a simple and popular approach adapted to evaluate the evolution between two successive shorelines. The results of the EPR between the different pairs of years across six different periods are shown in Figures 7(a and b). The rates of variation of the EPR shown in Figure 7(b) identify areas of strong accretion and erosion, respectively, up to 190 and −150 m/yr in the Yanbu Al Sinayyah coastal area. Figures 7 indicate that the spatiotemporal change rate trends are different between all periods.

- Shoreline changes 1965–1980

The rates of shoreline position changes calculated by the EPR method during this period are illustrated in Figure 8(a) and indicate that the Yanbu coastline is mainly subjected to progradation: 54.15% of all transects are accretional and 39.16% of them have a statistically significant accretion while 45.85% of all transects are erosional and 26.53% have statistically significant erosion. The maximum erosion value is −162.5 m (−10.9 ± 0.68 m/yr) situated on the Yanbu commercial port, and the average erosional rate is −1.71 m/yr. The maximum accretion distance is 1494.4 m (100 ± 0.68 m/yr), with an average rate of 8.17 ± 0.68 m/yr located at the Yanbu Al Sinayyah area.

This period is especially marked by the beginning of anthropogenic pressure on the coastal area. Accretion zones have reached their greatest spatial expansion.
Figure 5. Long-term shoreline change rate using LRR and WLR – 1965–2019.

Figure 6. Littoral zone changes and location of the accretional (blue colour) and erosional areas (in red) along Yanbu coast during the period 1965–2019.

growing to about 8 sq. km while the eroded areas cover 0.1 sq. km as a result of various amenities on the coast. During this period the built up area goes from 3.5–38 sq. km. In 1965 there was no built-up area in the Yanbu Industrial city. The largest seaward extension of the shoreline is materialized by unprecedented development of infrastructure and port facilities. Urban growth also led to a great expansion of the built-up area towards the sea in the Yanbu Al Sinaiyah zone. The urban and infrastructure growth of this period could be explained by the launch of the second Saudi national plan and the 1973–1983 consolidation of the oil boom [52].

- Shoreline changes 1980–1988

This shortest period recorded considerable fluctuations between progradation and erosion as calculated by the EPR method (Figure 8b). This period is distinguished by notable sections of high erosion rates. The average rate is $-3.55 \pm 1.82 \text{ m/year}$; 59.74% of all transects are erosional, and 32.77% of them have...
a statistically significant erosion rate while 40.26% of all transects are accretional, and 20.17% have statistically significant progradation. The maximum erosion distance is $-1602.7 \text{ m} (-200 \pm 1.82 \text{ m/yr})$ situated on the waterfront industrial Yanbu area and the average erosional rate is $-12.41 \text{ m/yr}$. The maximum accretion value is $190 \pm 1.82 \text{ m/yr}$ with an average rate of $9.59 \pm 1.82 \text{ m/yr}$ located at the KFIP area.

This period is especially marked by an intense human activity consisting of dredging and digging channels on the land side. Accretion zones reached about 3.6 sq. km while the eroded areas cover about 2.3 sq. km as a result of various amenities on the Yanbu coastline. The built-up areas expanded from 38 to 72 sq. km.

- **Shoreline changes 1988–2000**

The average EPR statistics for this period are presented in Figure 8(c) and show that the Yanbu coastline was accretional at this time: the average rate was $2.18 \pm 1.7 \text{ m/yr}$; 68.03% of all transects were accretional and 28.87% of them had a statistically significant

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**Figure 7.** End point change rates for all transects in m/year for periods 1986–1998, 1998–2005, 2005–2019 and 1986–2019. (a) The transects with negatives values (red colour) indicate erosion and the positive values (blue) show accretion rates. (b) A graphic representation and comparison of average change rates for all periods.
Figure 8. End point change rates for transects for periods (a) 1965–1980, (b) 1980–1988, (c) 1988–2000, (d) 2000–2010, and (e) 2010–2019; transects with red colour indicate erosion and the blue colour show accretion rates.
accretion, while 31.97% of all transects were erosional and only 8.98% of them had statistically significant erosion. The maximum accretion distance was 822.8 m (68.5 ± 1.7 m/yr) located at Sharm Yanbu. The maximum erosion distance was −990.9 m (−82.5 ± 1.7 m/yr) situated in the KFIP. This period recorded the smallest areas affected by the amenities: accretion zones occupied only 0.18 sq. km while the eroded areas covered only about 0.01 sq. km.

- Shoreline changes 2000–2010

The average EPR statistics in this period presented in Figure 8(d) indicate an erosive trend: 59.41% of all transects are erosional and 20.68% of them had a statistically significant erosion, while 40.59% of all transects were accretional, and only 12.75% of them had statistically significant accretion. The maximum erosion distance is −499.2 m (−49.2 ± 2.26 m/yr) located at Yanbu Al Sinaiyah, and the average erosional rate was −4.62 m/yr. The maximum accretion distance was 931.7 m (91.8 ± 2.26 m/yr) situated in the KFIP and the average accretional rates was 6.73 m/yr. The accretion zones represent 3.3 sq. km while the eroded areas covered about 1.1 sq. km.

- Shoreline changes 2010–2019

The average EPR statistics for this period are presented in Figure 8(e). This last period shows a progradation tendency: 52.38% of all transects were accretional; 18.78% of them had a statistically significant accretion, while 47.62% of all transects were erosional, and 12.08% of them had statistically significant erosion. The maximum accretion distance was 1386.6 m (154.4 ± 2.28 m/yr) located at Yanbu Al Sinaiyah, and the average erosional rate was −536.1 m (−59.6 ± 2.28 m/yr) situated in the KFIP area. Accretion zones occupied 3.23 sq. km while the eroded areas covered about 1 sq. km.

6. Discussion

6.1. The driving factors of spatiotemporal dynamics of Yanbu coastline

The socioeconomic development of coastal cities has been mainly focused on large expansion of coastal infrastructure projects [53]. Long-term spatiotemporal changes in coastline shape measured over different periods from 1965 to 2019 shows that the kinematics of this shoreline is mainly controlled by human activities. The most important changes resulted in an accretion of the land seaward, but EPR rates vary along the coast. One the other hand some sections have been eroded mainly by digging and dredging the sea to enlarge the sea port zone, build access channels or develop other socio-economic infrastructures.

The dynamics of shorelines between the different periods shows that before the existence of the industrial city the significant modifications were associated with the commercial port of Yanbu as shown in Figure 9(a).

After the choice of Yanbu as the second industrial portal of the kingdom and the development of the industrial city, major modifications (erosion and accretion) affected this part of the coastline from 1975 onwards as illustrated in Figures 9(b and c).

The detailed analysis of the rates over time shows an increasingly anthropized range, first in the Yanbu commercial port area, then on the Yanbu al Sinaiyah coastline mainly from the 1980 image data sources. The pivotal period in the modification was around 1975 (the boom period) which corresponds to an unprecedented extension of the ports (commercial and industrial) as well as the urban and industrial city towards the Red Sea. Figure 10 shows the urban growth of Yanbu.

This analysis also indicates that during all periods the King Fahd industrial port and its neighbours have experienced successive seaward extensions which appear in Table 4. The maximum rate (erosion or progradation) can reach 190 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 them from the superposition of the multitemporal shorelines between successive periods. The coastal zones in the study area have prograded artificially by about 17 sq. km and eroded by about 3 sq. km (Table 4) This massive expansion is associated with the additional berths and terminals of the port which involved large amounts of land reclamation and backfilling as well as construction works [54,55].

6.2. Impact of shoreline change to the Yanbu coastal area

- Changes in coastline shape have affected the coastal environment like the ecosystems, marine habitats and benthic communities of the near-shore area. Pollution problems can also be posed by the industrial city.

- The morphology of the coastline has been modified. The various works of extension of the port highlight an enlargement of the coastal plain, the creation of semi-closed lagoons and the disappearance of several reefs and islets [56]. Coastal urbanization, extraction, dredging and shifting of coastal sands will affect the morphology of the shoreline [57]. Although accretion is more common, in some places the beach has eroded. These eroded portions also contribute to the modification of the morphology of the coastline.
**Figure 9.** Illustration of major coastline change areas along Yanbu coast for different periods between 1965 and 2019: (a) Yanbu commercial port from 1965 (left) and 1980 (right); (b) Yanbu Waterfront from 1980 to 1988; and (c) Yanbu Waterfront in the last stage from 2000 to 2019.

**Table 4.** The End Point Rate (EPR) and increased/decreased coastal and built up areas of Yanbu city during different time periods.

| Shorelines periods | EPR max. (m/yr) | EPR min (m/yr) | EPR mean (m/yr) | Accretion Area (km²) | Erosion area (km²) | Build up extent (km²) |
|--------------------|----------------|----------------|-----------------|----------------------|-------------------|---------------------|
| 1965–1980          | 100            | −10.9          | 3.64            | 8.15                 | 0.1               | 38                  |
| 1980–1988          | 190            | −200           | −3.55           | 3.66                 | 2.29              | 71.5                |
| 1988–2000          | 68.5           | −82.5          | 2.18            | 0.18                 | 0.05              | 104.4               |
| 2000–2010          | 91.8           | −49.2          | −0.01           | 3.3                  | 1.1               | 137.2               |
| 2010–2019          | 154.4          | −59.6          | 2.54            | 3.23                 | 1                 | 208.4               |

*For Uncertainties of EPR for each period see Table 2. The areas are approximate because they don’t take into account Sharm Yanbu and very small areas.

The risks linked to changes in the morphology of the coast are multiple:

- The extension of low-lying areas on the coastal fringe can be a major source of flood risk. Some urban areas of the city of Yanbu are built on the site of ancient lagoons or sabkhas.
- The risks of flooding revealed by [30,58], can be also exacerbated by changes made in coastal area. Note that a large part of the city is established on an area that was covered by wadis, as can be seen on the 1965 image (see Figure 6). The risks of urban flash flood need to be carried out by studies on flood mitigation with urban stormwater infrastructure.
- Changes in the topography of the coastline can affect the entire coastal strip: subsidence, constitution of sabkhas, and rise of salt water table which can contribute to exacerbate seismic risks.
- The bathymetry of the coastal zone and the coastal geomorphology are completely modified, because a
large part of the coastline is backfilled or dredged.
• For all these aspects it is strongly recommended to define an integrated management plan of Yanbu coastal resources for all future development strategies and policies of the industrial city.

7. Conclusion

Yanbu shorelines positions from 1965 to 2019 were extracted by digitizing from six multisource and diachronic remote sensing data using GIS techniques. Change rates statistics were computed through the use of the DSAS application. The rates of change were calculated using two approaches: one in the changes between successive period pairs (1965–1980, 1980–1988; 1988–2000, 2000–2010; 2010–2019) using the EPR function of the application and the other over the entire period considered by LRR and WLR functions. This long time period (54 years) that encompassed the economic boom, urban expansion and the choice of Yanbu as the industrial portal of the kingdom and was marked by a progressive human occupation of the coast.

The statistical results obtained from the long-term analysis highlight the predominance of accretion phenomena, especially in the industrial city, where the highest rates were recorded and maximum accretional values reached. This trend is explained by the expansion of the industrial city on the coast and especially by the construction and extension of the commercial port and the King Fahd Industrial port, with large sea areas that were backfilled, leading to the disappearance of some islands and reefs. The percentage of all transects that are accretional is 54.92% and the maximum accretion value is 32.32 ± 2.27 m/yr (LRR statistic). The maximum erosional transect value recorded at the waterfront area reached −32.7 ± 2.27 m/yr (LRR function). For two successive coastlines, trends and values are variable (some are erosive others progressive). The maximum EPR progradation rates vary from 68 to 190 m/yr, while the maximum erosional rates range from −10.9 to −203 m/yr. Erosion affecting some transects was mainly recorded in the Sharm Yanbu and the industrial city and accretion affected Sharm Yanbu, the Commercial port and the industrial city. The confrontation between the rates in the two approaches used indicates that there are trend changes and slow movements of the reference line between different dates. Human activities are the main agents of shoreline change.

The kinematics of the coastline and the encroachment of the continent on the sea imply changes in the geomorphology of the littoral which exacerbates the risks related to floods, with the extension of the zones of low altitudes on the littoral fringe. The marine environment and Wadi outfalls are also affected, which could increase the vulnerability of the coastal area.
Disclosure statement

No potential conflict of interest was reported by the author(s).

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