Soaring Building Collapses in Southern Mediterranean Coasts: Hydroclimatic Drivers & Adaptive Landscape Mitigations

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Abstract

The low-lying, arid coastal regions of the Southern Mediterranean basin, extending over 4600 km, face daunting sea level rise and hydroclimatic changes due to shifting weather patterns. The impacts of the above on coastal urban buildings and infrastructure still need to be more qualified and understood. Alexandria, a historic and densely populated port city representative of several coastal cities in the Southern Mediterranean, has experienced over 280 building collapses near its shorelines over the past two decades, with the root causes still being investigated. We explore the decadal changes in coastal and hydroclimatic drivers along the city’s coastline using a GIS-based multi-criteria analysis in the areas where buildings collapsed from 1974 to 2021. Our results suggest that collapses are correlated to severe coastal erosion due to sediment imbalance caused by the decades-long inefficient landscape and urban expansion along the historic city’s waterfront. This severe erosion, combined with sea level rise, upsurges seawater intrusion, which raises the groundwater levels in coastal aquifers, disrupting soil stability and accelerating corrosion in building foundations until they collapse. We identified a coastal area of high vulnerability with over 7,000 buildings at risk, surpassing any other vulnerable zone in the Mediterranean Basin. We conclude that several coastal and densely urbanized areas in the Southern Mediterranean are at greater risk of building collapses due to similar hydroclimatic changes. Therefore, we propose a landscape-based coastal mitigation approach to implement adaptive transformations to curb these risks that apply to Alexandria and other southern Mediterranean cities facing the same challenges.

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Total buildings' collapses in Alexandria under shoreline retreat rate in the last 2 decades (2001-2021)

Western part

- Al Amraya district (1) - 30 buildings collapses
  - Max EPR: -3.8 m/yr

- Gharb district (2) - 96 buildings collapses
  - Max EPR: -31.13 m/yr

Central part

- Al Gomrok district (3) - 26 buildings collapses
  - Max EPR: -0.65 m/yr

- Wasat district (4) - 65 buildings collapses
  - Max EPR: -1.09 m/yr

Eastern part

- Shark district (5) - 47 buildings collapses
  - Max EPR: -2.72 m/yr

- Al Montazah district (6) - 26 buildings collapses
  - Max EPR: -10.97 m/yr

Legend:
- Red: Shoreline_2021
- Blue: Shoreline_2001
- Green: Shoreline_1959
- Orange: Shoreline_1877

Source: Erli ArcGIS 10.8

- 4: Wasat district
- 5: Shark district
- 6: Al Montazah district

Map showing the coastline changes from 1935 to 2022.
A continuum of green to gray shoreline stabilization techniques:

- Including soft (green) allows for more dynamic coastal responses armoring suitable for most areas in Shark and Wasat districts.

- Hard (gray infrastructure) involves creating artificial lands above level in the low lying areas in Al Montazah (Abou Qir area) and Gharb districts (western port area).

- Creating corridors between land and water environments for migratory fish and wildlife.

- Artificial sand nourishment and built-up mineral spaces.

Ecosystem-based adaptation through:

- Green open spaces connecting the green street system with the coastline that includes salt-tolerant landscapes.

- Land-use waterways and implementing adaptive landscape design along waterways to improve inhabitants' engagement in city climatic resilience.
SOARING BUILDING COLLAPSES IN SOUTHERN MEDITERRANEAN COASTS: HYDROCLIMATIC DRIVERS & ADAPTIVE LANDSCAPE MITIGATIONS

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Highlights:

1. Coastal buildings collapses increased 10 times over 20 years in the Mediterranean port city of Alexandria, threatening 7,000 buildings.
2. Collapses correlate with areas of chronic and severe shoreline erosion and sea level rise, accelerating coastal aquifers' seawater intrusion.
3. The above seawater intrusion raises groundwater levels to reach coastal buildings' foundations, accelerating their corrosion and collapse.

Keywords: Coastal erosion, Sea level rise, Seawater intrusion, Building collapses, Southern Mediterranean, and Adaptive coastal design.

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Plain language Summary. We investigate the cause of the increase in the number of collapsed buildings along the 70 km-long coastlines of the historic port city of Alexandria in the Southern Mediterranean. The city is identified for its high vulnerability to sea level rise and its similarity to other coastal urban areas in the region that were not prone to these risks. We found that rising sea levels are increasing seawater intrusion in coastal aquifers, disrupting soil mechanical properties, and corroding building foundations, leading to their collapses. Over 7,000 buildings near the city coastline are at risk of collapse, more than any other part of the Mediterranean. Similar patterns are observed in other coastal cities in developing nations suffering from recent hydroclimatic changes. We suggest cost-effective and nature-based coastal landscape adaptation strategies to mitigate these risks in Alexandria and similar cities in developing nations.
Abstract. The low-lying, arid coastal regions of the Southern Mediterranean basin, extending over 4600 km, face daunting sea level rise and hydroclimatic changes due to shifting weather patterns. The impacts of the above on coastal urban buildings and infrastructure still need to be more qualified and understood. Alexandria, a historic and densely populated port city representing several coastal cities in the Southern Mediterranean, has experienced over 280 building collapses near its shorelines over the past two decades, with the root causes still being investigated. We explore the decadal changes in coastal and hydroclimatic drivers along the city's coastline using a GIS-based multi-criteria analysis in the areas where buildings collapsed from 1974 to 2021. Our results suggest that collapses are correlated to severe coastal erosion due to sediment imbalance caused by the decades-long inefficient landscape and urban expansion along the historic city’s waterfront. This severe erosion, combined with sea level rise, upsurges seawater intrusion, which raises the groundwater levels in coastal aquifers, disrupting soil stability and accelerating corrosion in building foundations until they collapse. We identified a coastal area of high vulnerability with over 7,000 buildings at risk, surpassing any other vulnerable zone in the Mediterranean Basin. We conclude that several coastal and densely urbanized areas in the Southern Mediterranean are at greater risk of building collapses due to similar hydroclimatic changes. Therefore, we propose a landscape-based coastal mitigation approach to implement adaptive transformations to curb these risks that apply to Alexandria and other southern Mediterranean cities facing the same challenges.
# 1. Introduction

Coastal areas are home to two-thirds of the world’s cities, accounting for ~37% of the global population (Post et al., 2018). The sustainability of their coastal infrastructure and buildings is crucial to warrant liveable conditions and maritime trade, ensuring the continuity of vital supplies across the globe. However, several of these coastlines, notably low-lying arid coasts, are at risk of sea level rise, increasing seawater intrusion, and coastal flooding. These risks are exacerbated by land subsidence resulting from coastal aquifers’ over-exploitation (Fig. 1) due to the increase in local population and expanse of aridity conditions. The above result is an increase in structural erosion and infrastructure instabilities leading to the failure of buildings near the coast (Ohenhen & Shirzaei, 2022). The phenomenon is particularly observed in developing nations (Post et al., 2018) where more coastal building collapses are being reported, averaging over 300 yearly fatalities (Dada et al., 2023). The hydroclimatic drivers of such an increase remain poorly known due to the lack of published case studies. Consequently, mitigation measures are out phased with the magnitude and expanse of these degradations in several coastal cities suffering from relative sea level rise.

The IPCC’s AR6 and the MedECC reports designated the southern Mediterranean basin, with its expansive 4600 km-long sandy, low-lying coastlines extending from northern Tunisia to the east of the Canal of Suez in Egypt, as a hotspot for sea-level-rise impacts for which literature is lacking. Both reports pointed out that the historic port city of Alexandria is among the world’s most vulnerable urban areas to sea level rise. The same vulnerability is shared among other populous Southern Mediterranean cities (Hzami et al., 2021). However, its impact on coastal building infrastructure remains widely unquantified, let alone understood, due to the lack of published reports. From 2014 to 2020, Alexandria topped Mediterranean cities with 86 buildings that ultimately collapsed and 201 partial collapses, resulting in a death toll of 85 inhabitants (Helal, 2022). The origin and drivers of this rising number of building collapses are mainly unknown.

Herein, we explore the hydroclimatic and anthropogenic drivers that accelerate these building collapses in Alexandria with the lesson learned to apply to other low-lying coastal cities that are observing similar phenomena (e.g., the 12-story beachfront residence in the Miami suburb of Florida in 2021). In particular, we explore the correlation between the location and structural characteristics of collapsed buildings and areas of high shoreline retreat. We also identify hotspots that require pressing adaptive planning and design strategies implementing natural-based coastal landscape solutions to improve the resilience of these urban areas to the ongoing impacts of shoreline degradations. Consequently, this investigation explores the problem of coastal building collapses in the Southern Mediterranean, using the historic port city of Alexandria as a case study that is representative of other similar regional coastal cities undergoing increasing shoreline retreats. The degradation of these coastlines increased their vulnerabilities to devastating coastal hydroclimatic extremes (e.g., Storm Daniel in Derna in Libya in September 2023 with more than 11,000 life casualties), calling for the urgency of coastal transformation studies in these populous regions to ensure infrastructure resilience to ongoing climatic changes. Our study identifies adaptive coastal transformations, mostly using cost-effective nature-based...
solutions, to mitigate the root cause of the problem in developing nations, as further discussed in the implications of this study.

2. Materials and Methods

2.1 Global Overview of Coastal Building Collapses

Building collapses on the coastlines are globally observed to be associated with the dynamic of groundwater levels, whether fresh or saline, in coastal aquifers. Figure 1 summarizes the most recent up-to-date assessment of changes in fresh groundwater levels of coastal aquifers. Notably, in areas of elevated changes in aquifers levels in Tunisia, Italy, Nigeria, Ghana, California, Florida, and Brazil, collapses are widely observed and summarized below.

In the Southern Mediterranean basin, notably in Tunisia, coastal municipalities observe severe buildings structural damage associated with shoreline erosion (Fig. 1b), particularly in semi-informal zones where protective measures are insufficient (Salhi et al., 2024). This vulnerability is accentuated in the central coastal areas of the country, home to tourist developments and private beaches, facing a heightened erosion risk (Amrouni et al., 2019). A particular concern in these areas is the proximity of touristic structures to the shoreline, often in violation of regulatory guidelines, leading to both partial and total structural collapses. Geospatial analyses reveal the concentrated risks of building collapse due to coastal flooding, especially in densely populated areas such as the historic coastal city center of Tunis, where approximately 57% of buildings are highly exposed (Bellert et al., 2021). Further away, in the central part of the Mediterranean basin in Italy (Fig. 1c), similar patterns are observed. Notably, the collapse of coastal buildings in the nation’s southern part increased by 9% from 1991 to 2001, where it is expected that thousands of coastal homes could be at risk of structural failure and potentially collapse in the next 50 years (Dolce et al., 2021).

In Africa, in Lagos, Nigeria, a notable coastal subsidence rate exceeding 4 mm/year is observed using interferometric Synthetic Aperture Radar observations from 2018 to 2021 (Ohenhen & Shirzaei, 2022). The land subsidence, associated with coastal aquifer discharge, resulted in frequent building collapses in the city, delineating an area with heightened susceptibility that affected between 255 and 4,050 structures (Fig. 1d) (Ohenhen & Shirzaei, 2022). Similarly, coastal erosion in Accra, Ghana, is an ongoing concern for the stability of coastal infrastructure. Recent observations employing digital topographic maps and aerial photogrammetry revealed that 79% of the shoreline is currently experiencing erosion, causing severe damage to coastal structures (Fig. 1e) (Addo & Addo, 2016). Reports of coastal building collapses in Africa are particularly difficult to assess due to the lack of accessible public records, unreported incidents, and local authorities often unable to identify the cause of these structural failures.

In California in the San Francisco Bay, sea level rise poses a significant inundation risk to coastal urban areas and infrastructures, where subsidence rates are ~ 2 mm/year along most
of the coastal areas, with some locations reaching ~10 mm/year due to compacting artificial
landfills and Holocene mud deposits (Fig. 1f) (Shirzaei & Bürgmann, 2018). As a result of
the risks of building failures, ~18,300 households were displaced in San Francisco in 2014,
representing 11% of the coastal residential buildings in the city (Brechwald & Resilience
Planner, 2018). Similar structural failures have been observed on Florida’s coastline. For
instance, on June 24, 2021, Champlain Towers South, a 12-story condominium structure
located in Surfside, Florida, collapsed due to a structural failure. This catastrophic event
ranks among the most fatal building collapses in the history of the United States, resulting in
the confirmed deaths of 98 individuals (Kong & Smyl, 2022). The tragic Surfside
condominium collapse has highlighted the urgent need to address the impact of hydroclimatic
changes on coastal structures in the US. From 1994 to 2020, aquifers and sea level records
reveal a substantial rise in groundwater levels exceeding the building’s basement (Parkinson,
2021). In a similar setup, the coastal erosion along the Brazilian resort town of Atafona, north
of Rio de Janeiro on the Atlantic Ocean, averaging ~6 m/year between the years 1984 and
2016, led to 500 houses collapsing (Fig. 1g) (Vassileva et al., 2021; Pearson, 2023; Valpassos
& CUNHA, 2023).

These above cases show the interplay between the status of sea level rise, coastal
aquifers, and changes in land use in defining the amplitude and extent of the risks of coastal
building collapses. However, in developing nations, observations for these three elements are
lacking, causing an alarming rate of coastal building collapses, as exemplified in the case of
the port city of Alexandria.

2.2 Study Area: Alexandria

Alexandria is the largest port in the Southern Mediterranean basin, located on one of the
busiest global maritime routes (Nagati & Stryker, 2020) and Egypt’s second most populous
city, with over 5.3 Million inhabitants living within a few kilometers of the coastline (Ritchie
et al., 2024). With its 70-km-long waterfront stretching East-West on the northern outlet of
the Nile River Delta, the 3000-year-old city is expected to be partially submerged by 2050
(Hilmi et al., 2022). The urban area of the port city of Alexandria consists of a large town
divided into six districts: (1) Al Amreya, (2) Gharb (West), (3) Al Gomrok, (4) Wasat
(Middle), (5) Shark (East), (6) Al Montazah, and two small cities, Borg El Arab and New
Borg El Arab, which together form the metropolitan area of Alexandria (GOPP, 2011). With
a population density of 4.800 people/km² (El-Mallakh, 2020), Alexandria is the largest urban
area in the Nile Delta and North Africa.

Alexandrian coastline includes several significant beaches and harbors that separate the
Mediterranean Sea from inland Lake Mariout, as shown in Figure 2. The city’s total area is
1459.6 km², of which the built-up area is 336.3 km², with the highest concentration
observed near the seawall, which is just 0.4 m above sea level (Pagnoni et al., 2015; Abd
El-Ghani et al., 2017; El-Hattab et al., 2018). More than half of residential areas are
informal settlements (Barakat, 2020). Starting in 2010, several storm surges exceeding 1.2
meters above mean sea level have caused severe coastal flooding and damage to seawall
buildings and infrastructures. As medicanes in the Eastern Mediterranean basin are
becoming more frequent due to its warming waters (Romero & Emanuel, 2017), such storm surges with ravaging deteriorations are increasingly observed (Abutaleb et al., 2018).

### 2.3 Building Collapse Data Set

The port city of Alexandria has experienced over 280 building collapses near its shorelines over the past two decades, with the root causes still being investigated. Our study generated a holistic Geographical Information System (GIS) data set of 280 collapsed buildings in the six districts of Alexandria's historic urban areas (Fig. 2). The database is compiled from site visits, governmental reports, private constructors published statements, and numerous news archives. The dataset assessed total and partially collapsed buildings from 2001 to 2021. The generated records included building locations, size, construction material, age, and floors number.

### 2.4 Monitoring Long-term Shoreline Evolution

We use the Digital Coastal Analysis System (DSAS) to monitor the long-term changes in coastline position. The method is described in Thieler et al. (2009), and is implemented using Sentinel 2A scenes from 2021 and digitized topographic maps (1887, 1959, and 2001). In this approach, the DSAS algorithm generates cross-shore transects along Alexandria’s coastline. Each cross-shore transect has a length of 1000 meters with 50 m spacing. We use ArcGIS Pro to create a GIS-integrated time series with calculated rate of change statistics, which allows for visualizing and understanding how the geometry and position of the coastline have evolved over the last century. Our analysis uses two statistics from the DSAS model: (1) Net Shoreline Movement (NSM), which provides the reported overall separation between older (1887) and current (2021) coastline locations, and (2) the End Point Rate (EPR), which represents the annual rate of shoreline retreat averaged over the last century. The statistical method of linear regression is used to quantify the root mean square (RMS) error in the georeferencing process. RMS errors are used to quantify errors associated with manual digitization of the map and are not necessarily indicative of its resolution. The observed RMS error of <0.5 pixels (the actual range is between 0.3 and 0.4 pixels) corresponds to a margin of ±40 m over the study period (1887–2021), i.e., ±0.29 m/yr.).

### 3 Results

#### 3.1 Rapid Shoreline Evolution

Recent changes in the coastal dynamics of the port city of Alexandria have led to significant alterations in the shoreline, causing some regions to experience limited accretion and others to suffer from erosion at a maximum pace of 24-36 m/yr (Ali and El-Magd, 2016). The latter increases salt intrusion into shallow coastal aquifers a few kilometers inland, negatively affecting the soil quality and moisture levels (Zhongming et al., 2021). The seawater intrusion is further aggravated by excessive groundwater abstraction, leading to more saline intrusion into coastal aquifers (Abd-Elhamid, 2010).
The increased seawater intrusion near buildings’ foundations is caused by both coastal aquifers’ extraction and shoreline retreats (Amrouni et al., 2019). As such, understanding the evolution of shorelines is crucial to assessing their impact on the case of collapsing buildings. The shoreline evolution during the period extended between 1887, 1959, 2001, and 2021 revealed a variable rate along Alexandria’s sandy beaches. Considering the significant increase in urbanization that started in the 1950s, we can subdivide the temporal period assessment into natural and human-induced scales. As mentioned in Table 1, the calculated Net Shoreline Movement (NSM) based on the Digital Shoreline Analysis System (DSAS) tool of the Alexandria districts varied from the eastern to western ridges during the last century (1887-2021). Shoreline monitoring from 1887 to 1959 and 2001 during the natural period indicates that the coastlines are stable, according to Esteves and Finkl (1998), with an End Point Rate (EPR) of -0.57 and -0.13 m/yr (EPR), respectively. However, between 2001 and 2021, the Alexandria coast experienced a severe erosion rate with a maximum EPR rate of -3.64 m/yr, as shown in Figure 3. The spatial extent of the impact of coastal erosion differs widely among the urban districts. The most affected district by the extreme erosion is localized on the western coast along the Garb district (EPR equal to -31.13 m/yr) and on the eastern shore along the Al Montazah district (EPR equal to -10.9 m/yr) (Fig. 4). Moreover, the Al Amreya and Shark districts are affected by severe (EPR of -3.6 m/yr) to intense erosion (EPR of -2.7 m/yr), respectively. The central area of Alexandria, located in the Al Wasat district, is characterized by an eroded shoreline rate with an EPR of -1.09 m/yr. A stable shoreline movement rate characterized the Al Gomrok district from 2001 to 2021, as shown in Figures 3 and 5. Among the urban districts examined, Al Amreya had the highest proportion of inundated built-up areas, ranging between 11.2% and 14.1% of the total built-up area under the two scenarios of 0.5 and 2 meters, respectively, as shown in Figure 3. A study conducted in the Al Gomrok district found that the built-up area susceptible to inundation was 0.09% and 0.01% of the total built-up area under 0.5 m and 1 m scenarios, respectively (El-Hattab et al., 2018).

3.2 Decadal Increase in Coastal Building Collapses

Coastal building collapses in Alexandria have been increasingly observed in the last two decades, with 117 collapses occurring between 2013 and 2015 compared with just one collapse between 2001 and 2004 (Fig. 6) (Daftar Ahwal Cairo-based research institute (DADRI), 2020; Seif Eddin, 2021; Helal, 2022). Our mapping of these collapses shows the most significant number occur in an area of the Gharb district ~ 1.83 km from the coastline. Second comes the Al Gomrok district, with the area witnessing collapses located from ~ 0.80 to 1.50 km from the coast. Third comes the Wasat district, where the areas undergoing collapses are located in the first 2 km from the coastline. The newly built residential communities in the Al Amreya district, which are ~ 1 to 2 km away from the coastline, also witnessed several collapses, representing ~11% of Alexandria’s total building collapses over the last twenty years (Fig. 2). Earlier studies suggested that the lack of maintenance of old buildings, inefficient landscape transformation, urban expansion, and lack of wastewater infrastructure are
considered the main factors accelerating the successive collapse of city buildings (Abd El Sabour, 2009; Abdelnaser, 2014). Moreover, deficiencies in construction regulations and legislations concerning the designation and execution of buildings are also regarded as a crucial reason for property damage and consequent collapses (Abdelnaser, 2014). However, these factors are shared with all city constructions where no collapses are observed. Consequently, they cannot alone explain the geographical distribution of collapses, as observed in Figure 2, where the vicinity of the coastline is correlated to the highest number of events. Hence, the impact of the decadal change of coastal dynamic on the corrosion of building foundations is valid. We also observe that beach erosion enables seawater intrusion in coastal aquifers, raising groundwater levels, altering the ground's structural stability, and corroding building foundations. Periodic exposure to saline groundwater accelerates the corrosion of subsurface infrastructure, such as concrete, steel, bricks, and masonry, causing premature failure (Setiawan et al., 2022). Hence, the increase in medicaines and their associated storm surges can also play an important role in corroding foundations in Alexandria and increasing building collapses.

Another factor that can be considered is the continuous ground settlement in some parts of the city. This causes excessive differential deformation of buildings’ foundations and infrastructure, increasing their risk of structural damage. Additionally, environmental factors can adversely affect the structural resilience of the coastal buildings in the city, such as air pollution, waterway contaminations, and changes in air humidity. Furthermore, current inefficient management strategies for the Alexandria waterfront and institutional settings create a limited contribution to urban resilience and overlaps and conflicts between these institutions due to ineffective management strategies (Fouad et al., 2023). However, the impacts of hydroclimatic changes are potentially interwoven with the above factors and, if left unaddressed, would amplify existing migration trends to urban areas (Czaika & Reinprecht, 2020).

3.3 Coastal Buildings’ Structural Characteristics

The physical characteristics of older and contemporary building structures in the coastal areas of the port city of Alexandria play an important role in assessing the causes of collapses. The primary building material for standing structures is either concrete for contemporary structures or limestone blocks for older ones (Khalaf & Abdelmegeed, 2018). This is because both construction materials are abundant, cost-effective, and easily accessible in the surrounding environment. For instance, the northern coasts of the Egyptian western desert include limestone in several locations close to the city. Limestone is also used in the cement industry as an essential component in concrete fabrication and a block for older bearing-wall systems. Concrete residential building structures usually range from 6-15 floors, whereas limestone-bearing wall structures range from 1-6 floors in height (Ali & Yang, 2014).

The old downtown of Alexandria is composed of the two districts of Gharb and Al Gomrok. The ground in these two districts comprises a historic landfill of silty, alluvial, and sandy layers overlaying limestone (Zayed et al., 2020). A significant seawater intrusion has
been observed in these coastal areas, resulting from the increased groundwater extraction for irrigation and domestic supply (Mahmoud, 2019). Furthermore, due to groundwater overexploitation, seawater intrusion into coastal aquifers has caused clayey alluvial soils to destabilize due to the rise in groundwater. This results in heightened land subsidence, local topographic deformation, and karstification, such as sinkholes and central cavities (Werner & Simmons, 2009), substantially damaging buildings and infrastructures and causing life casualties. The multiplication of damaged buildings in these areas and the high cost of their rehabilitation has caused many inhabitants to abandon structurally damaged buildings and relocate to new urban areas further inland (Sušnik et al., 2015).

Foundation systems for concrete buildings of a few stories include shallow isolated footings. However, pile caps and raft systems are used for higher multiple-story buildings. In contrast, bearing wall system foundations include isolated concrete footings for medium-rise buildings and typically formed block footings for shorter buildings (Magbool & El-Abassy, 2021). As such, the increase in recently built multiple-story buildings in the downtown area exposes their foundation to rising groundwater levels, further accelerating their corrosion.

In studying the history of Alexandria as an ancient city and following the remnants unveiled from deep excavations, the older ancient urban areas are several meters below the current city, indicating a continuous landfilling to curb sea level rise over the last 3000 years. This is reflected by the fact that historic structures always suffer from the rise of underground water surrounding their foundations and its corrosion effect over time, affecting the building's stability (Figs. 4 and 5). Thus, cracks are frequently observed in the lower floors owing to the differential settlement of the buildings. The adverse effects of rising groundwater levels are even more evident in older and shorter buildings. The latter is also observed in recent higher buildings built illegally on shallow foundations. The case of these recent multiple-story buildings in the old downtown is even more critical as brackish groundwater continues to rise due to seawater intrusion, causing corrosion of the foundation by the chemical reactions between cement and seawater, leading to a quicker deterioration of such materials (Ragab et al., 2016).

3.4 Causes of Coastal Erosion and its Impacts on Ground Stability

Beach erosion monitoring of the Alexandrian shores reveals hotspot areas with a pronounced ‘chronic’ erosion rate exceeding 3 m/yr, mainly expressed in recent decades. The affected areas were located in the city’s urbanized eastern and western regions. Shoreline regression is primarily due to the reduced sediment trapped by dams, which interrupts the sediment flux of the Nile Delta (Frihy, 1994). Since the construction of the Aswan High Dam in the 1960s and built-up coastal management (dikes, wave breakers, jetties, etc.), coastal urban areas have suffered from critical sediment imbalances (Hzamí et al., 2021). There is a positive relationship between the regression of sediment unbalance of supplies to the foreshore and the collapse of coastal buildings where the most affected district by a Maximum EPR rate of -31.13 ±0.18 m/yr expressed a total of 96% of building collapse during the last periods of 2001-2021. As most of Alexandria’s study zones are entirely managed by maritime structures, the coastal sediment input driven by longshore drift, mainly...
from northwest to southeast, has completely trapped the coastal management structure upward. The positive accretion rate recorded in the neighboring maritime management corresponds to artificial sand nourishment and built-up mineral spaces.

Ibrahim (2023) employed radioisotopes $^7$Be and $^{137}$Cs to trace land subsidence and annual erodibility at 25 sites along Alexandria. For short-term (months) stability, $^7$Be (half-life, 35.5 days) indicator levels showed that approximately 78% of the area was deficient. In contrast, areas with low, moderate, and high stability were 18%, 4%, and 5%, respectively. For long-term (years) stability, $^{137}$Cs (half-life, 30 years) indicator levels showed an approximately 80% shallow stability. At the same time, the remaining area was predicted to be 12.8%, 5.6%, and 1.6% for low, moderate, and high stability, respectively. Additionally, $^7$Be results indicated wide variations of soil subsidence ranging from 0.6 cm to 83 cm. The highest value was observed for the central part of Al Amreya district. Other sites recorded high subsidence, such as the eastern part of the Al Montazah district, with values of (16.67 cm) and (9.1 cm) respectively. Therefore, the eastern part of Alexandria suffers from high soil subsidence and erosion; consequently, it is considered a more vulnerable zone, as shown in Figures. 6 and 7.

The effects of soil erosion on construction are significant as it destabilizes building foundations, increasing the need for repairs. The latter is increasingly unaffordable by the inhabitants due to the worsening economy with increased inflation and the rising cost of building materials (Ghaly, 2022), hence increasing the number of abandoned houses and the homeless population once these buildings collapse or become uninhabitable (Gyamfi-Aidoo, 1987). Furthermore, during the winter, rainwater drainage causes an additional rise in groundwater levels, adding to the effect of seawater intrusion. The increased frequency and amplitude of Eastern Mediterranean storms may lead to further soil compaction, recession, and subsidence, deteriorating city building foundations. For instance, studies carried out on the soil of Alexandria in the short- and long-term using radioisotopes ($^7$Be and $^{137}$Cs) showed that most of the city’ ground suffers from severe erosion that exceeds the average of other coastal cities (Saleh et al., 2024).

Further measurements of erosion rates across various timescales are needed in light of the increasing risk of soil loss resulting from hydroclimatic factors as they modulate building collapse across the city. Radionuclides such as $^7$Be and $^{137}$Cs can be used as sediment mobilization and redistribution tracers in undisturbed and cultivated landscapes over various timescales. Thus, we evaluated the stability of Alexandria soil using the natural radionuclides $^7$Be for short-term stability and $^{137}$Cs for long-term stability.

### 4 Adaptive coastal transformation to mitigate rising hydroclimatic risks

As the city of Alexandria is one of the largest ports in North Africa, its increased vulnerability to relative sea level rise and increased storm surges have local and regional socioeconomic consequences, including disruption in maritime routes due to its vicinity to the Suez Canal, one of the world busiest shipping routes. As such, mitigating the coastal vulnerability induced by rising hydroclimatic fluctuations requires an adaptive, sustainable, and cost-effective coastal transformation along the city’s 70-km-long waterfront, suffering
different risk levels, which must be considered in the future planning process. In early 2000, Egypt initiated an Integrated Coastal Zone Management plan (ICZM) for all its Mediterranean coast. The plan was expected to build a geographical database and establish a monitoring system utilizing remote sensing techniques to create a decision support system (EEAA, 2008). One of the critical objectives of ICZM was to increase public awareness of coastal hazards and stimulate sustainable development. Despite extensive planning for the ICZM, it was never implemented due to decision makers’ perception that hydroclimatic extremes are occasional and rare events, and hence, such investment is not a priority (UNEP/MAP/PAP, 2008). This fact is questioned nowadays under the increased frequency of storm events in the Southern Mediterranean basin. This perception is now challenged by the increasing frequency and amplitude of these coastal risks over the last 20 years.

There are five main adaptation approaches to mitigate coastal submersion and flooding risks that apply to Alexandria: hard protection, soft protection, accommodation, ecosystem-based adaptation, and managed retreat (Bongarts et al., 2021).

The first approach is the hard protection, or “grey infrastructure” advance responses, which is widely implemented in Northwestern Europe, East Asia, deltas, and densely populated coastal areas, using structures like seawalls and dikes to control rising sea levels and storm surges. While these offer immediate shoreline stabilization, they often exacerbate erosion and can hinder natural coastal responses (Ballinger, 2003; Hilmi et al., 2022). Additionally, they may be economically unsustainable and socially unacceptable due to their high costs, aesthetic attributes, and environmental impacts (Hinkel et al., 2018; Esteban et al., 2019). The hard protection also involves creating artificial land above sea level. It’s particularly advantageous in densely populated areas, as in the case of Alexandria, as it can provide accessible new sites for development that are already connected to the urban fabric (Alves et al., 2020). However, this approach can be detrimental to the coastal ecosystems and habitats (Warner et al., 2018), contributing to ‘ocean sprawl’ and ecological disruption (Bishop et al., 2017).

The second approach is soft protection, which includes dune rehabilitation and beach nourishment. It allows for a more dynamic coastal response (Van Rijn, 2011) and is considered an environmentally friendly option compared to hard protection. However, the costs of implementing sand nourishment can be prohibitive for large areas as it depends on the availability of specific types of sand reserves (Fegley et al., 2020). As such, this approach can only be applied in localized spots of a few hundred meters at most of Alexandria’s seafront.

The third is the accommodation strategy, which involves adapting existing infrastructure to accommodate rising sea levels and increased storminess (Alves et al., 2020). This includes a range of urban planning and building architectural solutions, such as elevating buildings, reinforcing foundations, and developing floating structures (Trang, 2016). However, these solutions require significant resources, are in their experimental phase on specific vital buildings, and have not yet reached the technical readiness level to be implemented on a large
scale in a city with a rapidly degrading seafront, as in the case of Alexandria (Alves et al., 2020).

The fourth approach is ecosystem-based adaptation, which focuses on utilizing natural coastal ecosystems for protection (Cheong et al., 2013). While this approach is cost-effective and successful in wave attenuation, reducing the impacts of coastal hazards from increased storminess, its implementation in areas with increased aridity and fluctuating hydroclimatic conditions, such as Alexandria, is challenging (Gao et al., 2020). Additionally, ecosystem-based adaptation may pose risks of introducing invasive species that must be carefully evaluated as they can impact fishing activity (Rinde et al., 2016), one of Alexandria’s pillars of food security. Recent international examples of applications of ecosystem-based approaches in urban coastal environments showcase the potential to develop adaptive, social-ecological inclusive solutions (van Bergen et al., 2021; Nijhuis et al., 2023). As displayed by the examples, it requires multiscale planning strategies and design principles that take the natural landscape as the basis for working with natural processes to benefit socially and ecologically inclusive and safe urban coastal landscapes (Nijhuis, 2022).

Finally, the managed retreat involves relocating infrastructure or populations from high-risk coastal areas (Hauer, 2017; Hilmi et al., 2022). Though potentially the most effective for submersion risk mitigation (Haasnoot et al., 2021), it is often socially controversial, involving complex economic and cultural considerations (Hino et al., 2017). For Alexandria, the inland retreat is particularly challenging as the city is longitudinal, and its inland part is bordered in the south by Lake Mariout, as shown in Figure 2a. Hence, any relocation will involve a remote distribution of part of the population and infrastructure, which can be socially unacceptable for the city inhabitants who are culturally attached to the proximity to the coastline. Different U.S. and European cities successfully managed retreats with varying levels of inhabitants’ acceptance and implementation strategies (Bragg et al., 2021). French policies successfully demonstrate the need for an anticipatory and learning approach to manage retreats (Rocle et al., 2021). A similar effort would be urgently needed today in Alexandria to anticipate unavoidable population displacements from high-vulnerability areas where coastal damages might be irreversible under the currently available technical solutions and available resources to implement them.

All of the above adaptation strategies require active and coordinated involvement of municipalities, landowners, citizens, and government entities, which is unfortunately absent in Alexandria and for the most highly populated cities in the Southern Mediterranean basin. The participation of all these parties in strategic planning, design, and decision-making is the path forward for the resilience and adaptability of coastal landscapes- not just physically but socioeconomically as well.

5 Discussion and Regional Implications

Mitigating the multifaceted challenges associated with the 70-km long shoreline degradation of the longitudinal city of Alexandria, facing rising sea levels, augmented
storminess, chronic coastal erosion, and rapidly corroding coastal buildings, is untenable using a single adaption strategy. A landscape-based coastal mitigation approach is paramount to address Alexandria's coastal challenges while considering the complex morphodynamical setup, ecological diversity, economic context, social fabric, and land institutional framework shared among other North African and Mediterranean port cities.

As the decadal shoreline retreat substantially varies along the coastline from one district to another (Figs. 6a and 7a), each localized mitigation approach must be weighted to the amplitude of the observed coastal degradation. Currently, the coast rehabilitation of Alexandria is witnessing an excessive implementation of hard protection responses where breakwaters are installed along the coasts of Wasat, Shark, and part of Al Montazah districts (Fig. 2), where the highest rate of shoreline retreat and building degradation is observed as shown in Figure 4a. Although hard protection offers immediate shoreline stabilization, this solution is relatively expensive and negatively affects the city’s coastal environment and natural habitats. However, soft protection in the form of beach nourishment is being implemented in localized areas of both the Gharb (western port) and Al Montazah (Abou Qir port) districts, as shown in Figures 8a and b. Nevertheless, pursuing this option involves committing technically and financially to beach nourishment for perpetuity (McDougall, 2017).

In addition to ongoing hard and soft protections, natural coastal landscape development should also be encouraged, allowing for the design, planning, and management of public spaces that improve public connectivity to the maritime environment (e.g., (Fouad et al., 2023)), which in turn will increase awareness of hydroclimatic extremes supporting the efforts to address the multifaceted aspects of coastal degradation. In urban landscape development, particularly in the coastal community of Alexandria, living shorelines, sand engines, breakwaters, bioswales, rain gardens, infiltration and exfiltration trenches, and constructed wetlands can be tested. Moreover, lessons learned from other port cities showing similar challenges showcase how systemic, integral, and multi-layered solutions across scales can be achieved for coastal protection. This involves designing solutions that consider the morphodynamical and ecological characteristics of the Alexandrian coast.

To preserve the coastal areas of Alexandria, a combination of soft and hard engineering techniques known as "soft defence," "ecosystem-based adaptation," and "accommodation strategy" can be implemented (Fig. 9a) (Climate Institute, 2019). A new green street system that includes high-tide gardens and salt-tolerant landscapes is proposed along the city’s coastline, as shown in Figure 9. During high tides, these saltwater landscapes serve as "bio pumps" as long-rooted, phreatophytic trees transpire significant amounts of water, thereby controlling hydraulics and reducing the duration of saltwater inundation (Huber et al., 2017) and controlling seawater intrusion in coastal aquifers, hence avoiding the rise of the water table to reach buildings’ foundation. Consequently, it is essential to connect the main coastline green street to the inner-city fabric through a green-blue infrastructure and enhance the quality and functionality of waterways, connecting the inner-city to the seashore. Implementing these ecological principles and green solutions will enhance stormwater
infiltration and better control groundwater levels in coastal aquifers. As 40% of Alexandria’s city development focuses on regenerating the street network (Elsawy et al., 2019), implementing the suggested new green street system connected to the main coastal road will increase the number of inhabitants connected to the coastline and hence improve their awareness of the risks associated to sea level rise and hydroclimatic fluctuations (Fig. 9). Currently only those living on the seafront have such awareness (Fouad et al., 2023). Implementing soft defence in the Gharb district efficiently decreases seawater intrusion, as the district witnessed the highest decadal value of shoreline retreat and the relatively highest record of building collapses in the last two decades. Accommodation strategy should be applied in densely populated Al Gomrok, Shark, and Wasat districts by adapting existing infrastructures to mitigate the rising sea levels. Al Amreya can employ the managed retreat strategy as a newly urbanized district. This process includes soft-engineered solutions that can be applied over time as a “rewilding” design approach to public and private property, re-designing the infrastructure, streets, and buildings, and implementing major infrastructure upgrades. As a result of the transition to more water-based transportation systems, new building types that feature raised platforms for living and submerged living units may be incorporated.

A comprehensive and transformative vision for Alexandria's waterfront, as shown in Figure 9a, is needed to create an open and accessible space that promotes urban resilience against hydroclimatic fluctuations. By utilizing a spatial landscape-based coastal mitigation approach across six districts, we can introduce a new layer of parks, boulevards, and recreational spaces that absorb rainwater, buffer from storms, and connect Alexandria's inner-city fabric to its park and waterfront assets. These solutions, shown in Figure 9b, c, d, and e, can serve as an initial insight to mitigate the anticipated coastal changes, providing a roadmap for the city's climate resiliency plans, which require more in-depth studies to be urgently performed.

Regeneration of the waterfront of the six districts discussed above to create a continuous line of defence against rising sea levels in Alexandria is urgently needed. To achieve this, dunes and algal deposits can be constructed to build slope revetments using impermeable gabions that can resist breaking waves. Wooden pillars must support the first ridge of the coastal building to enhance the coastal dynamic under the structure and should be constructed along the entire waterfront, from Al Amreya to Al Montazah. Risks of coastal flooding in lowlands in the Gharb and Al Gomrok districts can be mitigated by using 4 m high dunes with vegetation to stabilize the outer face. Finally, adding ~10 km of new coastal parks to the Wasat and Shark districts will stabilize seawater intrusion, hence avoiding groundwater level rise to buildings’ foundations in these districts, which account for 40% of the total building collapses in the city. Furthermore, the managed retreat is the most sustainable soft management to be implemented in the Shark and Wasat districts. For this purpose, created green and blue spaces can be integrated with recreational areas and waterfront living concepts, creating multi-functional and climate-resilient spaces near densely populated areas, as shown in Figure 9b, based on regional wetlands and salt marshes. This approach achieves adequate protection and provides a scenic and functional space for the community.
Future research incorporating the temporal dimensions of architectural structures in Alexandria promise to refine the outcomes of this present study. Furthermore, a proper understanding of the soil mechanical characteristics within Alexandria, coupled with a comprehensive statistical examination of prevailing building construction norms, can elucidate the intricate interplay between differential subsidence and suboptimal engineering practices as primary drivers of structural failures. While our investigation is focused on Alexandria, the lessons learned on mitigating the increase in coastal building collapses as a consequence of sea level rise apply to several Mediterranean cities in Tunisia, Libya, Morocco, and Algeria, as well as regions within the Persian Gulf area, thereby offering a broader perspective on mitigating the risks associated with building collapses through informed coastal engineering and coastal landscape adaption planning strategies.

6 Conclusion

The coastal city of Alexandria is a crucial case study that is representative of the rising hardship of Southern Mediterranean cities under the continuous rise of sea levels and increases in hydroclimatic changes. Particularly for cities with substantial informal coastal settlements, fragile buildings, and inefficient infrastructure that rapidly deteriorate and collapse near the shoreline due to increased corrosion in their foundation by seawater intrusion and rise in groundwater levels. Our coastal assessment of the amplitude of shoreline retreats along the city’s 70-km long coastline reveals that districts with the higher rates of building collapse over the past two decades are the ones closer to the coastline. Severe shoreline retreat is observed to increase seawater intrusion in these areas, triggering a rise in groundwater levels in coastal aquifers reaching the building foundations, accelerating their bottom-up corrosion, generating ground structural instability, and hence causing their collapses. Incorporating a hybrid coastal mitigation approach based on landscape solutions in Alexandria will be crucial for tackling the impacts of increased extreme hydroclimatic events and sea level rise in the Southern Mediterranean that, if unaddressed, can cause more alarming building collapses patterns. The adaptive landscape approach has considerable potential to meet the rising challenges of low-lying coastal cities while meeting the environmental, economic, and social constraints at local scales. The lessons learned in this analysis apply to other port cities in developed nations in North Africa and other arid areas sharing the same hydroclimatic and socioeconomic setup as Alexandria and call for more detailed studies to meet their national commitments to address ongoing rapid coastal degradations associated with climate change impacts.
Data Availability: This paper synthesizes published reports on building collapses. All data used in this investigation is openly available in Pelling & Wisner, 2012; El-Sheikh, 2016; Daftar Ahwal Cairo-based research institute (DADRI), 2020 and Helal, 2022. A copy of all the data, graphs, and statistical analyses used in the manuscript will be made available on the Center for Open Science repository open final acceptance. All figures were generated using ArcGIS Pro 3.2.1 tools.
References:


Table 1. The results of the statistical shoreline evolution analysis at the beaches of Alexandria, Egypt, during the periods 1887-2021, 1887-1959, 1959-2001, and 2001-2021. NSM: Net shoreline movement rate (m). EPR: The endpoint rate (m/yr) established by the bathymetric and topometric maps (1887-1959) scenes and Landsat and Sentinel photogrammetric orbital scenes (2001-2021). Negative values indicate erosion rates.

<table>
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<th>Study site (Coast length)</th>
<th>Years</th>
<th>Max EPR</th>
<th>Min EPR</th>
<th>Average EPR</th>
<th>Median EPR</th>
<th>Error EPR</th>
<th>Max NSM</th>
<th>Min NSM</th>
<th>Average NSM</th>
<th>Median NSM</th>
<th>Error NSM</th>
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Figure 1. (a) Global map showing the recharge (in green) or discharge (recharge) of coastal aquifers near urban areas. Their dynamic result in significant structural instability, leading to building collapses modified from (Post et al., 2018). (b) Localized damages in coastal buildings in different countries. The figure was created by Adobe Inc. (2019). Adobe Photoshop. Retrieved from https://www.adobe.com/products/photoshop.html and Microsoft Corporation. (2018).
Figure 2. (a) The vulnerability of the six urban districts of the Alexandria Governorate has increased in the last ten years, where most collapsed buildings are located at a maximum distance of ~2 km from the coastline. (b) The percentage of buildings that collapse in Alexandria’s six districts. (c) A city vulnerable to SLR and coastal erosion witnessed the collapse of 287 residential buildings, causing the death of 86 inhabitants and 782 affected families between 2014-2020, accounting for 31% of the total collapse in Egypt. The map reveals an increase in collapsed buildings in the western district, close to the coastline. Source: (Daftar Ahwal Cairo-based research institute (DADRI), 2020; Seif Eddin, 2021; Helal, 2022). The figure was created by Adobe Inc. (2019). Adobe Photoshop. Retrieved from https://www.adobe.com/products/photoshop.html and Microsoft Corporation. (2018). Microsoft Excel. Retrieved from https://office.microsoft.com/excel
Figure 3. Relationship between building collapse and shoreline rates (Maximum EPR: ±0.18 m/yr) during the 2001-2021 period in Alexandria, Egypt. The observed erosion rates are classified according to Esteves and Finkl (1998): accretion (> 0.5 m/yr), stable (0.5 to -0.5 m/yr), erosion (-1 to -0.5 m/yr), intense erosion (-1 to -3 m/yr), severe erosion (-3 to -5 m/yr) and extreme erosion (>5 m/yr). Negative values indicate erosion rate. Error bars correspond to the EPR errors illustrated in Table 1. Adobe Inc. (2019). Figure created in Adobe Photoshop. Retrieved from https://www.adobe.com/products/photoshop.html.
Figure 4. (a) Spatio-temporal assessment of shoreline movement during the last century in years 1877, 1959, 2001, and 2021 in the eastern coasts of Alexandria City. (4) Wasat district, (5) Shark district, (6) Al Montazah district. (b) Degradation of shoreline in Sidi Bishr near the Al Montazah district (from 1935 till 2022). The Integrated map was created in the GIS environment by ESRI ArcGIS Software.
Figure 5. (a) Spatio-temporal assessment of shoreline movement during the last century in years 1877, 2001, 1959, and 2021 on the western coast of Alexandria City; (1) Al Amreya district, (2) Gharb district, and (3) Al Gomrok district. (b) Degradation of the shoreline in Al Shatby on the western coast (from 1935 till 2022). The integrated map was created in the GIS environment by ESRI ArcGIS Software.
Figure 6. The evolution of building collapses in the last two decades has revealed anthropogenic and natural degradations, including a lack of management implementation and coastal erosion, and the impact of several storm surges of 1.2 m above the MSL (typical of the North coast: 0.4-0.5 m), resulting in coastal flooding and damage to coastal structures in December 2010, January 2011, and October 2015. The number of collapsed buildings in Alexandria throughout the last two decades indicates an increase in building collapse rates after 2011, when the unstable security situation allowed many landowners to build unofficially without permission in slums and agricultural lands, violating the law. According to official reports, Alexandria is among the top cities with illegal buildings, with 14,521 without licenses. Source: (Pelling & Wisner, 2012; El-Sheikh, 2016; Daftar Ahwal Cairo-based research institute (DADRI), 2020; Helal, 2022). Figure created in Origin Pro, Version 2022. OriginLab Corporation, Northampton, MA, USA.
Figure 7. (a) Spatio-temporal assessment of the shoreline movement during the last century in 1877, 1959, 2001, and 2021 on the eastern coasts of Alexandria City and the locations of the areas used for ground validation of buildings’ deterioration. (b) A 13-story apartment collapsed building, trapping several people under the rubble. (c) Continuous groundwater infiltration in the buildings’ structure (from the bottom up), subsidence of the Quaternary water-saturated substrate, and (d) Seawater submersion into urban areas in Abou Qir Bay. The Integrated map was created in a GIS environment by ESRI ArcGIS Software.
Figure 8. Currently implemented mitigation procedures in Alexandria: (a and b) beach nourishment supported by dike and groyne in the western port and Abou Qir port of area 176,000 m$^2$ and 56,655 m$^2$ successively. (c) In 2019, the local authorities invested $14 million in dropping 4,700 concrete blocks around the historic fortress of Gharb district to protect it from waves of coastal erosion. The figure was created by Adobe Inc. (2019). Adobe Photoshop. Retrieved from https://www.adobe.com/products/photoshop.html and Microsoft Corporation. (2018).

Figure 9. (a) The conceptualization of spatial hybridization approach for future coastal hazard mitigation, the strategy should include maintenance, enhancement, or restoration of a
vegetative buffer (green belt) along Alexandria. (b) Around 10 km of new coastal and waterfront parks stretching from Wasat to Shark districts. (c) Coastal structures can be built using dunes, algal deposits, and impermeable gabions; wooden pillars can support the first ridge of the building and enhance the coastal dynamics in the Gharb and Al Gomrok lowlands. (d) A new green street system that includes high-tide gardens and salt-tolerant landscapes is proposed along the city’s coastline. (e) Waterways’ development increases the city’s ability to mitigate climate extremes and improve inhabitants’ engagement in city climatic resilience through connectivity to maintained urban spaces along the canals connecting the inner-city fabric to the coastline. The figure was created by Adobe Inc. (2019). Adobe Photoshop. Retrieved from https://www.adobe.com/products/photoshop.html and Microsoft Corporation. (2018), the concept images were generated using Midjourney (2023) and Photoshop.
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Figure 1.
Figure 3.
Figure 4.
Total buildings' collapses in Alexandria under shoreline retreat rate in the last 2 decades (2001-2021)

Western part
- Al Amreya district (1): 30 buildings, Max EPR = -3.6 m/yr

Central part
- Gharb district (2): 96 buildings, Max EPR = -31.13 m/yr
- Al Gomrok district (3): 26 buildings, Max EPR = -1.09 m/yr
- Wasat district (4): 65 buildings, Max EPR = -2.72 m/yr

Eastern part
- Shark district (5): 47 buildings, Max EPR = -10.97 m/yr
- Al Montazah district (6): 26 buildings, Max EPR = -10.97 m/yr
Figure 8.
Figure 9.
A continuum of green to gray shoreline stabilization techniques:

Including soft (green) allows for more dynamic coastal responses armoring suitable for most areas in Shark and Wasat districts

Creating corridors between land and water environments for migratory fish and wildlife

Artificial sand nourishment and built-up mineral spaces

Ecosystem-based adaptation through:

Hard (grey infrastructure) involves creating artificial lands above level in the low lying areas in Al Montazah (Abou Qir area) and Gharb districts (western ort area)

Green open spaces connecting the green street system with the coastline that includes salt-tolerant landscapes

Inner-city waterways and implementing adaptive landscape design along waterways to improve inhabitants' engagement in city climatic resilience