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Original Article

Analyzing Coastline Alterations through Remote Sensing and Detect the Factors that Lead to this Phenomenon: An Investigative Example of Tyre Shoreline, South Lebanon

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Abstract - *The rising impact of coastal erosion and accretion has heightened the vulnerability of coastal regions to potential harm. Consequently, the evaluation of coastal alterations and shoreline dynamics through coastline assessments is of utmost significance. In this context, the Digital Shoreline Analysis System (DSAS) emerges as a valuable instrument for conducting Historical Trend Analysis (HTA). DSAS allows for the examination of past and current shoreline positions and configurations, playing a pivotal role in investigating shoreline morphodynamics. It serves as an essential element for comprehending and monitoring the evolution of coastal areas.*

Moreover, the study of shoreline erosion and accretion is crucial for identifying contributing factors, including both anthropogenic and physical elements, that drive these processes. Understanding these factors is essential for effective coastal management and mitigation strategies. A shoreline assessment was carried out along the Tyre shoreline over two distinct periods: from 1975 to 2001 and from 2001 to 2018. The comprehensive findings from this extended assessment across sixteen regions revealed varying outcomes. During the initial period (1975-2001), there was a heightened susceptibility to both erosion and accretion, with a prevalence of eroded areas (68.7%). The regions most affected by erosion during this phase were Qasmieh, Bahr Salyieb, and Rashidieh. Conversely, the subsequent period of the study (2001-2018) showed reduced sensitivity to both erosion and accretion, with a dominance of accumulated areas (62. 5%). The assessment of the Tyre shoreline, utilizing DSAS, has brought to light the dynamic sensitivity of the coastal area in Tyre to environmental changes across diverse temporal segments. An investigation into the factors influencing these changes has underscored the pronounced impact of anthropogenic factors in this region. The allowance for sand extraction and instances of ignorance and violation within the coastal zone, notably manifested through unauthorized constructions, serve as evidence of the vulnerability of the Lebanese legislative system concerning coastal environmental issues. This interpretation emphasizes the need for a more robust regulatory framework and heightened awareness to address and mitigate the adverse effects on Tyre's coastal ecosystem.

Keywords - *DSAS, HTA, Long-term shoreline evaluation, Anthropogenic pressure.*

1. Introduction

The coastal zone is a dynamic environment capable of undergoing significant changes within short periods [1]. This is especially relevant given the increased frequency and intensity of coastal disasters, which have heightened the vulnerability of coastal areas to change [2]. Over extended periods, the shoreline's position can shift by hundreds of meters or more [3]. This variability makes the coastline a critical leverage point where even minor changes in location can significantly impact the entire coastal environment) [4]. The cyclic instability of beach morphodynamics defines shoreline variations, making beaches some of the most dynamic landforms on the planet, with their shapes changing regularly from day to day or even hour to hour [5].

For centuries, beach erosion, accretion, and shifting shorelines have disrupted the dynamic equilibrium of coastal areas worldwide [6]. Coastal erosion involves the episodic removal of material at the shoreline, leading to land loss as the shoreline retreats landward [7]. In contrast, coastal accretion refers to the accumulation of natural materials on the shoreline, resulting in the shoreline's advancement seaward and land gain [8]. Sand accretion is crucial in forming offshore bars (sediment deposits parallel to the shoreline underwater), dunes (sand mounds or ridges formed by the wind just inland of the beach), barriers, and spits (long, narrow sediment deposits parallel to the shoreline) [9].

Coastal erosion and accretion are some of the most widespread geological phenomena, with potential increases anticipated in the future [10]. In 2018, Luijendijk's examination of shoreline data derived from satellites found that 24% of the world's sandy beaches are eroding at rates greater than 0.5 meters per year, 28% are experiencing accretion, and 48% remain stable [11].

Consequently, researchers have been evaluating shoreline modifications worldwide using various methods. Erosion and accretion rates are often calculated using least-squares regression to predict the behavior of dependent variables. Additionally, advanced statistical methods such as basic functions [12] and time-series forecast methods [13] are employed to predict future shorelines based on historical shoreline positions.

Shoreline change detection and the rate of positional change are crucial for numerous aspects of coastal zone management, such as hazard zonation, island development studies, marine transport, sediment budget analysis, and coastal morphodynamics modeling [14]. Additionally, shoreline monitoring is essential for understanding coastal processes [15] and gaining a precise understanding of the temporal and spatial scales of shoreline location, which is vital for researchers, engineers, and coastal managers [16]. To effectively combat erosion, it is necessary to understand the processes at various scales, the interactions of all elements along the coast, and different timelines [17]. Monitoring shoreline changes is also crucial for identifying the nature and causes of changes at specific locations, assessing human impact, and planning management strategies [18].

1.1. Digital Shoreline Analysis System (DSAS) and Identification of Coastal Erosion and Accretion on Tyre's Shoreline Through Research

1.1.1. General Background and Parameters of DSAS for Shoreline Evaluation

To gain a comprehensive view of ecological patterns and processes, coastal researchers and managers require synoptic, geographically referenced information over wide coastal regions [19]. Time series analysis is a vital component of shoreline analysis, requiring long-term historical data to identify sections of the coast with shoreline alterations [20]. Historical data are critical because they can be used to detect changing coastline segments both spatially and temporally, as well as analyze erosion and accretion rates to predict shoreline locations.

Utilizing remote sensing and GIS, shoreline detection is assisted. Remote sensing is pivotal in discerning coastal surface changes, encompassing ground surface types, boundary shifts, pre- and post-change trends, and the type, distribution, and quantity of alterations [21]. Moreover, GIS plays a critical role in establishing a digital database of historical shoreline positions, thereby facilitating the assessment of present and future shoreline dynamics. This necessitates the application of diverse GIS modeling approaches [22].

DSAS is a free software tool that interacts with Esri ArcGIS software. It has undergone modifications and upgrades over time, resulting in various versions, ranging from ArcView 3.2 to ArcGIS 10. In 2013, a web-based version (DSAS web) was published by USGS. DSAS version 5.0 (v5.0) was released in December 2018 and has been tested to work with ArcGIS 10.4 and newer versions. It is compatible with both Windows 7 and Windows 10 operating systems.

DSAS can be applied to Historical Trend Analysis (HTA) due to several positive factors. Firstly, by using available spatial data such as maps and aerial photographs, historical coastline positions can be mapped and analyzed over time. Secondly, individual or selected transects can be studied to evaluate their historical changes and trends at discrete alongshore positions. Thirdly, DSAS can be used to estimate shoreline change at specific transects, and the tool's output can be used to assess the time series of change at particular sites. Fourthly, the study of shoreline geometry, including foreshore steepening measured by the distance between mean high and low water marks as noted in [23], as well as the examination of orientation to examine rotating tendencies, as done by [24], can be conducted using DSAS. Finally, DSAS can also be used to predict future trends and identify the natural or anthropogenic forces that have caused historical changes in the shoreline, as demonstrated by [6]

DSAS generates perpendicular transects at user-defined intervals from a reference baseline. These transects intersect the shoreline, and the distance between this intersection point and the baseline is utilized to compute shoreline change, either through distance measurements or statistical analysis. All calculations are recorded in a table linked to the transect file via the attribute table. Furthermore, DSAS can analyze the morphodynamic behavior of the coastline and changes in its foreshore geometry [25].

DSAS is widely employed to represent shoreline features, such as the mean high water mark and cliff top, across multiple layers spanning different periods. The software offers several statistical change metrics, including Shoreline Change Envelope (SCE), End Point Rate (EPR), Net Shoreline Movement (NSM), Linear Regression Rate (LRR), and Weighted Linear Regression Rate (WLR). These metrics have been documented in various studies [26].

Numerous studies have utilized DSAS as a reliable tool for shoreline detection, as demonstrated by [27, 28, 29].

These investigations have highlighted the software's high accuracy and effectiveness in detecting, analyzing, and predicting shoreline movement.

1.1.2. Indications of Coastal Erosion and Accretion in the Tyre Shoreline and Gaps in Existing Research

The research conducted by the Marine and Coastal Resources Program at the Institute of the Environment, University of Balamand, compared aerial photographs from 1962 with satellite images from 2010 and 2016. This study indicated that the Lebanese coastline experienced sea-filling, resulting in over 10 km^2 of new land between 2010 and 2016 [30]. According to [31], signs of erosion have appeared in South Lebanon within sandy beaches and dunes. Moreover, northward movement of sediment in the southern part of the Tyre spit has been detected, causing the coastline to recede by 10 to 30 meters and resulting in a depression of sand beaches by 0.30 to 0.60 meters. However, thin sand is being deposited towards the northern end of the Tyre spit [32].

In the southern part of the Tyre shoreline, a notable scarcity of sand is evident, with substantial beach rock bars protruding above the sand at heights ranging from 0.5 to 0.6 meters. This area, particularly El Mansouri, has encountered an estimated beach retreat of 20-40 meters, as documented [33]. The establishment of a nature reserve in the southern region of Tyre in 1998 effectively curtailed uncontrolled mining activities. However, despite this intervention, large sandy coves along the beach rock continue to manifest recent coastal retreat.

Despite several research efforts, no additional studies have been conducted since 2016 to monitor both erosion and accretion along Tyre's shoreline, particularly utilizing the DSAS. This lack of recent data significantly hampers the understanding and management of the coastal zone. Additionally, there is a noticeable gap in research that examines the key factors driving these shoreline changes. The absence of such studies results in a limited understanding of the dynamics influencing coastal erosion and accretion, making it challenging to develop effective management strategies. This deficiency in data and analysis weakens the overall management and conservation efforts for Tyre's coastal zone, leaving it vulnerable to ongoing and future environmental and anthropogenic pressures.

To address this gap, the current research aimed to detect shoreline changes in the study area using DSAS software over extended periods (1975-2018) and (2001-2018). Additionally, this study uniquely explores the factors contributing to Tyre's shoreline sensitivity to anthropogenic pressures, particularly during the initial period characterized by fluctuating erosion and accretion rates. This analysis supports the development of an integrated management plan to mitigate these phenomena.

This study holds significant importance due to its utilization of time series analysis, a powerful tool for understanding the intricate relationship between human activities and the coastal environment. Unlike other approaches, time series analysis allows for the distinction between natural and anthropogenic influences, enabling the identification of human-induced changes in coastal ecosystems. The extensive duration of measurements advocated in this study, spanning several decades, is crucial for establishing statistically significant trends. Consequently, the findings of this research have the potential to inform the development of sustainable management practices that balance the needs of human societies with the health and integrity of the marine environment.

2. Study Area

The Tyre shoreline is situated on the eastern shore of the Mediterranean Sea, in the southern part of the Lebanese coast, as depicted in Figure 1. This coastal region encompasses the Plain of Tyre, extending 25 kilometers north to the mouth of the Litani River from the occupation Palestine -Lebanon border in the south [34]. The study area includes sixteen regions, spanning from Qasmieh in the north of Tyre to El Naqoura in the south of Tyre, as illustrated in Figure 2. Among these sixteen regions, four are located to the north of Tyre, while the remaining twelve are situated to the south of Tyre.

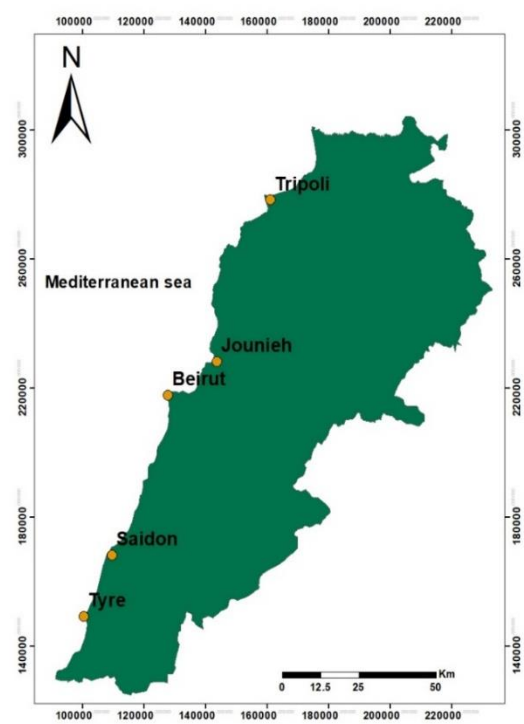

Fig. 1 Mapping the geographical locale of Tyre in southern Lebanon, positioned on the eastern shore of the Mediterranean Sea.

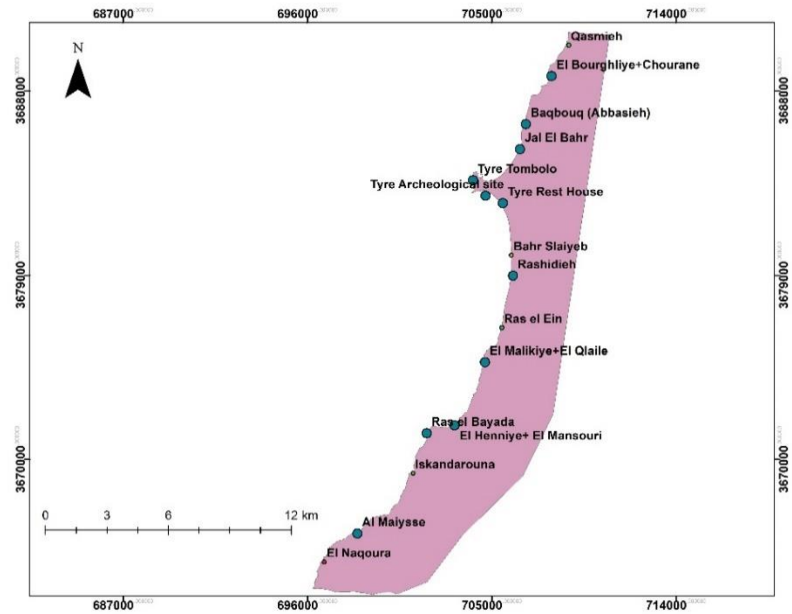

Fig. 2 Location of the geographical zones under study, covering a stretch from Qasmieh to El Naqoura, comprising 16 distinct areas

3. Material and Methods

3.1. Description of Data Acquisition

To digitize and analyse changes in Tyre's shoreline during the study periods of 1975-2001 and 2001-2018, raster data were required. Maps for this study were obtained from various sources, as detailed in Table 1. The Directorate of Geographic Affairs (DGA) supplied a topography map with a 1/20,000 scale for the year 2015. Aerial photography from 1975, featuring a 1-meter resolution and a 1/250,000 scale, covered the entire area except for a small section south of Eskandrouna. To fill this gap in 1975, satellite imagery from Corona Imagery (American Satellite Photography) was obtained, boasting a 2-meter resolution and a 1/250,000 scale. Additionally, the DGA provided a complete satellite image for the year 2001, featuring a 1-meter resolution and a 1/20,000 scale. Finally, a complete satellite image for the year 2018 was obtained from the DGA with a resolution of 50 cm and a scale of 1/20,000.

Data	Year	Scale	Resolution (m)	Origin
Topography Map	2015	1/2000	-	DGA
Aerial Photographs	1975	1/20.000	1 m	DGA
Satellite Imagery	1975	1/ 25000	2m	Corona Imagery
Satellite imagery	2001	1/20.000	1 m	DGA
Satellite imagery	2018	1/20.000	50 cm	DGA

3.2. Describing DSAS Shoreline Parameters and Quantifying Uncertainty Calculations

NSM and EPR are closely related but differ in their output. NSM provides information on the absolute distance of shoreline shift, whereas EPR offers the rate of shoreline change [26]. NSM is calculated as the difference between the oldest and the most recent shoreline, while EPR is calculated by dividing the distance of shoreline movement by the time elapsed between the oldest and most recent shorelines. The primary benefits of EPR are its simplicity in computation and the requirement for only two shoreline dates (see Equation 1).

$$EPR= \frac{NSM}{Time\ Between\ OLdest\ and\ Most\ Recent\ Shoreline} \quad (1)$$

Ideally, the uncertainty number should encompass both measurement uncertainties and positional uncertainties associated with natural factors affecting the coastline position, including wind, waves, and tides, as well as errors during digitization or global positioning system measurements [35]. Shorelines with higher uncertainty exert less influence on the trend line compared to data points with lower uncertainty [36].

In this research, positional uncertainty is calculated using mathematical notation that incorporates the square root of the sum of squared geo-referencing error, picture digitization error, and pixel resolution error (Equation 2). Therefore, the total error (Ep) in meters is the sum of errors related to image resolution (Er), the root mean geo-referencing error (Eg) of the data, and the error related to digitizing (Ed) the shoreline [37, 38, 39].

$$E_p = \sqrt{E_r^2 + E_g^2 + E_d^2} \quad (2)$$

$$E_{1975} = \sqrt{2^2 + 8.4^2 + 1^2} = 8.6 \text{ m}$$

$$E_{2001} = \sqrt{1^2 + 4.8^2 + 1^2} = 5 \text{ m}$$

$$E_{2018} = \sqrt{0.5^2 + 3^2 + 1^2} = 3.2 \text{ m}$$

Yearly error estimates were derived by annualizing the summations of Ep calculated for each time step of the satellite data, employing the following formula (Equation 3) [39].

$$E_a = \sqrt{\frac{E_{p1}^2 + E_{p2}^2}{t_2 - t_1}} \quad (3)$$

Where E_{p1}^2 represents the start year shoreline error, E_{p2}^2 is the end-year shoreline error, and t_{2-t_1} is the time difference between the two dates.

$$E_{1975-2001} = \sqrt{\frac{8.6^2+5^2}{2001-1975}} = 0.3 \text{ m}$$

$$E_{2001-2018} = \sqrt{\frac{5^2+3.2^2}{2001-2018}} = 0.3 \text{ m}$$

4. Results and Discussion

4.1. Analysis of DSAS Evaluation

4.1.1. NSM and EPR During the First Period (1975-2001)

The shoreline evaluation (Figure 3) categorizes erosion distances into different ranges, providing a detailed assessment of coastal changes. The very high erosion category includes areas where the shoreline has retreated from 50 meters to greater than 100 meters. High erosion is defined as shoreline retreat ranging from 25 meters to 49 meters, while low erosion covers distances from 0.4 meters to 24 meters. These same categories are applied to accretion, which refers to the advancement of the shoreline. For both erosion and accretion, the negligible category accounts for values within the margin of uncertainty, which is ± 0.3 meters.

During the first monitoring period, the Tyre shoreline experienced significant variations in both erosion and accretion. Specifically, Qasmieh, Bahr Slayieb, and Rashidieh were identified as areas with very high and high erosion, indicating severe shoreline retreat in these locations. In contrast, Tyre Tombolo experienced high accretion, suggesting substantial shoreline advancement. Additionally, regions like El Bourghliye and Chourane exhibited both high and low accretion, reflecting varying degrees of sediment deposition and shoreline growth. Further analysis during the first period revealed that while Qasmieh, Bahr Slayieb, and Rashidieh experienced high rates of erosion, areas such as Jal El Bahr, Ras el Ein, El Malikiye+El Qalile, and Iskandrouna had the lowest erosion rates. This indicates a significant disparity in the rate of coastal retreat across different regions. Meanwhile, El Bourghliye and Tyre Tombolo demonstrated varying rates of accretion, encompassing high, very high, and low rates (Figure 4). This variability underscores the complex and dynamic nature of coastal processes in the region.

From these observations, it can be concluded that there is a direct relationship between the rate of erosion or accretion and the distance of shoreline change. Specifically, as the rate of erosion increases, the distance over which erosion occurs also increases. This means that areas experiencing higher rates of erosion will see more significant land loss over time. Conversely, if the rate of erosion decreases, the distance affected by erosion will also decrease, leading to less pronounced changes in the shoreline. The same principle applies to shoreline accretion. When the rate of accretion is high, the distance over which sediment builds up, and the shoreline extends into the water increases. This results in more significant land gain in areas with higher accretion rates. On the other hand, when the rate of accretion decreases, the distance of shoreline extension also diminishes, resulting in less substantial changes in the shoreline's advancement.

In summary, there is a proportional relationship between the rate at which erosion or accretion occurs and the extent of the shoreline change. Higher rates of erosion or accretion lead to greater distances of shoreline change, while lower rates result in lesser distances. This relationship highlights the dynamic nature of coastal environments and underscores the importance of monitoring these rates to understand and predict shoreline changes accurately.

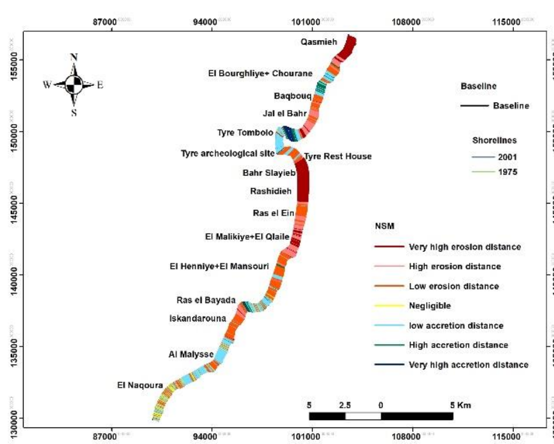

Fig. 3 NSM for Tyre Shoreline at the first period of (1975-2001)

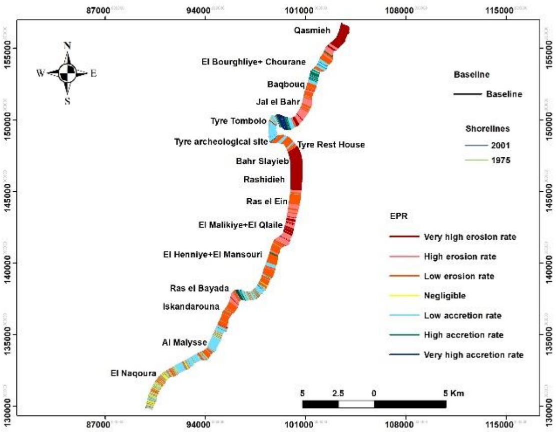

Fig. 4 EPR for Tyre Shoreline at the first period of (1975-2001)

4.1.2. NSM and EPR During the Second Period (2001-2018)

The second period of monitoring showed a marked decrease in the categories of very high and high erosion, both in terms of distance and rate, as depicted in Figures 5 and 6. During this period, low erosion was observed in areas such as El Bahr and Rashidieh, while low accretion occurred in regions including North of Bahr Slayieb, El Bourghliye, Malikiye+El Qlaile, El Henniye+El Mansouri, and Iskandarouna. However, significant accretion was noted in Qasmieh and Ras el Bayada, with these areas exhibiting very high accretion.

In comparison to the first period, the second period exhibited less pronounced alterations of the coastline. During this second period, the overall pattern showed that accretion exceeded erosion, indicating a net gain in shoreline advancement. This observation suggests that the processes contributing to the buildup of the shoreline were more dominant than those causing its retreat. This shift in the balance between erosion and accretion highlights a dynamic interplay between various coastal processes. Several factors may have contributed to this change. For instance, variations in wave energy could play a significant role; lower wave energy typically results in less erosion and more sediment deposition along the shoreline. Additionally, an increased supply of sediment, perhaps due to river discharge or coastal sediment transport, could enhance accretion rates.

Human interventions might also influence this balance. Coastal management practices such as the construction of groins, jetties, and breakwaters can alter sediment dynamics, promoting accretion in some areas while potentially exacerbating erosion in others. Furthermore, beach nourishment projects, where sand is artificially added to the shoreline, can directly contribute to accretion and shoreline advancement. Overall, Understanding the interplay of these factors is crucial for effective coastal management and for predicting future changes in the shoreline. By considering the influences of wave energy, sediment supply, human activities, and natural defenses, we can better anticipate and respond to the evolving nature of coastal environments.

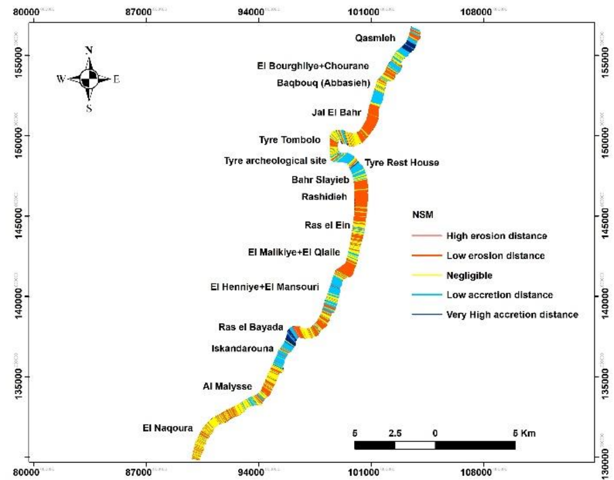

Fig. 5 NSM for Tyre Shoreline at the second period of (2001-2018)

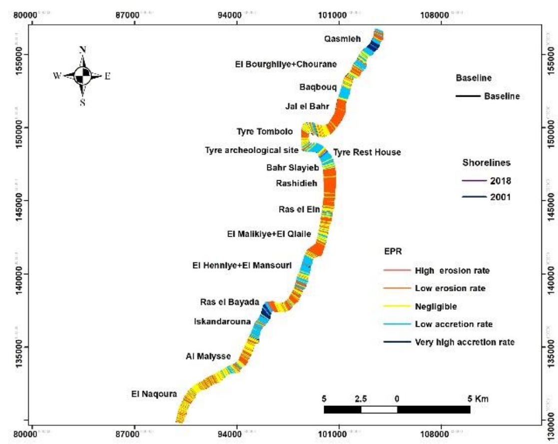

Fig. 6 EPR for Tyre Shoreline at the second period of (2001-2018)

4.1.3. Fluctuations in Erosion and Accretion Rates in Tyre Shoreline During Two Study Periods: 1975-2001 and 2001-2018

Based on the figures above and Table 2, various categories of regions between the two periods, and there were instances of erosion and accretion in the same region during the same period, suggesting that the study area is susceptible to the factors, both physical and human, that contribute to this fluctuation. During the initial period spanning from 1975 to 2001, a distinct pattern emerged along the Tyre shoreline, with 12 regions experiencing noticeable erosion while others underwent processes of accretion. However, the subsequent period from 2001 to 2018 exhibited a contrasting trend characterized by relative calmness, featuring notably low rates of both erosion and accretion across the coastline. An exception to this tranquil phase was observed in Qasmieh, where a stark contrast emerged with high levels of accretion recorded.

Table 2. Average of shoreline change (NSM) during the two periods at the study area

Region	Period 1975-2001			Period 2001-2018		
	Erosion	Accretion	Category	Erosion	Accretion	Category
Qasmieh	-72.1		Very High		+62	Very High
El Bourghliye+Chourane	-15.9	+26.7	Low erosion, +high	-10.6	+2.0	Low erosion and low accretion
Baqbouq (Abbasieh)	-20.4		Low		+17.9	Low
Jal El Bahr	-31.4		High	-9.8		Low
Tyre Tombolo		+ 99.2	Very High		+2.9	Low
Tyre Archaeological site		-10.3	Low		+7.7	Low
Tyre Rest House	-7.9		Low		+24.3	Low
Bahr Slaiyeb	-102.8		Very High		+10.7 m at the north	Low
Rashidieh	-76.6		Very High	-8		Low
Ras el Ein	-25		High	-0.6		Low
El Malikiye+El Qlaile	-38.5		High	-0.5		Low
El Henniye+El Mansouri	-7.4		Low		+9.4	Low
Ras El Bayada	-35.5		High		+53.1	Very High
Iskandarouna	-12.1		Low		+15.3	Low
Al Maiysse		+3.3	Low		±0.3	Negligible
El Naqoura		±0.3	Negligible		+0.008	Negligible

Table 3. Transformation of the Regions During the Period of the Study between Categories of Erosion and Accretion

Type of change	Region
From erosion to accretion	Qasmieh, Baqbouq, Bhar Saliyeb, El Henniye+Mansouri, Iskndarouna, Ras El Bayada, Tyre Archaeological site, Tyre Rest House
Stable in erosion	Jal El Bahr, Rashidieh, Ras el Ein, El Malikiye+El Qlaile, some sections of El Bourghliye
Stable in accretion	Some sections of El Bourghliye and Tyre Tombolo

Moreover, a significant shift in the trajectory of several beach regions was evident, transitioning from a state of erosion in the first period to one of accretion in the second. Noteworthy among these regions are Qasmieh, Baqbouq, Tyre Rest House, Iskandarouna, and Bahr Slyaieb, with the latter experiencing a subtle yet discernible increase in shoreline position, recording a modest accretion of (+10.7m) during this timeframe.

In contrast, El Naqoura remained largely unchanged throughout both periods under consideration. This remarkable stability can be attributed to its geological composition characterized by a rocky structure predominantly made up of Cenomanian Limestone. Despite the appearance of steadfastness, this rocky coastline is not immune to the forces of erosion [31] and the susceptibility of such formations to various forms of long-term erosion, including mechanical and biochemical processes.

The Long-Term evaluation, as depicted in Tables 2 and 3, yields significant insights into the dynamics of shoreline evolution over time. During the initial period from 1975 to 2001, the coastal landscape exhibited a heightened sensitivity to both erosion and accretion, with eroded regions prevailing, accounting for approximately 68.7% of the total observed regions. However, during the subsequent period from 2001 to 2018, a noteworthy shift occurred, characterized by a diminished sensitivity to both erosion and accretion, with accumulated regions now constituting the majority at 62.5%. Moreover, the analysis revealed that 31.2% of regions consistently experienced accretion, while 19% of regions consistently underwent erosion, indicating varying degrees of coastal stability or vulnerability across the studied regions. Notably, a striking transition was observed in 50% of the regions, shifting from a state of erosion to one of accretion, suggesting potential resilience or adaptive responses within the coastal environment.

Based on this evaluation of the Tyre shoreline via DSAS, it can be concluded that the Tyre shoreline was significantly affected by both anthropogenic and physical factors from 1975 to 2001, leading to alterations in the shoreline and varying amounts of erosion and accretion in different regions. These influences contributed to the transformation of some regions from erosion-dominated to accretion-dominated areas and vice versa, highlighting the sensitivity of the study area to these changes.

Understanding these patterns is crucial for effective coastal management. Areas with high and very high erosion may require interventions such as shoreline stabilization or erosion control measures. Conversely, regions with significant accretion could be monitored to ensure that sediment deposition does not disrupt natural processes or lead to environmental impacts. Continuous monitoring and detailed analysis are essential to developing targeted management strategies that address both immediate and long-term challenges posed by shoreline changes. This approach will help ensure the sustainable management and conservation of Tyre’s coastal zone, protecting it from ongoing and future environmental and anthropogenic pressures.

4.2. Responsible Anthropogenic Factors

The high accuracy results (0.3m) of the DSAS system during the evaluation of the Tyre shoreline facilitated the detection of erosion and accretion over a long period across sixteen regions. Unlike previous research, which failed to identify the primary factors leading to these changes, this study explored some of these key factors. It particularly emphasizes human-induced pressures due to the limited availability of data on physical elements such as currents, waves, and winds for the periods under investigation. The research narrows its focus to human activities, highlighting the importance of understanding anthropogenic impacts in the absence of comprehensive data on the dynamic physical forces associated with currents, waves, and winds during the specified study periods.

In this research, three primary factors are identified as responsible for erosion and accretion along the Tyre shoreline: sand extraction, artificial structures, and urbanization. Sand extraction disrupts the natural sediment balance by depleting beaches of their sand reserves, making them more vulnerable to erosion. Artificial structures, such as jetties and breakwaters, interfere with the natural flow of sediments, causing accumulation in some areas and depletion in others. Urbanization exacerbates shoreline instability through increased surface runoff and reduced sediment supply, as well as by adding pressure on coastal soils with the construction of infrastructure. Understanding these anthropogenic factors is crucial for developing strategies to mitigate erosion and promote sustainable coastal development.

4.2.1. Sand Extraction

The Lebanese Coastal Zone features a diverse geological structure comprising sandy and rocky shores, both susceptible to detrimental practices such as sand suction and gravel extraction. Natural dunes, vital for coastal stability, are exploited for construction needs, with an annual collection of approximately 1.5 million cubic meters of sand reported [40]. This exploitation contributes to coastal destabilization, increased erosion, and alterations in hydrodynamics [41].

Over the past 50 years, extensive sand removal has caused significant coastal retreats in the northern and southern parts of Tyre, particularly during the first period of the study (1975-2001). Various articles and research studies have confirmed this phenomenon. The Lebanese civil war, which lasted from 1975 to 1990, as well as the Israeli occupation of southern Lebanon from 1982 to 2000, led to a lack of control by the Lebanese government, allowing for illegal sand extraction along the shoreline.

Illegal sand mining has resulted in substantial coastal retreat in both the north and south of Tyre Tombolo. The sand was extracted from natural dunes and dredged from the sea at a depth of 6 meters. Additionally, in 1991, sand mining was conducted from the ocean floor. As a consequence of these activities, the northern portion of the beach retreated by approximately 70 meters between 1962 and 2002 [42].

A portion of the sand was directly extracted from the dunes, while the remainder was obtained by dredging from the sea at a depth of 6 meters and then pumped onto the shore. Additionally, from 1991, sand mining from the ocean floor was conducted for a period of 6 to 8 months, according to [43].

Moreover, from 1962 to 2002, the northern section of the beach experienced a substantial retreat of approximately 70 meters due to sand removal. This phenomenon was observed in both the north and south Tyre Tombolo, as noted in [42]. The researchers reported that the practice of sand extraction from Tyre’s beaches is not a recent phenomenon, dating back to the 1960s, with extraction rates reaching 1500 m^3 per day. Dune destruction and sand extraction were observed in several regions, including Baqbouq, Jal El Bahr, Bahr Slayieb, Qasmieh, El Bourghliye, El Qalaileh, and El

Malikiye, contributing to the erosion of Tyre's shoreline during the first period of the study (1975-2001).

Based on the data presented in Figure 3 and Table 2, it can be observed that Qasmieh had a very high erosion rate of -72.1 m during the first period due to sand extraction. Similarly, Jal El Bahr and Baqbouq experienced high erosion rates of -20.4 m and -31.4 m, respectively, primarily due to the destruction of dunes, as noted by [31]. It is worth noting that many of these dunes have been severely damaged or destroyed due to sand excavation, which is often followed by wind erosion [44].

During the first period of the study (1975-2001), Bahr Slayieb registered very high erosion of -102.8 m due to sand extraction. Similarly, Rashidieh and Ras el Ein beaches experienced very high erosion of -76.6 m and high erosion of -25 m, respectively, as a result of sand mining (Table 2). The extraction of sand from the Tyre shoreline began in the 1980s and at its peak, 350 to 400 trucks were withdrawn daily from Bahr Slayieb, reported by [45]. This extraction also affected the El Qlaileh beach, which has been gradually disappearing since its width was 90 m in 1962 and is now only 20 meters wide. In 1962, it was a sandy beach, but now it has turned into pebble dunes, with a coastline withdrawal of 70 ± 12 meters (1.4 meters per annum) [33].

Both sand extraction and human activities have impacted the regions of El Malikiye+El Qlaile and El Henniye+El Mansouri. In the southern part of El Mansouri, there are large beach rock bars that are visible above the sand level, indicating significant sand depletion. The beach retreat in this region is estimated to be between 20-40 meters. During the evaluation, El Malikiye+El Qlaile registered high erosion (-38.5m), while El Henniye+El Mansouri registered low erosion (-7.4m) in the first period.

The El Naqoura area has undergone two incidents of sediment extraction, leading to damage to its rocky coast. Initially, a layer of stone ballast was removed from the southern beach to support the abandoned Beirut-Cairo railway track constructed during world war II along the coastline.

The steep pebble beach, lacking sediment, has unstable coastlines that caused portions of the old track, resting on a +2m platform, to collapse into the sea during winter storms. Moreover, the rocky coast, characterized by several thin notches, has also experienced sediment removal. This situation has resulted in a sediment deficiency of 15,000 m^3 during winter storms, generating powerful breaking waves that impact the remaining beach rock [32].

Lebanese legislation, notably decree 151649 issued in 197 [46], permits the extraction of sand, primarily intended for port cleaning purposes. However, this legal framework lacks provisions safeguarding the environment. Consequently, in an era marked by lawlessness, individuals were incentivized to engage in sand extraction activities along the Tyre shoreline.

Subsequently, following this period, civil society associations mobilized against these detrimental practices that had profound impacts on the fundamental characteristics of Tyre Beach. Recognizing the need for environmental protection, these associations advocated for a more responsible approach to sand extraction in alignment with ecological preservation. This is what explained the calm period or low-vulnerability period to both erosion and accretion registered during (2001-2018).

4.2.2. Artificial Structure (Hydraulic Structure)

Governments and coastal communities have implemented various methods to mitigate the effects of erosion on the coastline. The literature mentions several protective structures, including dikes, rip-raps, detached breakwaters, seawalls, revetments, beach nourishment, dune stabilization, and surfing reefs, collectively known as hydraulic structures [47]. However, these structures often result in the creation of an artificial beach, a phenomenon prevalent along the Lebanese coastline. In fact, over 63% of the Lebanese coastline is artificial, with seawalls, revetments, and sea dikes being the dominant structures at 50.56%. Ports and marinas follow them at 30.28%, breakwaters at 8.77%, jetties at 7.28%, groins at 1.71%, and river mouth structures at 1.40% [48].

Tyre Tombolo

Researchers and scholars agree that foreign forces form natural tombolos, while anthropogenic tombolos are created by man-made infrastructure [49]. Thus, we can conclude that Tyre Tombolo is an example of an artificial tombolo, which was considered a difficult engineering structure during the bronze age.

Jetties and breakwaters are installed for various reasons, such as to control tidal flow in inlets and reduce the shoaling of channels by littoral material [50]. However, their construction and other shoreline hydro-technical developments can have significant impacts on local hydrodynamics. Dredging can negatively affect benthic conditions, while hydro-technical constructions can cause sandy sediments to accumulate in the coastal zone [51].

This sediment buildup can occur due to changes in wave direction as they approach the leeward side of the breakwater [49]. Moreover, jetties can obstruct the flow of water along the shoreline and cause sediment erosion [52]

The accumulation of sand was witnessed during shoreline evaluation at Tyre Tombolo (Figure 7). The northern side of the tombolo in the first period (A) registered very high accretion with an average of +100.1 m, and this is due to a hydraulic structure (breakwaters and jetties). Jetties and breakwaters in this site are located behind the cornishe and in Tyre harbor (Northern port).

Human intervention on Tyre's shoreline is not a recent phenomenon but has existed for centuries, resulting from various civilizations, and sedimentation in the area is also ancient. The Northern port of Tyre, which overlooks Byblos, Sidon, and Beirut, was known as the Sidonian harbor when Alexander the Great was laying siege to Tyre.

The surrounding areas of these sites are composed of coastal sediments with medium to low energy, which started to accumulate around 8000-6000 BP and reached a depth of eight to ten meters. Over time, sand accumulation has reduced the size of the old basin to almost half of its original size. The coastal area has been slowly encroaching on the sea since the Byzantine era, leading to the center of the ancient harbor being landlocked by about 100-150 meters. Researchers, sailors, and fishermen have discovered a submerged port surrounded by breakwaters, with an 80-meter long breakwater and a constant width of 12.7 meters, providing evidence of human intervention in the area dating back to ancient times [53].

Scientists have identified six stages of development for Tyre's harbor, with significant anthropogenic pressure throughout its history. Research by [53] has shown that the development of Tyre's northern basin harbor had a substantial impact on sedimentation patterns, largely due to influences from Roman and Byzantine societies. Current sedimentation rates are much higher than those of surrounding natural beaches, with rates from 6000-4000 BC compared to 10 mm/year from 500-500 AD. This increase in sedimentation is directly attributed to harbor development.

The Tyre harbor has undergone some changes recently, including the construction of a fish auction and the installation of breakwaters, which have resulted in a low accretion during the second period (shown in Figure 7 B) with a recorded value of +2.2 m (as mentioned in Table 2). This reshaping of the shoreline is caused by the redistribution of sediment transport along the coast due to the harbor development. It is known that wave diffraction and changes in the direction of longshore sediment transport occur downstream of a harbor, leading to shoreline reshaping characterized by updrift accretion and downdrift erosion [54].

Tyre Tombolo features three corniches located to the north, head, and south of the area. The northern corniche, measuring 935.9 meters in length and 10-14 meters in width, was constructed after 1975. The building of this structure has led to the narrowing of the beach and an increase in artificial distance, as well as the extension of reclaimed and filled areas. Such land reclamation activities have direct impacts on local coastal morphology, with potential ecological consequences that may affect the distribution of habitats and vegetation in coastal wetlands. The effects on aquatic communities and creatures can be physical, chemical, and biological [55].

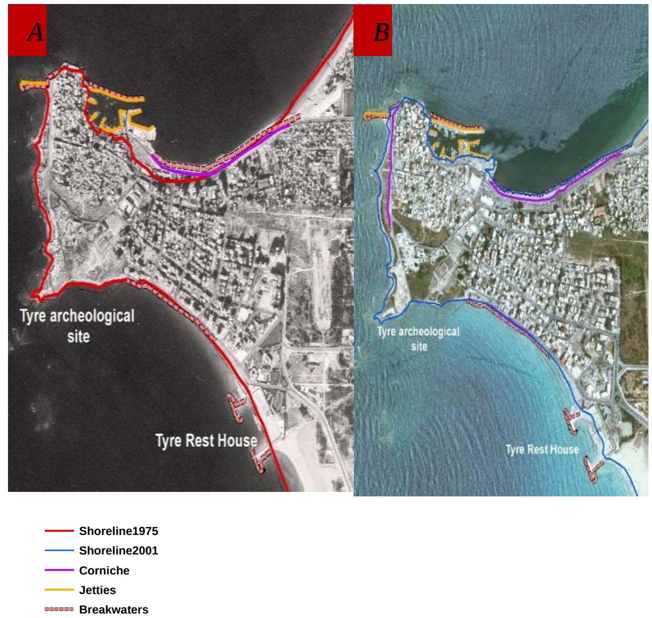

Fig. 7 Assessment of the tombolo during two different time periods, namely 1975-2001 (A) and 2001-2018 (B). It should be noted that the first observation was conducted using an aerial photograph in 2001, while the second *was* done through a satellite image in 2018.

4.2.3. Qasmieh and El Bourghliye+ Chourane

During the first period, from 1975 to 2001, Qasmieh experienced high erosion, resulting in a significant loss of land, with a recorded -72.1 m (Table 2). This erosion was primarily attributed to sand extraction and exposure to physical factors such as waves and tides, leading to the degradation of the coastline. However, during the second period, Qasmieh underwent a shift from erosion to accretion, with a recorded +62 m (Table 2). This positive change was facilitated by the introduction of new breakwaters, which effectively reduced the energy of the shoreline and contributed to the retention of sediments (Figure 8).

During the first period (1975-2001, A), the region of El Bourghliye and Chourane witnessed varying degrees of erosion and accretion. The average accretion was 26.7 m, while the average erosion was -15.9 m. The settlement area led to the dragging and excavation of sand, contributing to erosion. However, the presence of a single groin had two effects: it caused erosion on the downdrift side and accumulation of beach material on the updrift side, explaining the observed accretion of sand on the updrift side.

During the second period, the two sections that previously experienced erosion reversed to accretion, with a recorded value of +10.6 m. Conversely, the area that previously experienced accretion underwent erosion, with a recorded value of -4.7 m. However, this region remains unprotected, with ongoing settlement and the presence of groins. Continuous excavation activities by building owners also contribute to the changing shoreline.

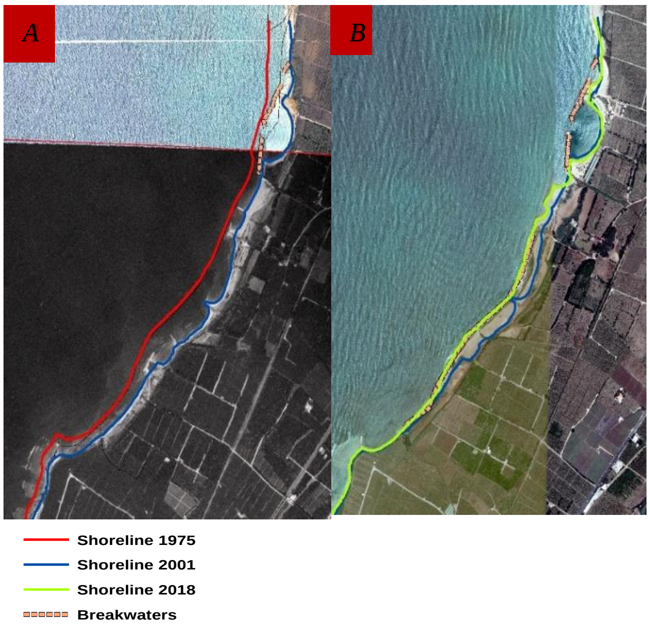

Fig. 8 Qasmieh beach evaluation at the period 1975-2001 (A) and at 2001-2018 (B)

4.2.3. Urbanization

Tyre's coastal zone is characterized by a diverse group of structures, ranging from high-rise apartments to tourist facilities, all governed by Lebanese laws such as Act 17 of Law 1925, No. 4810/1966, Decree No. 1300/1978, Law 402 of 1995, and Law 2017 [46], Urbanization extends to include agricultural and industrial facilities within its overall structure. These settlements have a notable impact on shoreline processes, as most are situated directly on or near the sea. Consequently, natural hazards like storms, hurricanes, and tsunamis [57], combined with high spatiotemporal variability [58], can interact with the presence of human activities in coastal areas, leading to complex interactions of impact drivers [59].

Unregulated recreational activities along the Tyre shoreline are exerting increased pressure on ecosystems, resulting in the loss of habitats and the destruction of natural defences such as dunes. This phenomenon has been substantiated by various researchers, including [60]. Additionally, structures situated on the shoreline rely on coastal defences, potentially causing both erosion and accretion, exemplified by the impact on the Tyre Rest House building (Figure 10). The presence of the Tyre Rest House building has significantly influenced the beach profile, especially due to its proximity to Bahr Slayieb. During the first period, both the Rest House area and Bahr Slayieb experienced erosion.

However, in the second period, Tyre Rest House witnessed a modest accretion of +24.3m (Table 2), with certain sections exhibiting very high accretion owing to the accumulation of sand between the two breakwaters. This sand accumulation also affected the northern region of Bahr Slayieb, where a low accretion of about 10.7m was observed.

The extraction of accumulated sand from Tyre Rest House is not a recent practice. In 2013, around 45,000 m^3 of sand had accumulated, prompting the Rest House administration to seek permission from the Ministry of Tourism and Tyre Municipality to extract 125,000 m^3 of sand—surpassing the accumulated quantity that had obstructed the swimming basin [60].

In contrast, in 1995, the Ministry of Works and Transport approved the removal of approximately 18,000 m^3 of sand as reported by [45], exceeding the permitted quantities according to the software (114,650 cubic meters underwater and 6,700 cubic meters above water, as reported [61].

Such practices fall under the framework of beach nourishment, contributing to shoreline erosion and accretion and having environmental impacts on Tyre's coastline.

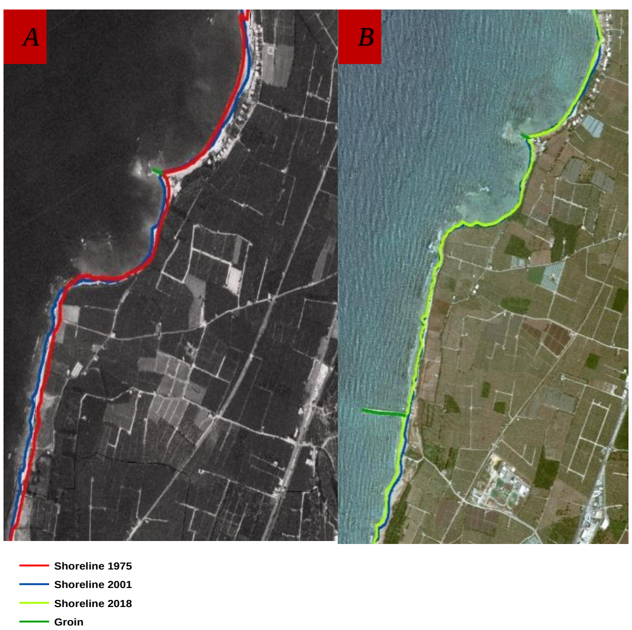

Fig. 9 El Bourghliye+ Chourane beach evaluation at the period 1975-2001 (A) an at 2001-2018 (B)

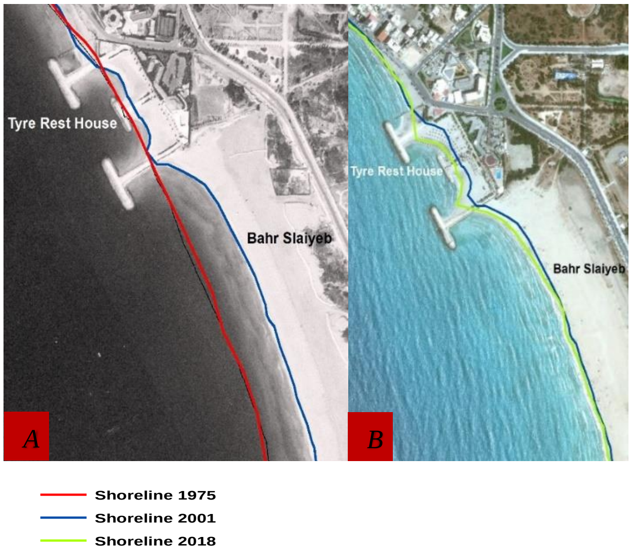

Fig. 10 Erosion and accretion patterns at tyre rest house: A comparative study of 1975-2001 (A) and 2001-2018 (B)

5. Conclusion

The evaluation of shoreline change detection plays a pivotal role in coastal management endeavors. By accurately assessing changes in the coastline over time, decision-makers can better understand the dynamic nature of coastal environments and formulate effective management strategies. These evaluations provide crucial insights into the extent and magnitude of erosion, accretion, and other coastal processes, enabling proactive measures to mitigate risks such as flooding and habitat loss. Additionally, by integrating remote sensing data and advanced technologies into shoreline change detection analyses, coastal managers can optimize resource allocation, enhance resilience planning, and ensure the sustainable management of coastal zones. Ultimately, the evaluation of shoreline change detection serves as a fundamental tool in safeguarding coastal communities, economies, and ecosystems against the challenges posed by natural hazards and anthropogenic pressures.

The research found that the Tyre shoreline experienced two primary issues, erosion and accretion, during a specific period. Employing DSAS to analyse these transformations over time proved highly beneficial. This approach facilitated a deeper comprehension of the shoreline's evolution, revealing not only erosion and sediment build-up but also changes in the adjacent land. DSAS effectively identified and quantified the various alterations occurring along the Tyre shoreline. Such insights are crucial for effective coastal management and future planning initiatives.

Based on the study's findings, it is evident that erosion and accretion have significantly impacted a substantial portion of the Tyre Coastal zone, with Qasmieh and Bahr Slayieb particularly vulnerable to these coastal changes. The primary drivers behind this phenomenon are predominantly attributed to anthropogenic factors, including activities such as sand extraction, the installation of hydraulic structures, and the rapid pace of urbanization. These human-induced factors, supported by Lebanese laws and regulations, have played a pivotal role in reshaping the profile of the Tyre coastal zone from 1975 to 2018. This transformation underscores the complex interplay between environmental alterations and human activities in the region. The consequences of these changes demand a comprehensive and sustainable approach to the conservation and management of the Tyre coastal environment, recognizing the necessity for a balanced coexistence of nature and human development.

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