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Vulnerability assessment of the South-Lebanese coast: A GIS-based approach

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ABSTRACT

The sea-level rise phenomenon affects several socio-economic and ecological aspects worldwide, particularly in terms of coastal erosion and saltwater intrusion. While the Mediterranean region is showing an increase vulnerability to the sea-level rise, in this study, we implement the Coastal Vulnerability Index (CVI), between 2005 and 2013, on the Southern Lebanese coast. The selection of this study area is related to its commonly known vulnerable sandy beaches. The CVI is derived from six physical and geological variables that are estimated using Geographical Information System and Remote Sensing techniques. Results show that this eastern Mediterranean coast has a moderate (66% of its total lengths) to high coastal vulnerability (30% of its total lengths) to the sea-level rise. As predicted, sandy beaches in our study area represent the most vulnerable regions. On the other hand, an absence of a Pearson correlation between the amount of the sea level rise and the sea surface temperature, is shown. It is probably related to the direct human interference that eclipsed the climate change as the main driving force in that period (i.e. 2005–2013). In this context, we propose an intervention strategy that focuses on offering 'soft' technics performed at the sandy beaches and in dune systems. Stakeholders are encouraged to implement this approach to combat the coastal vulnerability of these areas. And by applying the proposed method to other limited-resources/datasets countries, regional organizations and institutions could have vital information to reduce the impact of the SLR at a larger-scale.

1. Introduction

Historically, sea levels have been fluctuating between one hundred meters below to 6 m above the present level with changes in global temperatures (Donn et al., 1962; Oldale, 1985; Smith and Tirpak, 1988). However, during the last century, sea level has risen at a significantly larger rate than any previous several millennia (Church and White, 2006; Church et al., 2008). Thus, the Sea Level Rise (SLR) is considered closely related to the global warming and a key indicator of the world climate change (Bindoff and Willebrand, 2007). This phenomenon results from three primary contributing factors: (i) ocean thermal expansion; (ii) mountain glaciers and polar ice caps melt; and (iii) change in terrestrial storage (Dasgupta et al., 2009). SLR, which is often experienced through its effect on extreme levels (Church et al., 2008), causes severe ecologic and socio-economic impacts (Church and White, 2011). The most affected areas are the coastal zones presenting severe coastal erosion, flooding of wetlands and estuaries, saltwater intrusion, and threats to socio-economic activities and infrastructure (Kos'yan et al., 2012; Jonah et al., 2017).

The *Intergovernmental Panel on Climate Change (IPCC)* reports that the mean global elevation varies between 43 and 73 mm/year with an average of 58 mm/year (Stocker et al., 2013); the Mediterranean sea shows an increase of 2.44 ± 0.5 mm/year between 1993 and 2012 (Bonaduce et al., 2016). Yet, the change of sea level at regional- and global-scale might not be aligned with local levels on a particular coast. Thus, producing local-based studies is vital particularly when their findings have greater practical importance in terms of improving information for decision-makers (Smith and Tirpak, 1988).

In this context, the coastal vulnerability assessment becomes a fundamental research at national and regional level, especially when preparing for the possibility of such a rise. Vulnerability is defined simply as the consequences of natural phenomenon, of given intensity, on a subject (Lollino et al., 2014; Mhawej et al., 2016). However, three broad characterization of vulnerability related to SLR could be found in the literature (Dolan and Walker, 2006). The first views vulnerability in terms of exposure to hazardous events and their effects on people and structures (Dolan and Walker, 2006). The second perspective characterizes vulnerability as a mixture of socio-economic factors that influence the degree to which someone's life, livelihood, property, or assets are put at risk by the occurrence of a hazard event (Blaikie et al.,

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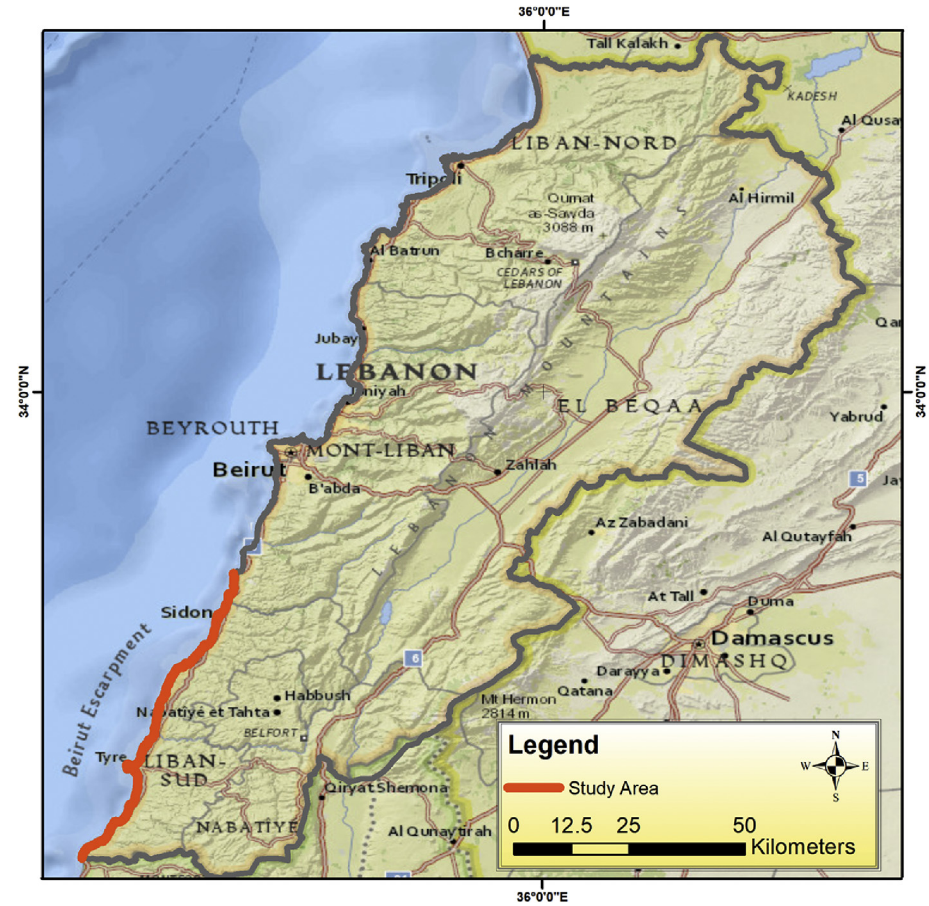

Fig. 1. Location of the Southern Lebanese zone (*Sources: National Geographic, Esri, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp*).

Table 1
Lengths and percentages of the geomorphological structures of the Southern Lebanese coast.

Type	Length (km)	Percentage (%)
Artificial Beach	1212	12.9
Rocky Beach	13.5	14.4
Sandy Beach	32.54	34.9
Pebble Beach	9.82	10.6
Estuary	0.33	0.3
Low Cliff	20.3	21.8
Cliff	4.81	5.1
Total	**93.3**	**100**

2014; Dolan and Walker, 2006). The third combines the previous perspectives by integrating both the physical event and the limited capacity of communities to respond for such a rise (Wu et al., 2002; Dolan and Walker, 2006).

Several types of indices are being used to assess the coastal vulnerability to SLR (Smit and Wandel, 2006). They provide a prompt and consistent approach for characterizing the relative vulnerability of different coasts (Kay and Travers, 2008; Goodhue et al., 2012). These indices were systematically cited in the IPCC report in 1991 on *Common Methodology for vulnerability assessment* (Abuodha and Woodroffe, 2006). The most commonly used are *Synthesis and Upscaling of Sea-level Rise Vulnerability Assessment Studies (SURVAS)* (e.g. Nicholls and de la Vega-Leinert, 2000), *Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise (DINAS-Coast* and *DIVA)* (e.g. Hinkel and Klein, 2003), *Simulator of Climate Change Risks and Adaptation Initiatives (SimCLIM)* (e.g. Warrick et al., 2005), *Community Vulnerability Assessment Tool (CVAT)* (e.g. Flax et al., 2002), *Coastal Vulnerability Index (CVI)* and *Coastal Social Vulnerability Index (CSoVi)* (e.g. Boruff et al., 2005).

CVI, developed by Gornitz (1990), classifies the vulnerability to the sea level rise into five levels (i.e. Very Low, Low, Moderate, High and

Table 2
Thresholds used in the CVI calculation.

Level	Very Low	Low	Moderate	High	Very High
Variables	1	2	3	4	5
Geomorphology	Artificial Shoreline, Rocky Beach	Cliff	Low Cliff	Pebble Beach, Estuary	Sandy Beach
Coastal Slope (%)	> 45	30; 45	15; 30	8; 15	< 8
Relative rate of Sea Level Rise (mm/year)	According to the vulnerability linked to erosion and advancement				
Erosion/Advancement (m/year)	> +2	+1; +2	+1; −1	−1; −2	< -2
Average Tidal Height (m)	> 6	4; 6	2; 4	1; 2	< 1
Average Wave Height (m)	< 0.55	0.55; 0.85	0.85; 1.05	1.05; 1.25	> 1.25
CVI					

Fig. 2. (a) the zone of maximum advancement coast at Saida; (b) the zone of maximum recoil at Adloun. (Source: Google Earth Images. Dates: April 2005 and April 2013).

Very High). This index is the most widely used in the literature (e.g. Thieler and Hammar-Klose, 1999; Dwarakish et al., 2009; Hereher, 2015). An alternative version of this index is currently being used in Australia and New Zealand; it is the Coastal Sensitivity index (CSI) (e.g. Abuodha and Woodroffe, 2010; Goodhue et al., 2012). CVI provides a simple and straightforward method to assess coastal vulnerability based only on the physical characteristics of the studied coast. While the addition of socio-economic factors is not possible due the unavailability of such datasets in Lebanon, CVI remains the most adequate index that could be applied to the Lebanese coastal areas to evaluate their vulnerabilities for a better planning and management in hazardous areas.

Even though that several studies based on this index has been conducted in the Mediterranean basin (e.g. Karymbalis et al., 2012; Khouakhi et al., 2013; Faour et al., 2013; Hereher, 2015), in Lebanon, only a very limited number of related research projects exist; the only available study was produced by El Hage et al. (2011) assessing the coastal vulnerability and estimated the impact of SLR on land cover types and underground aquifers between 1962 and 2005 in the North of Lebanon.

In this paper, we evaluate the CVI in the Southern Lebanese coast, with a focus on Tyr Coast Nature Reserve (TCNR), a vital biome with scarce studies, using an improved methodology that uses high spatial resolution Google Earth images for a period of eight years (2005–2013). The novelty of the proposed approach lies in the possibility of implementing it over other limited-resources/datasets countries. Moreover, to our knowledge, it is the first study of its kinds in the selected area and a much-needed assessment to highlight the impact of SLR on these coasts. This research is highly important for local management bodies and decisions-makers, and when expanded to other regional coasts, it could provide regional organizations and institutions with vital information to combat this phenomenon at a larger-scale. This is particularly true because the selected study area is an expansion of the Levantine basin. Similar to previous studies since 1993 (e.g. Cazenave et al., 2002; Church et al., 2008), the Geographic Information System (GIS) and Remote Sensing techniques (RS), which have been proving to be a cost effective and efficient tool, are used in this study. Findings are discussed and followed by a proposition of an ecological mitigation technique to conserve sandy coasts and dunes in the selected area.

2. Materiel and methods

2.1. Study area

The Southern Lebanese coast is located in the eastern part of the Mediterranean basin. The study area extends from Sidon (or Saida) to Nakoura, with a total length of 93 km (Fig. 1). It is characterized by a high geomorphological diversity (i.e. rocky beach, sandy beach, pebble beach, estuaries, cliff and low cliff). Main regions correspond to the sandy beach of Tyr and the cliffs of Bayyada and Nakoura (Table 1).

The Southern Lebanese coast is characterized by high ecological importance. The dominant sandy beaches are natural habitat of the endemic sea turtle in Lebanon (i.e. *Caretta caretta*, *Chelonia mydas*, *Dermochelys coriacea)*. Additionally, a nature reserve, namely Tyr Coast Nature Reserve (TCNR), exists within the boundaries of our study area. Other type of beaches, including artificial shores, rocky beaches, pebble beaches, estuaries, cliffs and low cliffs are also present in the region. The two main income-generating activities are fisheries and agriculture (SDATL, 2004). A significant population growth is documented in the area, and estimated to reach over one million in 2030 (SDATL, 2004). This expansion has led to an increase of the anthropic pressure exerted on the coast.

In Lebanon, only a small numbers of studies have been conducted to retrieve the wave height and/or the coastal sediments dynamics, which

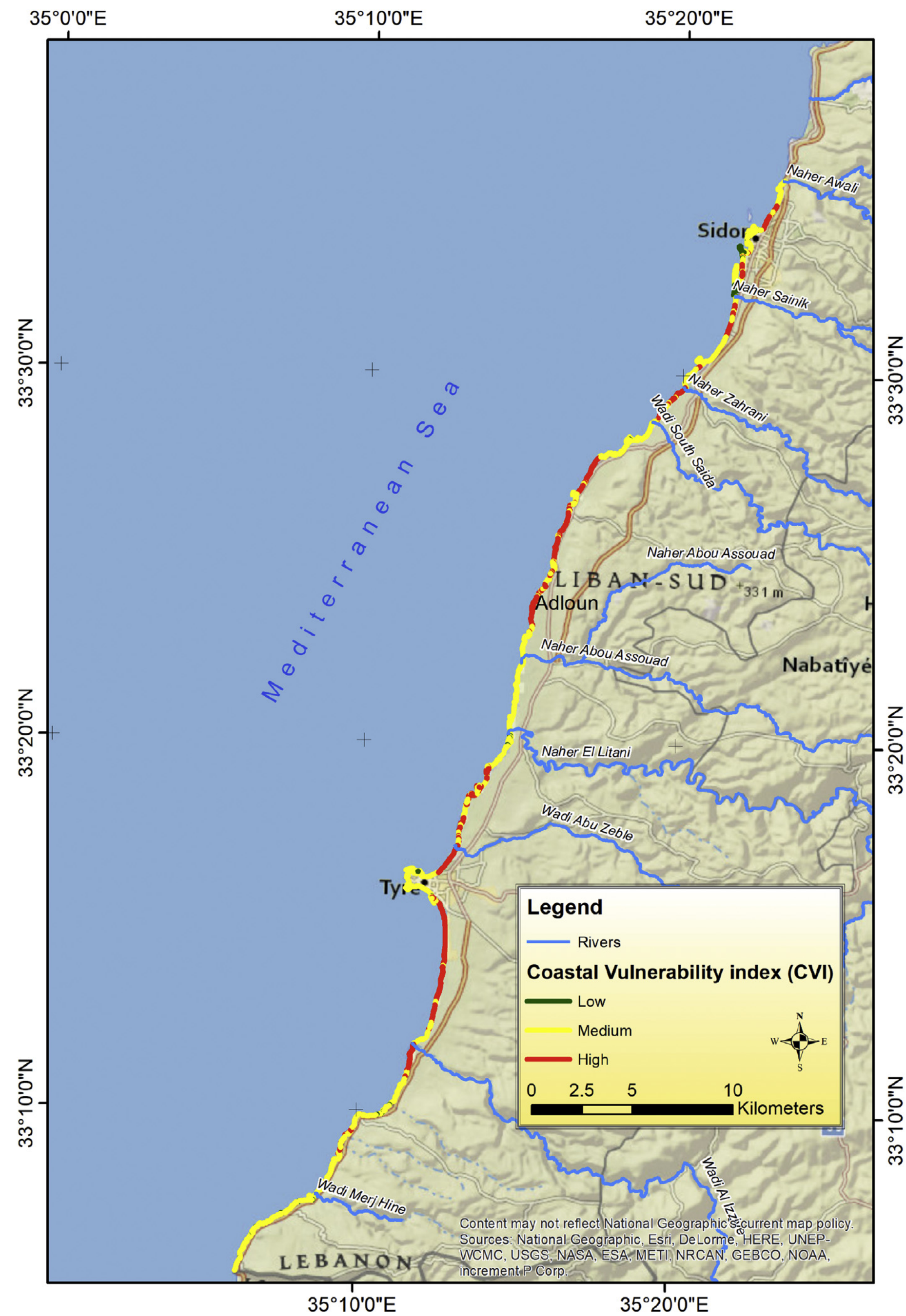

Fig. 3. Coastal Vulnerability Index (CVI) map of the Southern Lebanese coast (*Sources: National Geographic, Esri, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp*).

Table 3
Three levels of vulnerability of the Southern Lebanese Coast in km and percentages.

CVI	Low (2)	Moderate (3)	High (4)	Total
Length in Km	3.66	61.74	27.90	93.3
Percentage	4	66	30	100

were based on limited time-series in-situ datasets and covering regions located to the north of our study area (Beydoun, 1976; Kabbara, 2005; Aoun et al., 2013). However, their findings have showed a minimal variation in waves and tides, mainly because our coastal areas are part of the partially closed Mediterranean Sea (Ibrahim et al., 2013), coupled with low stream sediment loads for most of the year (Beydoun, 1976; Kabbara, 2005; Houri, 2005; BEACHMED-e project, 2006; Aoun et al., 2013; Zodiatis et al., 2014).

2.2. Coastal Vulnerability Index (CVI)

The Coastal Vulnerability Index is composed of physical and geological variables. The general formula is shown below:where:

a) *Geomorphology:* It is identified by photo-interpretation of the Google Earth images in 2005 and in 2013 and based on the geomorphological map produced by Sanlaville (1977);
b) *Coastal slope:* It is calculated through the Digital Elevation Model (DEM), expressed in percentage (%);
c) *Relative rate of sea-level rise:* It is retrieved qualitatively in

Fig. 4. Aerial views of A1: Adloun Coast - A2: Tyr Nature Reserve Coast, B1: Ras of Tyr Coast - B2: Saida Coast, C: Nakoura (*Source: Google Earth Images. Dates: April 2005 and April 2013*).

correspondence to the erosion or advancement of the coastline where these distances (retrieved using photo-interpretation of the Google Earth images) describe in absolute term the variation of the sea level. The proposed method is based on the hypothesis that any visible erosion or advancement is directly related to SLR. Thus, the limited availability of the in-situ real-values SLR datasets could be replaced with RS-based qualitative values enabling the calculation of CVI;

d) *Relative rate of erosion and advancement of the Coastline:* It is estimated from the displacement of the coast between two dates, which reflects the dynamics of the coast (Hereher, 2015);
e) *Average of the tide and f) Average of the wave height:* Based on the values reported in the Beach Med project (BEACHMED-e project, 2006);

Several methods described above required the usage of ArcGIS functions to save on time and resources. The CVI values are classified into five levels, ranging from Very Low (level 1) to Very High (level 5). The thresholds used are illustrated in Table 2.

2.3. Relationship between sea surface temperature (SST) and coastal changes values

Sea temperature values was derived from (El Hourany et al., 2017), where the monthly sea surface temperature (SST) product was obtained from MODIS satellite with a spatial resolution of 1 km; in this study, only the closest pixels to the coastline were selected. Then, the absolute trends for the SST and coastal changes datasets, produced previously in the CVI variable (c) *Relative rate of sea-level rise,* either positive or negative, at each pixel, were evaluated between April 2005 and April 2013. The SST was used mainly due to its direct association with the climate change that generally presents a global increasing in temperatures (Church and White, 2006; Domingues et al., 2008). Moreover, the variation in SST affects the SLR which in turn alters the coastal zones and causes coastal erosion (Rahmstorf, 2007). The relationship between these two trends is plotted through Pearson regression. While a positive or negative relation designates a correlation between SST and SLR, low or no relation shows that SLR was not affected by SST variations.

Fig. 5. The dune formations in the Tyr Coast Nature Reserve (TCNR) (*Source: Y. Ghoussein, 2016*).

Fig. 6. The dune cordon of the Tyr Coast Nature Reserve (TCNR) *(Source: Y. Ghoussein, 2016)*.

3. Results

3.1. Evaluation of the vulnerability index

During the eight years of study, the Southern Lebanese coast showed advancements in some areas and erosions in others. The maximum advancement is seen at 392 m near a landfill located in Saida (Fig. 2(a)) and the maximum erosion is visible in Adloun coast with 80 m (Fig. 2(b)).

Following the implementation of the CVI over the study area, only three levels of vulnerability are noted: Low (4%), Moderate (66%) and High (30%) (Fig. 3 and Table 3). The most vulnerable areas are located to the south and north of the city of Tyr, southern part of the city of Saida and between al-Zahrani and Adloun. Aerial views for these zones, as well as for the other two classes, are available in Fig. 4; "A1" and "A2" present high vulnerability to SLR where "A1" is the Adloun coast which is extending 2 km in length and "A2" is the 3 km coast of the Tyr Nature Reserve. "B1" and "B2" correspond to a moderate level of vulnerability, where "B1" is located in the town of Tyr with a length of 6 km and "B2" is the town of Saida with a length of 2 km "C" corresponds to a low level of vulnerability, represented by the city of Nakoura extending 124 m along the Mediterranean cost.

3.2. Analysis of the relationship between the sea surface temperature (SST) and sea-level rise (SLR)

Between April 2005 and April 2013, SST trend line ranges between −0.03 and 0.05, whereas, coastal changes shows values between −80 and 392 m, as previously stated. The low relationship (i.e. $R^2 = 0.013$) between SST and coastal changes values indicates a limited impact from the temperatures on the sea level rise.

4. Adaptation strategies for coastal zone

In this study, CVI identifies the sandy areas of the Adloun Coast and the Tyr Coast Nature Reserve are the most vulnerable to marine erosion. They are characterized by the presence of the natural dune formations with high ecological value and are not subject to urban pressure (SDATL, 2004). Thus, management plans are required to preserve those areas and to lower their vulnerabilities. In this context, we propose an approach based on a two-step action plan: (i) installation of the technical restoration structures and (ii) raising public awareness. This method is considered effective in protecting sandy beaches that are vulnerable to erosion (Posidune, 2007; Masria et al., 2015).

The first phase will require the installation of specific defense structures aimed at controlling the mobility of dune formations by reducing the wind speed and creating favorable conditions for the development of the vegetation cover of local species (ANCORIM, 2011). Several 'soft' coastal defense methods can be considered such as vertical wooden slats of variable permeability and height. They can be positioned parallel to the shore line at the foot of the dune to limit wind erosion by trapping blown sand, limiting the trampling of vegetation and promoting the functional dynamics of the dune system. Re-vegetation, are also used to stabilize the dune system and to reinforce the dynamic equilibrium (Posidune, 2007). It is proposed to vegetate the degraded zones of the dune with Marram grass (*Ammophila arenaria*). The Marram grass is frequently used in the restoration of the dune system for its capacities to trap blown sand and to limit wind erosion (Jungerius and Van der Meulen, 1988; Van der Biest et al., 2017).

The second phase consists of creating a spot for public awareness to encourage acceptance of the above-mentioned measures and to restrict public access to the beach.

The dune formations in the coastal reserve of Tyr already present some procedures, such as limiting the accessible areas to visitors (Fig. 5 a.b and c. d). These measures were applied as soon as the mentioned area became a natural reserve in 1998, showing their effectiveness nowadays in terms of highly diversified vegetation cover with several endemic species. We can also note the appearance of a fixed grey dune (Fig. 6). Without these actions, CVI would have generated a Very High vulnerability class.

5. Discussions and conclusions

A high vulnerability to sea level rise is shown in several regions along the Southern Lebanese coast. Generally, sea level is influenced by ocean waves, tides and meteorological fluctuations, as well as by anthropogenic causes (Church et al., 2008). As stated in previous studies, natural factors in the area, including waves, tides and local sediments transport trends, exert minor impact on the local sea levels (Beydoun, 1976; Kabbara, 2005; Houri, 2005; BEACHMED-e project, 2006; Aoun et al., 2013; Zodiatis et al., 2014). Main causes correspond to anthropogenic-related pressures, such as the construction of new sites and landfills as well as sand extraction, which are mostly visible in Adloun, Saida, Sarafand and Tyr areas. These findings are in accordance with other studies (e.g. Dasgupta et al., 2009; Nicholls and Cazenave, 2010; Kirwan and Megonigal, 2013). Thus, mitigation plans should be implemented while focusing on reducing the anthropogenic influences in these coastal areas.

The low Pearson correlation, performed between SST and coastal changes values, in the selected time frame (i.e. April 2005 and 2013) and on the Southern Lebanese coast, shows no major relationship between the sea level rise and the sea surface temperature. This may be attributed mainly to the human activities observed at the coast during the years of study, which align with previous studies (e.g. Khan et al., 2000; Garcin et al., 2011).

However, it is important to consider that the short study time frame (i.e. eight years) might not be sufficient to manifest the direct effect of the climate change. Moreover, the Mediterranean is a semi-enclosed basin; the thermal expansion that causes the melting of ice caps and Glacier Mountains might not affect significantly the sea-level rise in this basin.

The importance of this study resides in its capacity to assess the vulnerability of Southern Lebanese Coast, where no previous study was produced. It is particularly vital to assess this region because of its high urban growth rate in the last decade. The proposed approach enable the implementation of a globally-acknowledged index, namely CVI, in limited-resources/datasets countries. Thus, this research not only pave the way to local management bodies and decisions-makers, but also to regional organizations and institutions to obtain vital information when applying this approach with the aim of combating this phenomenon at a larger-scale.

Future studies should focus on installing tide gauges in the study area to monitor the sea level rise in a continuous manner. Using higher spatial and temporal resolution datasets is recommended. Extending the time frame of the study, as well as implementing this approach to regional coastal areas, are also advised.

To conclude, the southern Lebanese coast is characterized by the presence of various geomorphological structures (i.e. sandy beaches, rocky beaches, pebble beaches, estuaries, low cliffs, cliffs and artificial shores) that increase its ecological value. In this study, we assessed the coastal vulnerability in that area using a modified CVI. Results show that this coastline presents medium to high vulnerability. More specifically, sand beaches and associated dune such as the coast of Adloun and Tyr Coast Nature Reserve are the most vulnerable. The associated vulnerability can be attributed primarily to direct human activities observed on the coast. In this context, soft ecological methods such as windbreaks and replanting can be used to protect highly vulnerable areas.

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