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Spatiotemporal variations of the United Arab Emirates coastline each decade from 1991 to 2021

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Monitoring coastlines is a significant challenge in understanding their evolution, temporal and spatial variability, and impact on local marine ecosystems. Coastal anthropization, or the influence of waves and currents, can significantly alter the coastal landscape and morphology, presenting a daunting task. Severe consequences have been demonstrated, leading to the import of sand to eroding coasts and altering living conditions for marine ecosystems. Effectively managing these changes is essential, especially in countries like the United Arab Emirates (UAE), for their rich coastal biodiversity. The focus on the UAE is crucial to highlight the anthropic and natural development of its coastal cities through time. Several studies have extracted coastlines or measured erosion and accretion rates to track these changes, typically employing satellite imagery. Yet, the coastline of arid areas is not often monitored, raising concerns about the anthropic development of coastal cities and the preservation of their biodiversity on the long term. To address this gap, an algorithm was developed to automatically extract the coastline from satellite imagery using the Direct Difference Water Index (DDWI), an index that recently showed its efficiency in coastline extraction, the Otsu threshold, a fill operator and the Canny edge detector. The results reveal a significant evolution, along over 770 km of coastline, highlighting substantial anthropic development prior to 2013 associated with urban expansion into the sea. Sandbanks also exhibited a surprising increase in surface area around cities. Overall, excluding anthropic development, the UAE's coast has remained relatively stable, with minor erosion observed in the west of the country, potentially attributed to natural processes. This trend became more apparent after 2013, indicating a correlation between the maintenance of coastline stability and reduced urban development. This study offers an analysis of the coastline dynamics, that contributes to a deeper understanding of the effects of anthropisation on the unique coastal ecosystems of the UAE. It also provides insights for effective coastal management and urban planning.

KEYWORDS

coastlines, marine ecosystems, coastal urban development, coastal morphology, sandbanks

1 Introduction

Coastal marine areas, typically defined as the interface between open sea or ocean waters and the land surface, are renowned for their high marine biodiversity. This richness in species is attributed to the abundance of sunlight and nutrients, as well as the diverse habitats along the coastline that support various organisms (Farahat and Abuelgasim, 2019). These areas play a crucial role in preventing erosion, filtering pollutants, and providing food, shelter, breeding grounds, and nursery habitats for a multitude of species. Despite their importance, coastal marine areas globally face persistent threats from erosion and environmental degradation. These threats stem from natural phenomena such as floods, sea and ocean water intrusions, rising sea levels, typhoons, hurricanes, and shifting rainfall patterns (Lu et al., 2018).

Approximately 39% of the global population resides near coastal areas (Crowell et al., 2007). These regions have been transformed into economic hubs, bustling with significant economic and social activities. However, these activities often adversely affect coastal zones through urban sprawl, coastal infrastructure development, tourism, and marine transportation. Furthermore, human-induced activities contribute to coastal pollution by consistently disposing of solid and liquid waste, losing coastal habitats, and causing shoreline erosion. Consequently, monitoring marine coastal ecosystems is crucial, as they are among the most threatened systems due to natural and anthropogenic activities.

1.1 Coastline monitoring in the literature

Various indicators are employed to evaluate the health and ecological status of coastal marine ecosystems. These indicators encompass shoreline variations (Billet et al., 2023; de Oliveira and Barboza, 2024), intertidal flat zone biodiversity, and coastal pollution. The spatiotemporal monitoring of coastline changes is particularly significant, serving as a crucial indicator for assessing coastal areas' ecological and environmental status (Viaña-Borja and Ortega-Sánchez, 2019). Continuous temporal monitoring facilitates the identification of significant alterations and the comprehensive dynamics of the coastline.

Historically, coastline changes have been identified through field observation surveys, coastal maps, historical records and photos, tidal records, and coastal tide gauges. However, advancements in satellite observation have greatly simplified and enhanced the accuracy of monitoring coastline changes. Earth observation data offers an exceptional information source for mapping and monitoring these changes. This data type ensures consistent temporal coverage across various spatial scales and offers a broad spectrum of usable spectral information. Additionally, it provides global coverage and is more cost-effective.

Numerous studies have utilized remotely sensed data to monitor coastline variations and the potential causes of these changes. These investigations have predominantly employed broad band multispectral satellite data to assess coastal changes in open seas and inland water bodies, such as rivers and lakes (Alesheikh et al., 2007; Feyisa et al., 2014; Ozturk and Sesli, 2015; Mentaschi et al., 2018; Wu et al., 2018; Mishra et al., 2019; Viaña-Borja and Ortega-Sánchez, 2019; Awad and El-Sayed, 2021; Hossen and Sultana, 2023). The extensive historical archive of Landsat data has served as an ideal resource in these studies for mapping and monitoring coastal variations over periods of up to 30 years. Beyond Landsat satellite data, some research has incorporated a combination of satellite imagery and digital elevation models to track coastline changes (Kale et al., 2019; Tsai and Tseng, 2023). Additionally, airborne data has also been employed to monitor coastal variations (Sesli and Caniberk, 2015; Xu et al., 2019; Wang et al., 2023). Synthetic Aperture Radar (SAR) data can also be employed to monitor shoreline variations (Savastano et al., 2024) or for object detection and tracking (Yasir et al., 2024). These studies commonly emphasize the significant impact of human-induced activities on coastal erosion and degradation.

Furthermore, these studies have effectively utilized the spectral information from multispectral data to precisely delineate the waterline. A widely used approach involves developing band ratio techniques. Some methods take advantage of the strong water absorption in the nearinfrared spectrum and the higher reflectance in the green spectrum, combined with thresholding techniques, to delineate the waterline (Awad and El-Sayed, 2021). Others have employed the mean high waterline, incorporating tidal and elevation data, to achieve this delineation (Zhang and Hou, 2020).

Algorithms are recently used in this field. It is the case of Viaña-Borja and Ortega-Sánchez (2019), Feyisa et al. (2014), and Abdelhady et al. (2022) as they automate the extraction on wide areas without the need to manually digitize entire coastlines or repeat the extraction operations for several areas. Models are also developed and utilised for shoreline monitoring and prediction (Awad and El-Sayed, 2021) or to detect and track objects (Yasir et al., 2024) for instance.

Despite the range of studies having improved coastline extraction, a notable research gap remains in the use of effective coastline monitoring techniques in the UAE. It is still not the case even if this country shelters a rich coastal biodiversity. Although numerous studies utilize multispectral data to extract the coastline using band ratio techniques, there is still a lack of automated solutions adapted to the specific context and challenges of UAE coastal areas. Existing techniques often rely on multispectral data like the Digital Shoreline Analysis System (DSAS) (Yasir et al., 2020; Hossen and Sultana, 2023) but overall, still do not sufficiently take advantage of algorithm integration. This addition makes the process faster and quickly mobilizable for other's areas applications. However, the use of complex methodologies might not be applicable in other countries with limited computational resources. This leads to the need to develop simplified approaches like using the Direct Difference Water Index (DDWI). As the environmental context of UAE greatly differs from the other countries context, it represents an opportunity to test this index and highlight its efficiency. In effect, the use of the Otsu threshold in addition of the DDWI did not give better results than with the DDWI alone in the United States. However, it was not tested elsewhere. Other methods such as the YOLOShip tracker (Yasir et al., 2024) have focused on tracking maritime object but have not been utilized or made for coastline delineation.

To fill this gap, this research develops a new algorithm combining the DDWI, the Otsu thresholding method, a fill operator and the canny edge detector to automatically detect and

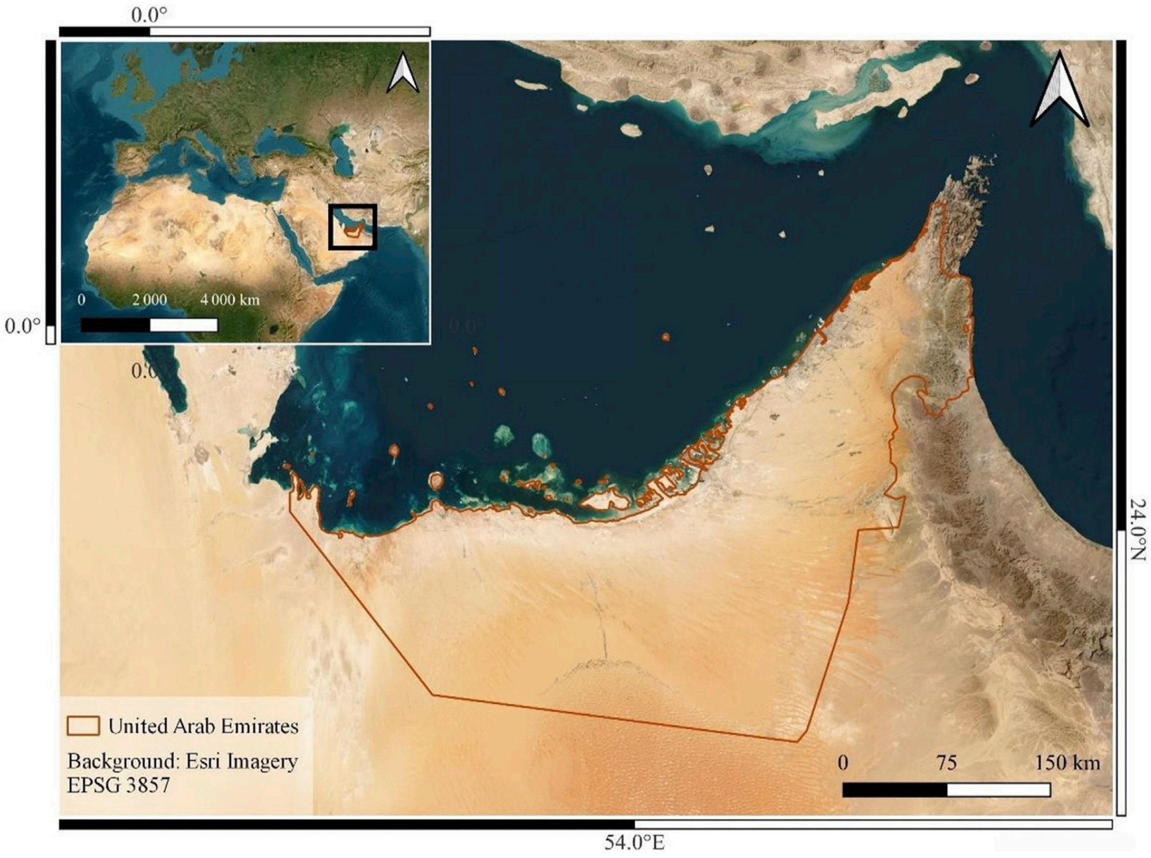

FIGURE 1
Study area.

extract the coastline. The choice of the DDWI was made based on its recent proven efficiency (Abdelhady et al., 2022) and the canny edge detector is a new addition to improve the extraction as Yasir et al. (2020) showed it. This study aims at enhancing the accuracy and efficiency of coastline monitoring using this comprehensive approach. It will contribute to developing coastal ecosystems management strategies in the UAE. The development of this automated approach seeks to address the existing research gap and provide essential insights to understand the coastal evolution between 1991 and 2021 due to both natural and anthropogenic factors.

1.2 Local context

The coastal regions of the United Arab Emirates (UAE) exhibit significant biological and ecological diversity within their marine and coastal habitats. The coastlines of the UAE stretch along the Arabian Gulf and the Sea of Oman (formerly the Gulf of Oman). Historically, these areas have been hubs for various human activities, including trade, marine transport, food sourcing, and pearl mining. In fact, it is estimated that over 70% of the local population of the UAE has historically resided in coastal regions (Alqaydi et al., 2017).

Since the establishment of the UAE in the early 1970s, significant pressures have been exerted on coastal areas due to massive expansions and the development of coastal infrastructure associated with rapid economic growth. These pressures have included the construction of new seaports, shoreline modifications for urban structures, the creation of man-made islands, and the development of tourist attractions. Such activities have significantly altered the country's coastal shorelines. Consequently, in-depth knowledge and understanding of the status of coastline variability and coastal habitats are crucial for the proper management of risks associated with coastal habitat degradation and coastline variation.

1.3 Study area

The United Arab Emirates (UAE) is a relatively small country situated at the extreme western edge of the Asian continent and the southeastern part of the Arabian Peninsula. It covers a total area of 83,600 km^2, spanning latitudes 22° 50′ to 26° 4′N and longitudes 51° 5′ to 56° 25′E (Figure 1). The UAE shares its borders with the Sultanate of Oman to the east and south and the Kingdom of Saudi Arabia to the west. It also abuts two major bodies of water: the Arabian Gulf to the north and the Sea of Oman to the east. Excluding the numerous small islands scattered along the Arabian Gulf, the UAE's total coastline extends approximately 770 km, with 700 km bordering the Arabian Gulf and a smaller 70 km stretch along the Sea of Oman.

TABLE 1 Landsat images.

Satellite	Spatial resolution (m)	Date	Time	Tide level (m)	Cloud coverage (%)	Path	Row
Landsat 8	30	13/06/2021	06:52:18	1.27	0	161	43
		02/08/2021	06:39:47	1.4	0.3	159	42
		22/11/2021	06:40:28	1.34	0.02	159	43
		13/11/2021	06:46:16	1.41	0.65	160	42
		13/11/2021	06:46:40	1.41	0.28	160	43
		26/10/2021	06:59:06	1.41	0.01	162	43
Landsat 8	30	26/08/2013	06:54:31	1.43	0	161	43
		18/12/2013	06:41:12	1.35	1.87	159	42
		13/09/2013	06:42:06	1.41	0.8	159	43
		07/11/2013	06:47:39	1.33	0.61	160	42
		07/11/2013	06:48:03	1.32	0.3	160	43
		07/12/2013	07:00:16	1.49	0.37	162	43
Landsat 5	30	31/12/2001	06:31:43	1.27	1	161	43
		05/04/2001	06:19:41	1.38	0	159	42
		05/04/2001	06:20:05	1.38	1	159	43
		21/10/2011	06:25:50	1.51	3	160	42
		21/10/2001	06:26:14	1.51	0	160	43
		12/05/2001	06:38:52	1.44	0	162	43
Landsat 5	30	15/09/1991	06:16:26	1.45	0	161	43
		17/09/1991	06:03:41	1.17	10	159	42
		29/06/1991	06:03:16	1.13	6	159	43
		03/05/1991	06:08:11	1.43	3	160	42
		03/05/1991	06:08:35	1.43	0	160	43
		02/06/1991	06:21:26	1.44	0	162	43

The country comprises seven emirates, with Abu Dhabi being the largest in land area and population. This emirate also boasts the longest coastline of the country. The UAE is situated in one of the most arid and dry regions of the world. Its landscape features vast deserts, including extensive sand dune fields in the west and rugged, scattered mountains in the northeast and along the Oman border. The climate is predominantly arid and hot, although local coastal and mountain climates contribute to a diverse range of environments, including Gulf islands, coastal regions, and desert areas (Abuelgasim et al., 2021).

The Arabian Gulf waters are generally shallow, with an average depth of 90 m (Farahat and Abuelgasim, 2019). Much shallower waters are found along the coastal areas of the UAE. Within these regions, large tracts of scattered mangrove canopies line the country's coast. Additionally, the extreme environmental conditions and significant seasonal variations in the marine environment along the Arabian Gulf waters foster the development of various seagrass species. In contrast, very little mangrove forests and seagrass areas are found along the coastal areas of the UAE facing the Sea of Oman.

2 Material and methods

2.1 Data

Landsat 8 and 5 satellite images were selected for their extensive record of imagery over the study area (Table 1). They have a 30 m multi-spectral spatial resolution. Six different paths and rows were chosen for the years 1991, 2001, 2013, and 2021 to encompass the entire UAE coast (Figure 2). The choice of these dates lies in the wish to range across several decades from the oldest possible acquisition images available until nowadays. As the oldest date available using Landsat 5 is 1984, it was decided to begin the analysis around 1990 and to analyze each decade until 2020 the evolution of the coastline. In effect, the coastline should not depict drastic changes in its shape as the natural changes of a coastline happen on the long term, except when there is anthropisation. Data selection for each ten-year interval was constrained by availability. Images were chosen based on water levels at the time of acquisition to ensure comparability of the coastline across different dates, as capturing images on the same day in different years does not guarantee

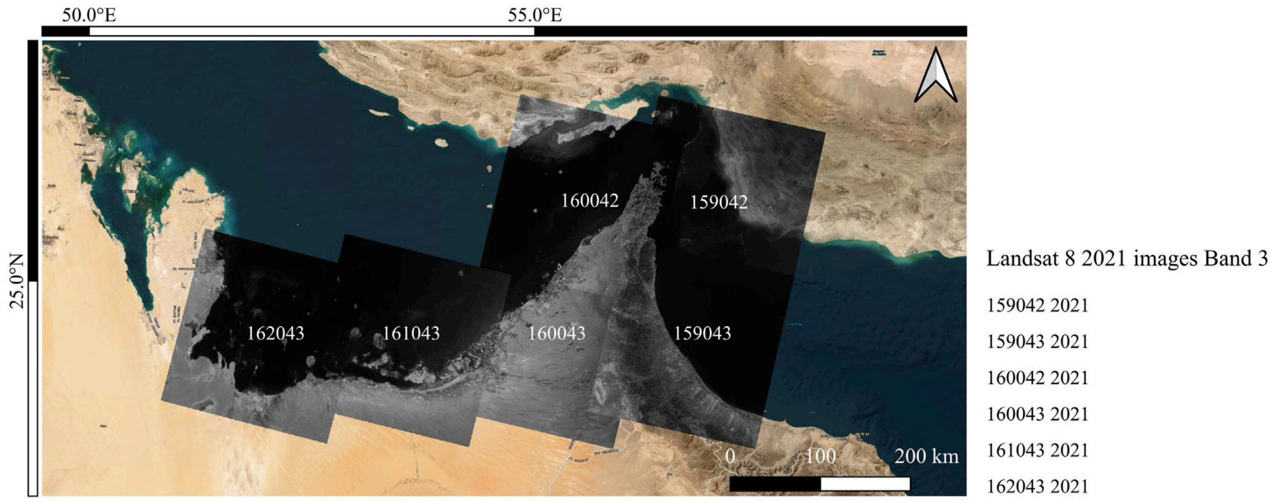

FIGURE 2
Geographic location of satellite images.

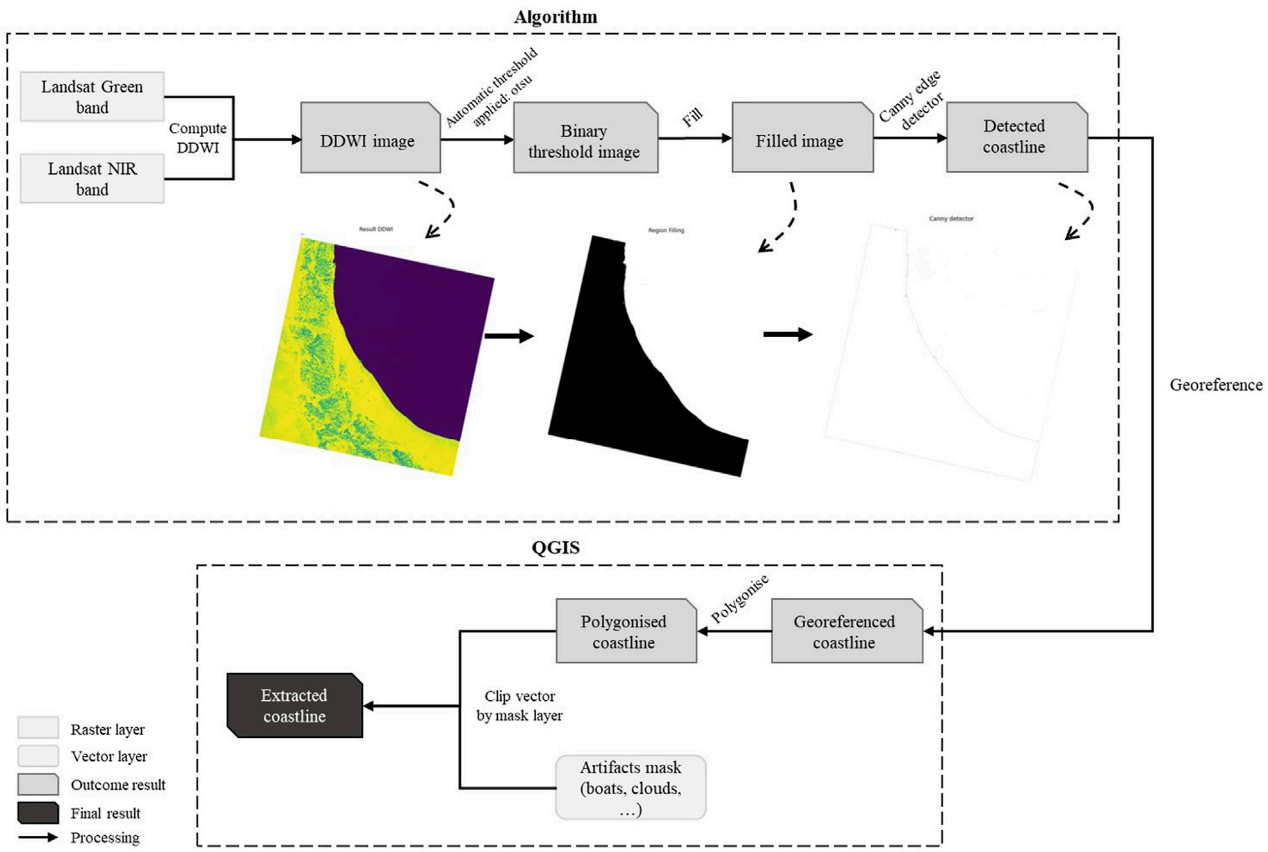

FIGURE 3
Methodology.

identical tide levels. The cloud cover in the images was kept below 10%. A water level of 1.41 m was used as a reference, representing the most frequent occurrence among the tide levels observed in the images, with a maximum deviation of ±0.23 m. This data was obtained from the tide tables of Abu Dhabi harbour, accessible on the SHOM website (https://www.shom.fr/en/).

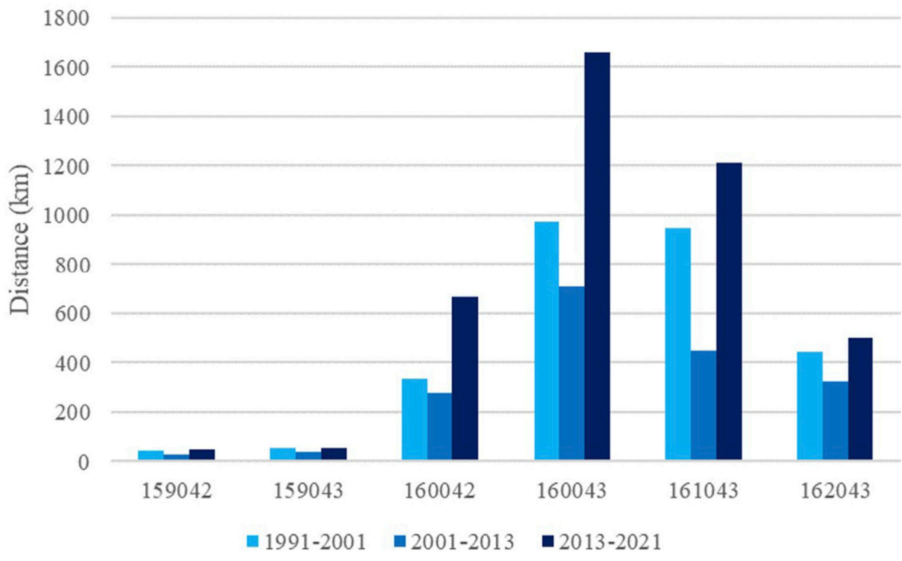

FIGURE 4
Evolution of coastline from 1991 to 2021 in function of each satellite image area: coastline which remained unchanged.

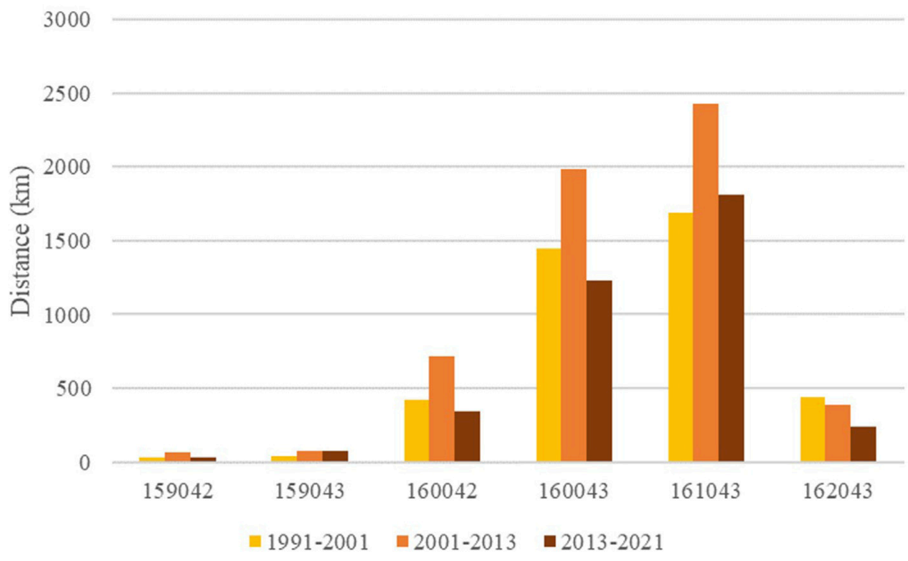

FIGURE 5
Evolution of coastline from 1991 to 2021 in function of each satellite image area: coastline which changed.

2.2 Methodology

In this study, an algorithm (Figure 3) was developed to automatically extract coastlines, proving particularly effective for water bodies adjacent to desert landscapes, as in the case of the UAE. In effect, such a tool has not been created before, especially for desert areas.

After the literature, using band-ratio techniques are efficient for this type of analysis. Then, the algorithm begins by calculating the Direct Difference Water Index (DDWI) using the nearinfrared and green portions of the spectrum, corresponding to bands 5 and 3 in Landsat-5 and 8 imagery. The DDWI distinguishes between submerged areas and the shore and has proven its efficiency (Abdelhady et al., 2022). DDWI is used as it has a physical significance due to the contrast between land and water bodies as demonstrated by Abdelhady et al. (2022). The reason for not choosing the NDWI lies in the results obtained with the previous study mentioned that showed lower accuracy for shoreline detection in comparison to the DDWI. Visual interpretation can lead to errors due to the similarity in colour between the sand underwater and that on the shore, particularly because these areas are shallow and the desert environment provides a seamless transition between the

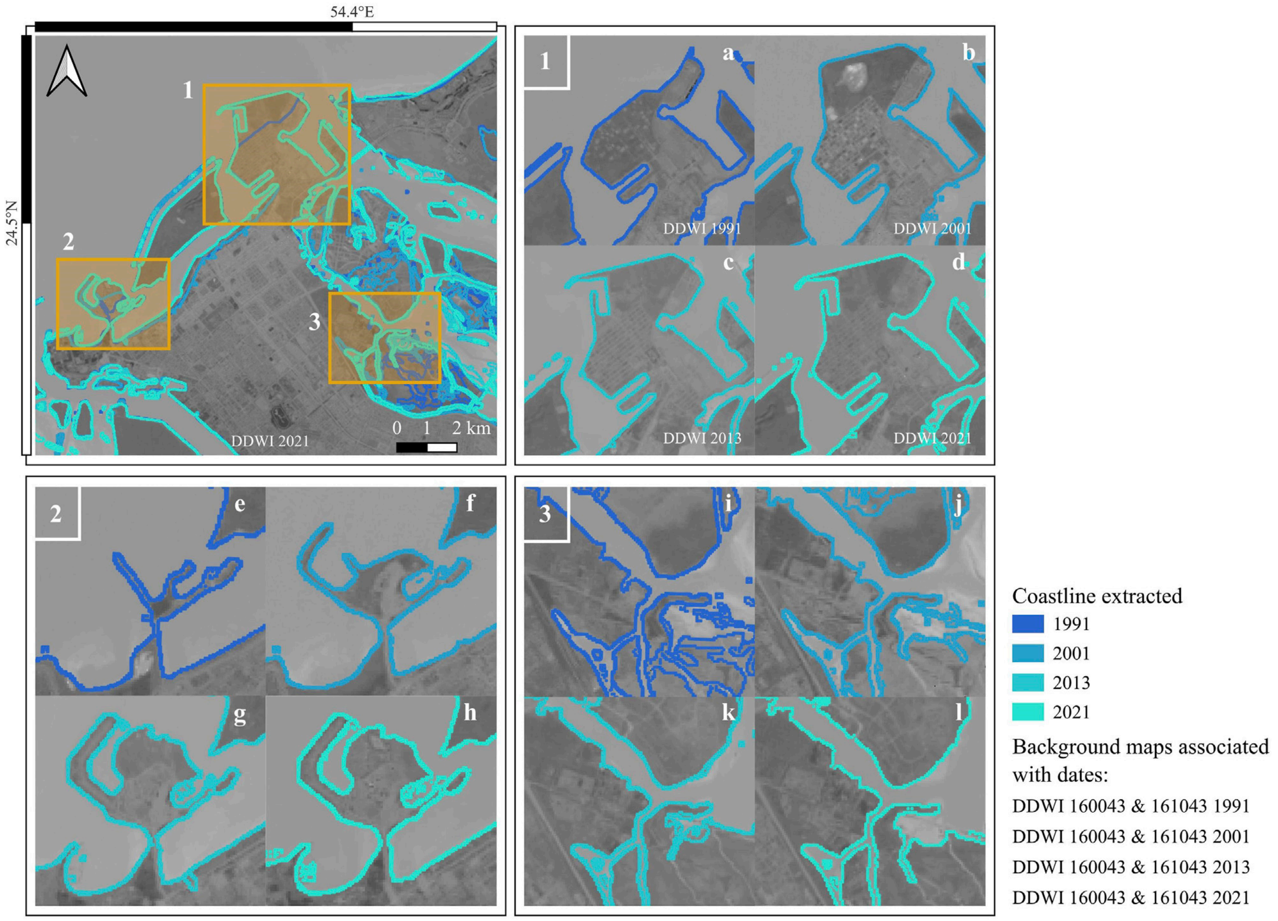

FIGURE 6
Focus on zoomed coastline extracted in Abu Dhabi city: 1) **(a-d)**: Port Zayed from 1991 to 2021, 2) **(e-h)**: Kasser Al Amwaj from 1991 to 2021, 3) **(i-l)**: Mangrove National Park from 1991 to 2021.

submerged sand and that on the shore. The DDWI is computed using the equation:

$$\boldsymbol{DDWI = Green - NIR}$$

An Otsu threshold is computed to distinguish land from water. The Otsu threshold (Otsu, 1979) is used to separate the pixels of an image into two categories based on pixel intensity. This method was selected for its use by Abdelhady et al. (2022). Additionally, adjusting the multiplier value when calculating the threshold in the algorithm for uint16 and uint8 images is essential. This adjustment is necessary because the transformation into an "np.array" alters the power of 2 depending on the format: 2 ˆ 16 for Landsat-8 and 2 ˆ 8 for Landsat-5.

The subsequent step involves filling the voids in the binary image to create distinct masks for water and land, utilising the segmentation operator "fill." Following this, an edge detection operator known as the "Canny edge detector" is employed to delineate the coastline from the image. These operators were selected due to the proximity of clouds, boats, and islands to the coast, which could have been erroneously identified as part of the coastline if mathematical morphological operators had been utilised. The Canny edge detector facilitates the extraction of all boundaries, enabling the manual elimination of artefacts at a later stage.

The algorithm outputs an extracted raw coastline image, which must be georeferenced anew due to the loss of georeferencing during processing. This is accomplished by applying the original satellite image points to the processed image. Although this technique should not result in any displacement issues, it is important to note the presence of two different CRS in the area: WGS 84/UTM 39N (EPSG 32639) and UTM 40N (EPSG 32640). Subsequently, the georeferenced coastline is polygonized and then clipped using a mask layer designed to eliminate boats, clouds, and other non-coastal artefacts with the aid of QGIS software. The "Polygonize (raster to vector)" and "Clip vector by mask layer" tools are employed for these tasks.

3 Results

3.1 Impact of anthropic development

The coastline of the UAE has evolved differently from 1991 to 2021. To precisely understand the variations, the study area was

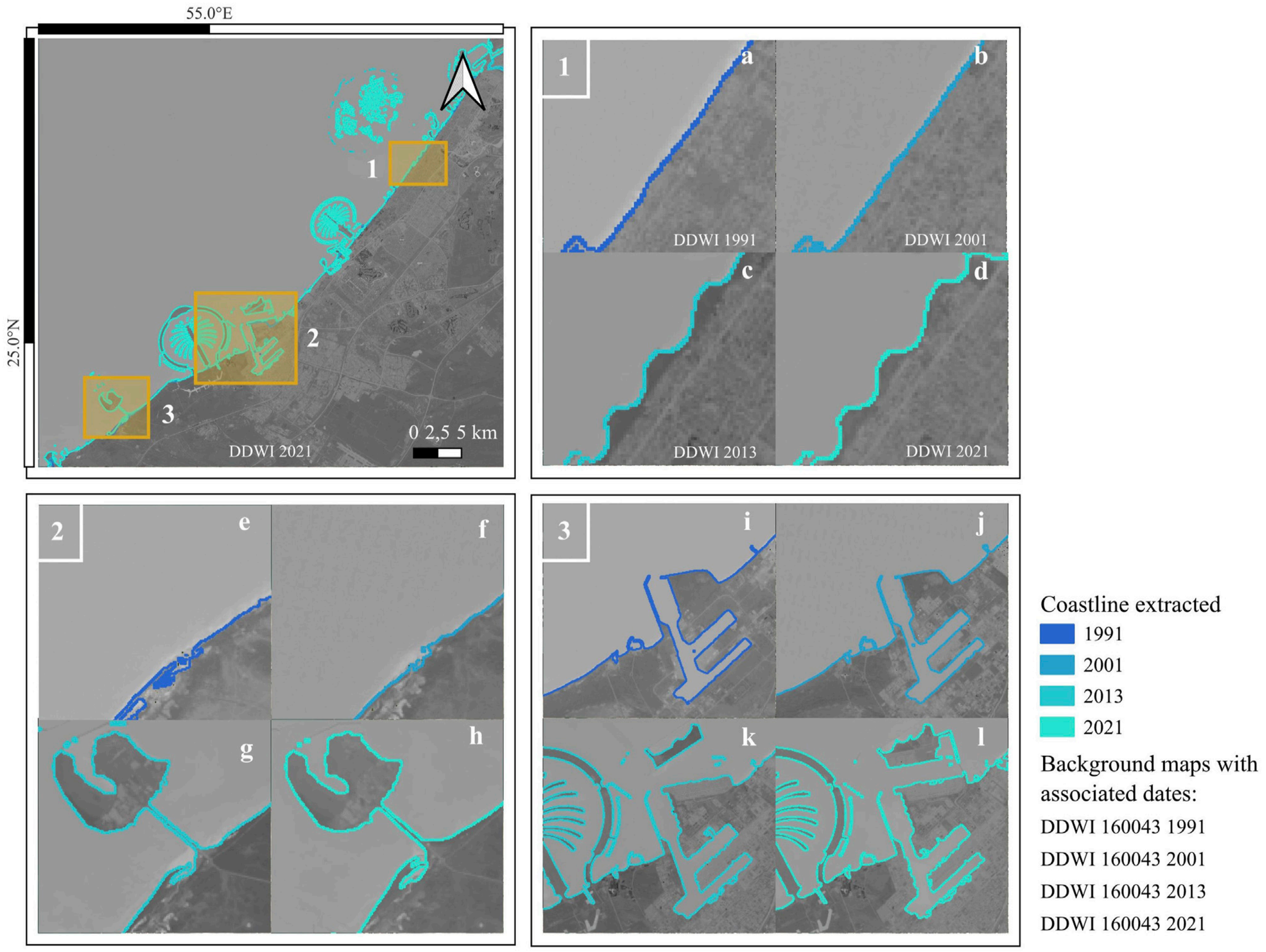

FIGURE 7
Focus on zoomed coastline extracted in Dubai city: 1) **(a-d)**: Jumeirah from 1991 to 2021, 2) **(e-h)**: Jebel Ali Freezone from 1991 to 2021, 3) **(i-l)**: Dubai Water Front from 1991 to 2021.

divided based on the extent of each satellite image used to extract the coastline: 159,042, 159,043, 160,042, 160,043, 161,043, and 162,043. It reveals that the changes did not occur consistently over the 30 years (Figures 4, 5). For instance, in area 160,043, the coastline evolved rapidly from 1991 (2,306 km) to 2013 (2,690 km) and more slowly thereafter (2,884 km in 2021) (68,165 km^2). These values exceed the original length of the coast mentioned at the beginning of the paper because the general computation typically represents only a single line, which does not account for islands and various anthropogenic developments. The values here include these islands and the smallest anthropized areas. The marked increase between 1991 and 2013 indicates that the coastline underwent more significant changes after 2001 than before. A similar trend is observed in other areas, with lower values due to the varying amounts of coastline considered.

Significant variations occurred between 1991 and 2013, with a peak during the 2001–2013 period in 160,043 (2,690 km) and 161,043 (2,874 km), corresponding to the Abu Dhabi and Dubai areas, respectively. Prior to 2013, these two cities underwent urbanization, expanding inland and towards the sea (Figures 6, 7), which included the creation of artificial islands, accounting for the aforementioned expansion. The marked similarity observed post-2013 indicates a deceleration of this growth. The change in the beach pattern in Dubai in Figure 7-1 between 2001 and 2013 marks very well this drastic evolution. In Abu Dhabi, there are areas that went under important anthropic expansion like in Figures 6-1, 2. There is also an important change that can be noticed in the mangrove national park in Abu Dhabi that expanded between 1991 and 2013 towards the north-west before retreating on 2021 image.

This trend is consistent across other areas, except for 159,042. This zone, situated along the eastern coast of the United Arab Emirates adjacent to the Sea of Oman in Fujairah emirate, exhibited minimal natural and anthropic coastal evolution (Figure 8-3). The changes that did occur have diminished over time and stayed consistent (Figures 8-1, 2). In contrast to the other regions, Fujairah experienced reduced coastal changes. Being smaller than Dubai and Abu Dhabi, Fujairah has a shorter coastline, which accounts for the lesser extent of change.

The remaining three areas do not correspond to urban locations; therefore, their evolution is not as critical as that of the others, yet they exhibit a similar pattern. This may be attributed to the influence exerted by the other areas. Furthermore, the results are derived from a spatial resolution of 30 m, indicating that any coastline changes

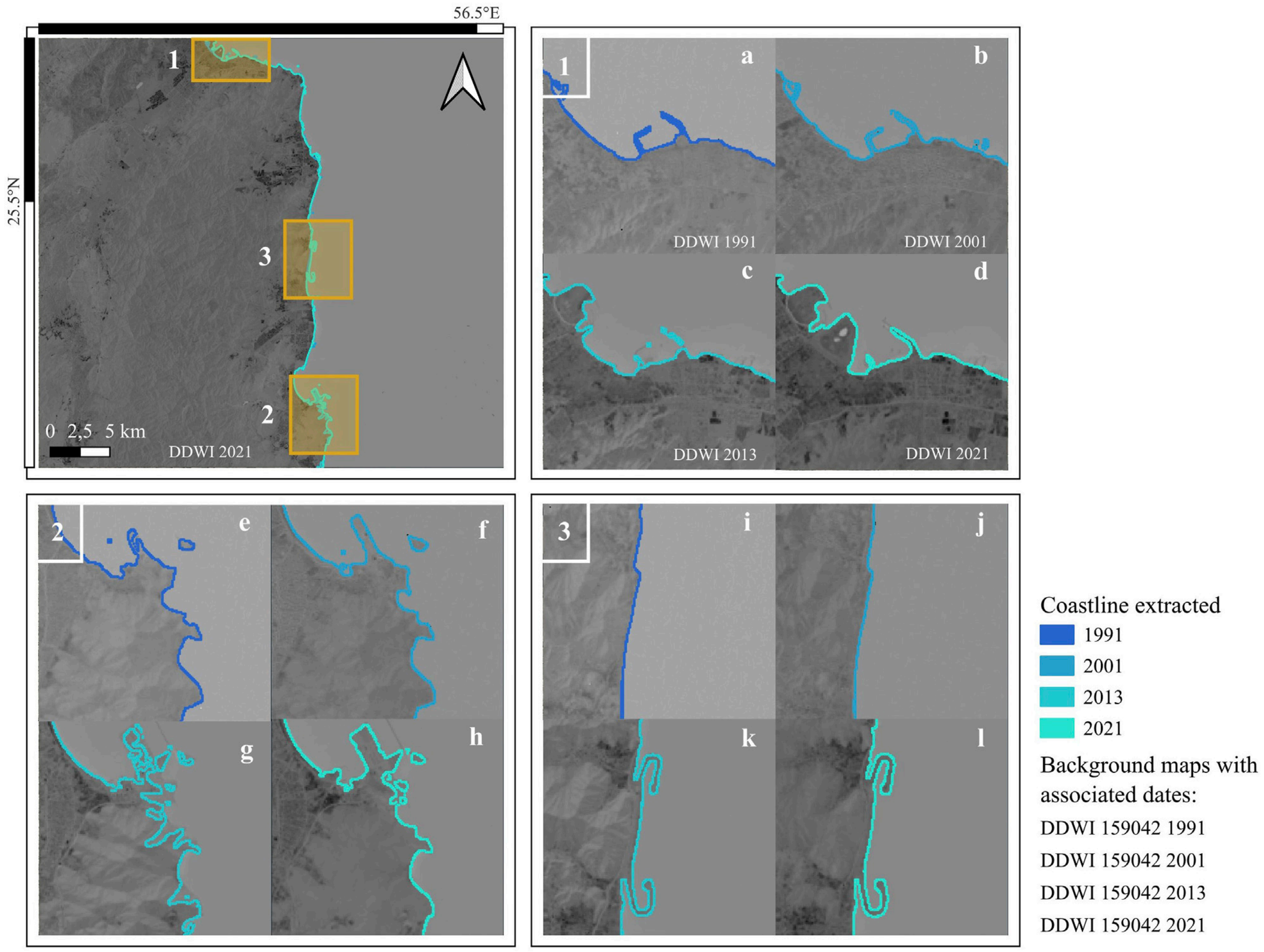

FIGURE 8
Focus on zoomed coastline extracted in Fujairah emirate: 1) **(a-d)**: Sambaraid from 1991 to 2021, 2) **(e-h)**: Khor Fakkan Port from 1991 to 2021, 3) **(i-l)**: Al Danah from 1991 to 2021.

less than 30 m are not accounted for. Consequently, the variations observed over 30 years are significant.

3.2 Sandbanks variations

Apart from the general evolution, the line extracted by the algorithm enables the definition of various types of coastline variations. Figure 9 displays a line corresponding to the limits of the DDWI computed within the algorithm. At first glance, the extraction appears accurate. However, some features, such as canals, are not always detected, as observed in Figure 9a′.

Sandbanks also present a complex case. They are challenging to define because they are both a part of the coastline and separate from it, alternately submerged and exposed by the tide due to their location in shallow waters. In this study, sandbanks are included in the delineation of the coastline as they are visible on satellite images, particularly in the results of the DDWI.

Since 1991, the seaward evolution of sandbanks has been evident (Figure 9d), indicating an increase in their size. These sandbanks are depicted as a lighter shade of grey compared to the sand islands. However, not all newly emerged areas are sandbanks. For instance, the area that appeared south of Figure 9c is associated with the establishment of mangrove plantations along the coast.

3.3 Coastal erosion and visual accuracy

Not all changes indicate an expanding coastline. Some areas, particularly in the west of the UAE near Qatar, exhibit erosion over time (Figure 10). On the UAE's east side, there is little significant natural change, except in anthropogenic zones that have undergone development, notably the construction of ports such as Fujairah Port.

Previous figures (Figures 6–10) show the precision of the extraction of the coastline as there is no reference coastline available to compare the accuracy. In this study, the coastline extracted in 1991 is considered as the reference to define a basis for the following analysis. This approach has already been used by Giordano et al. (2003) to assess the results of coastline extraction while no reference coastline already existed.

Overall, according to the different figures and to the year 1991, it appears the algorithm extracted correctly the coastline for each

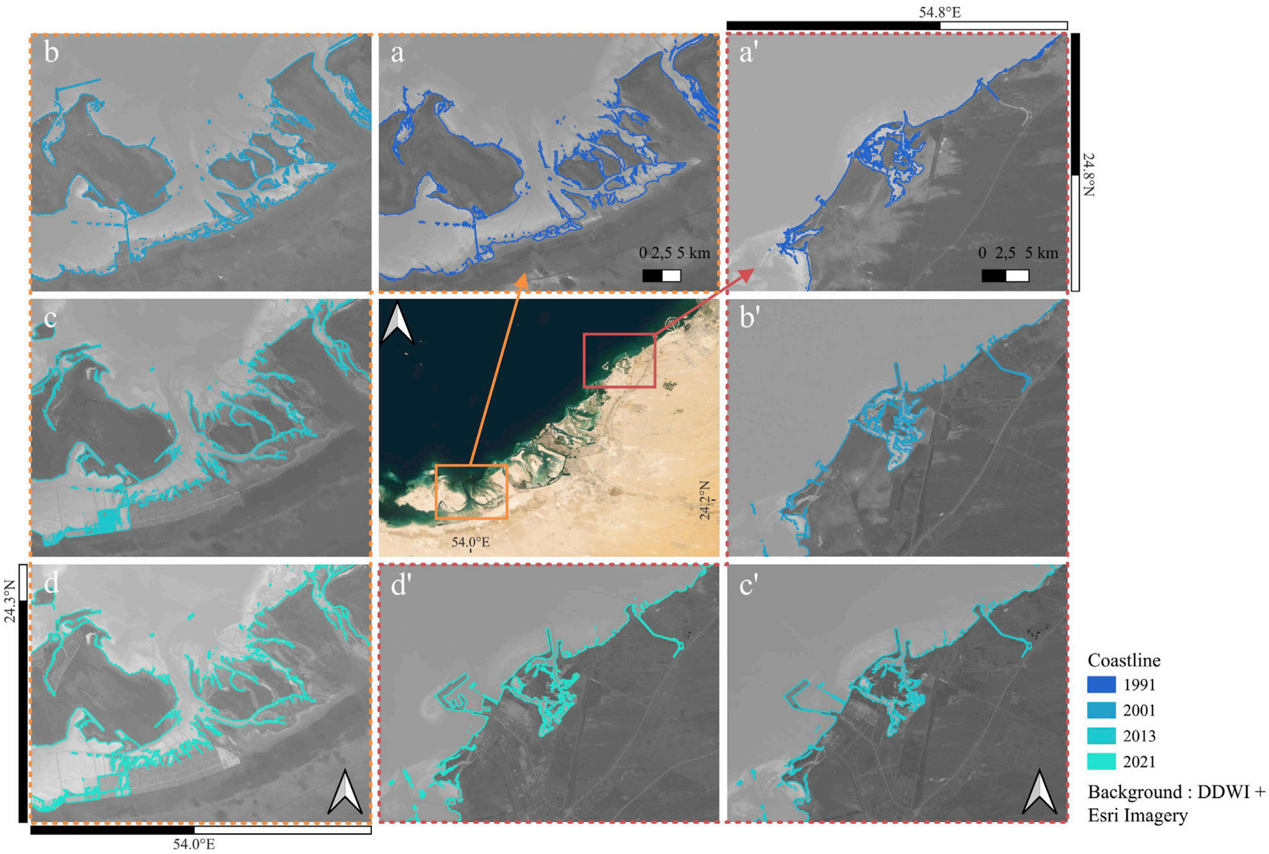

FIGURE 9
Focus on coastline extracted in the south and the north of Abu Dhabi city: **(a-d)**: Southwest of Abu Dhabi from 1991 to 2021 - **(a'-d')**: Northeast of Abu Dhabi from 1991 to 2021.

decade. This is especially visible on Figures 6–8 as the extracted coastlines overlap the 1991 one. It appears that no land area was forgotten and delineate the land from water without major mistakes visible. Figure 8-1 presents a small dot extracted in 2013 as coastline that could come from anthropic construction as it was not there in 1991. The same conclusion can be drawn from Figures 6-3, 7-3.

Figures 9, 10 also highlight a visibly accurate extraction of the shoreline as there is an overall overlapping of 1991 coastline with the other years. Among the changes, an anthropic infrastructure appeared (Figure 10-1). The sandbanks are also considered, for example, on Figure 9-1 and on Figure 10-1 and can also explain the evolution. This depicts the closeness of the sandbanks to the land as these are sand areas located in shallow waters. Even if they are considered in the analysis, they are still interesting as they represent the evolution of water currents along the shore and help visualize the coastal dynamics. This could lead, for instance, to the expansion of land areas due to sand accumulation on the long term.

4 Discussion

4.1 Coastal development and sandbanks

The developed algorithm can extract coastlines, albeit with some inaccuracies, particularly when the coastline features sandbanks and discontinuous elements such as canals. These inaccuracies may result from the similar reflectance of pixels in these areas or the choice of the Otsu threshold within the algorithm. Abdelhady et al. (2022) suggested that the Otsu threshold might not optimally delineate land and water. They preferred detecting the minimum value threshold of DDWI to distinguish between the two classes. However, their study was not conducted in a desert context, which presents additional challenges to differentiation.

Therefore, this paper demonstrates that employing DDWI in conjunction with the Otsu threshold is effective, despite certain inaccuracies, as it distinctly delineates land from water and accounts for sandbanks, which also exhibit high reflectance in band 5 of Landsat satellites. Sandbanks, being near the surface in shallow waters and similar in composition to land, are consequently detected as land. Thus, it is essential to consider this factor when determining whether observed differences over time are attributable to coastal evolution or the inclusion of sandbanks. Overall, this method can be extended to other scenarios and generalized as it showed its efficiency in places with great differences between water and land (Abdelhady et al., 2022). The results of the current study show that it is also feasible to use this method in desert countries but sandbanks should be taken into account as well. The year 1991 was considered as the reference to conduct the analysis based on the automatic extraction, taking into account the errors that can exist.

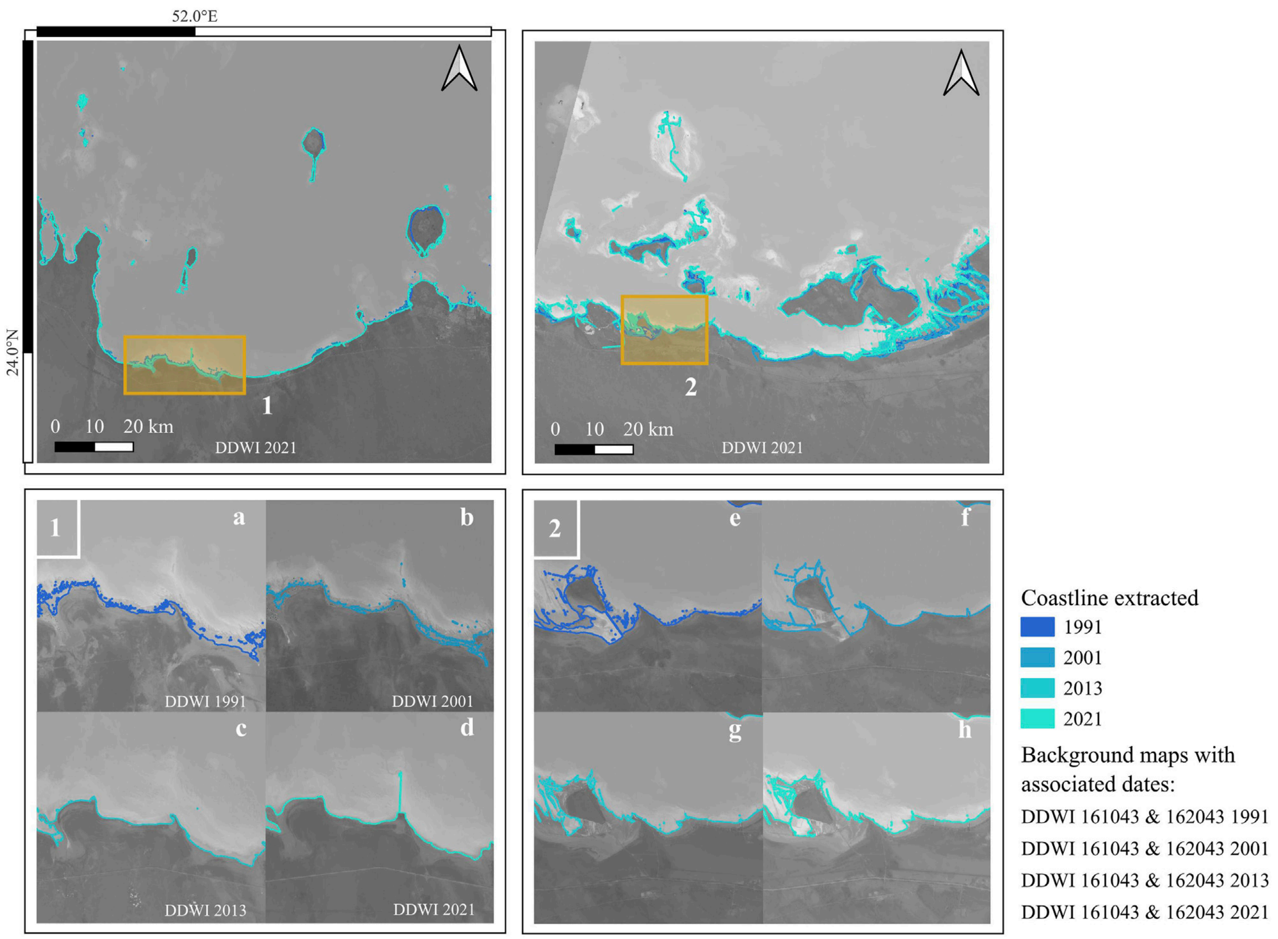

FIGURE 10
Example of coastline erosion in the west of Abu Dhabi emirate: 1) **(a-d)**: Mahmiyyat Al Suqour from 1991 to 2021, 2) **(e-h)**: Al Mirfa and Qirayn Al 'Aysh from 1991 to 2021.

As previously mentioned, sandbanks south of Abu Dhabi have expanded their surface area toward the sea. In the absence of anthropic activity impacts on the coast, this increase can be attributed to sediment deposition resulting from continuous backfill erosion by waves in anthropic areas, as partially discussed in the introductory section of Kuisorn et al. (2014). Ripraps are commonly employed to mitigate this issue. Indeed, the creation of new islands such as Jumeirah Palm in Dubai and Abu Dhabi coincided with their expansion. The sediments introduced during these projects are prone to remobilization by coastal erosion, which, coupled with marine currents, transports sand from these islands to areas with weaker currents. Consequently, altering the coastline disrupts the natural direction of marine currents, leading to increased erosion of the new coastline and the transport of the newly deposited sand to areas with diminished current activity. This phenomenon also accounts for the absence of sandbanks in anthropic regions. Thus, the UAE's development has affected marine circulation in the Arabian Gulf and the Sea of Oman. Over the past 30 years, sandbanks have primarily evolved toward the Arabian Gulf in the north of the UAE but not in the northwest, where a decrease has been observed. The northeast and east have shown no significant changes, except in anthropic areas.

Working on each decade shows overall a relatively small evolution of the coastline excepted when the changes are anthropic. Then, its natural evolution does not request to study each year between each decade. However, for a thorough understanding of the anthropic development along the coast, it could be interesting to pursue such an analysis.

4.2 Induced coastal erosion

The erosion observed along the northwest coast of the UAE highlights that changes are not limited to sandbanks. Their evolution is primarily due to aeolian and wave erosion, concerning natural processes. In terms of anthropogenic factors, the construction of power plants, ports, or mangrove plantations directly impacts currents by diverting them. This diversion accentuates erosion around new infrastructure and displaces newly deposited sediments. Consequently, the coast has expanded mainly in areas of anthropogenic development and in the direction of currents, which transport eroded sediments. This study, spanning 30 years, captures these changes.

4.3 Limitations

The results, based on the DDWI, require analysis. Choosing a different index might have altered the detection process. However, the DDWI appears to have been the optimal choice for accurately delineating the coastline, having already demonstrated its effectiveness. Some inaccuracies remain, but the delineation closely follows the coastline when using the DDWI. Furthermore, the selection of the Otsu threshold was suitable for distinguishing between land and water. This algorithm proved its efficiency in extracting the coastline of an arid country like the UAE and can be used in other regions to test its efficiency under other conditions. The generalizability of this solution has been made easier as it only requires 2 satellite images in entry of the algorithm. The results demonstrate the algorithm's efficiency in accurately extracting coastlines, although some inaccuracies occur in areas with sandbanks. This suggests that it is likely reproducible in other regions It would be worthwhile to explore improvements by using or developing an index that more precisely differentiates between land and water, considering that sandbanks are currently included. Such an approach could enable monitoring of the coastline's evolution independently of the sandbanks. Additionally, future research should incorporate higher spatial resolution satellite imagery to improve the accuracy of the tracked coastline changes.

5 Conclusion

The evolution and morphology of the UAE coastline were monitored each decade from 1991 to 2021 using spatio-temporal remote sensing data and a bespoke algorithm. The results underscore a predominantly anthropogenic transformation of the coastline, largely attributed to urban expansion into the sea. The development of ports is a prominent example, as observed in Fujairah and on the Abu Dhabi side. The majority of the evolution of the coastline occurred before 2013, coinciding with significant urbanization and expansion during that period. Consequently, most of the coastline remained unchanged post-2013. Additionally, the evolution of the coastline is influenced by changes in sandbanks situated in shallow waters. Their detection indicates a gradual seaward extension of the coast due to sand accumulation. Nonetheless, not all coastal areas are accreting; some, particularly in the western UAE, are experiencing erosion. For future research, refining the algorithm to distinguish between sandbanks and the actual coastline would be beneficial. Moreover, employing higher spatial resolution imagery could enhance the accuracy of detection.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JS: Conceptualization, Investigation, Methodology, Software, Visualization, Writing–original draft. KA: Writing–review and editing. AA: Supervision, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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