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

Fouad, Sara S. ; Heggy, Essam ; Amrouni, Oula ; Hzami, Abderraouf ; Nijhuis, S.; Mohamed, Nesma; Saleh, Ibrahim H. ; Jomaa, Seifeddine ; Elsheshtawy, Yasser ; Weilacher, Udo

DOI
10.1029/2024EF004883

Publication date
2025

Document Version
Final published version

Published in
Earth's Future

AGU ADVANCING EARTH AND SPACE SCIENCES

Earth's Future

RESEARCH ARTICLE
10.1029/2024EF004883

Special Collection:
Forcing, response, and impacts of coastal storms in a changing climate

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

Sara S. Fouad[1], Essam Heggy[2,3], Oula Amrouni[4], Abderraouf Hzami[4], Steffen Nijhuis[5], Nesma Mohamed[6], Ibrahim H. Saleh[6], Seifeddine Jomaa[7], Yasser Elsheshtawy[8], and Udo Weilacher[1]

[1]Department of Landscape Architecture and Transformation, School of Engineering and Design, Technical University of Munich, Munich, Germany, [2]Viterbi School of Engineering, University of Southern California, Los Angeles, CA, USA, [3]NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, [4]National Institute of Marine Sciences and Technologies, University of Carthage, Carthage, Tunisia, [5]Department of Urbanism, Delft University of Technology, Delft, The Netherlands, [6]Institute of Graduate Studies and Research, Alexandria University, Alexandria, Egypt, [7]Department of Aquatic Ecosystem Analysis and Management, Helmholtz Centre for Environmental Research - UFZ, Magdeburg, Germany, [8]School of Architecture, Planning and Preservation, Columbia University, New York City, NY, USA

Key Points:

- Collapses of coastal buildings increased ten-fold over the last 20 years in the historic Mediterranean port city of Alexandria, threatening 7,000 buildings
- Collapses correlate with areas undergoing chronic and severe shoreline erosion and sea level rise, accelerating seawater intrusion in coastal aquifers
- Seawater intrusion uplifts the coastal groundwater levels to reach building foundations, accelerating their corrosion and collapse

Correspondence to:
E. Heggy,
heggy@usc.edu

Citation:
Fouad, S. S., Heggy, E., Amrouni, O., Hzami, A., Nijhuis, S., Mohamed, N., et al. (2025). Soaring building collapses in southern mediterranean coasts: Hydroclimatic drivers & adaptive landscape mitigations. *Earth's Future*, *13*, e2024EF004883. https://doi.org/10.1029/2024EF004883

Received 7 MAY 2024
Accepted 18 DEC 2024

Author Contributions:
Conceptualization: Sara S. Fouad, Essam Heggy
Formal analysis: Sara S. Fouad, Essam Heggy, Oula Amrouni, Abderraouf Hzami, Nesma Mohamed, Ibrahim H. Saleh
Funding acquisition: Sara S. Fouad, Essam Heggy
Investigation: Sara S. Fouad, Essam Heggy
Methodology: Sara S. Fouad, Essam Heggy

Abstract

The low-lying, arid coastal regions of the Southern Mediterranean Basin, extending over 4,600 km, face daunting sea level rise and hydroclimatic changes due to shifting weather patterns. The impact of these factors on coastal urban buildings and infrastructure must be better understood. Alexandria, a historic and densely populated port city in Egypt representative of several coastal towns in the Southern Mediterranean, has experienced over 280 building collapses along its shorelines over the past two decades, and the root causes are still under investigation. We examine the decadal changes in coastal and hydroclimatic drivers along the city's coastline using photogrammetric satellite images from 1974 to 2021. We explore the interconnectivity between shoreline retreat, ground subsidence, and building collapses. Our results suggest that collapses are correlated with severe coastal erosion driven by sediment imbalances resulting from decades of inefficient landscape management and urban expansion along the city's waterfront. This severe erosion, combined with sea level rise, increases seawater intrusion, raising groundwater levels in coastal aquifers. Degrading ground stability and accelerating corrosion in building foundations ultimately culminating in collapses. 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 propose cost-effective and nature-based techniques for coastal landscape adaptation to alleviate these dangers in Alexandria and other Southern Mediterranean cities facing similar climatic challenges.

Plain Language Summary

We examine the reasons for the rise in structural failures of buildings along the 70 km coastline of the ancient port city of Alexandria in the Southern Mediterranean. The city is internationally recognized for its significant susceptibility to sea level rise. Severe shoreline retreat due to coastal erosion and rising sea levels significantly accelerates seawater intrusion in coastal aquifers, compromising ground mechanical qualities and degrading building foundations. This ultimately results in their failure. Over 7,000 structures adjacent to the old city coastline are at risk of collapse, rendering it the most climate-vulnerable metropolitan sector in the Mediterranean region. Comparable tendencies are noted in other coastal cities in emerging nations undergoing recent hydroclimatic alterations and where mitigation plans have yet to be enacted. We propose cost-effective and nature-based techniques for coastal landscape adaptation to alleviate these dangers in Alexandria and other cities in emerging nations facing similar climatic 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 guarantee liveable conditions and maritime trade, ensuring the continuity of vital supplies across the globe. However, several of these coastlines, notably low-lying arid sandy coasts, are at higher risk of sea level rise, increasing seawater intrusion, and coastal flooding. These threats are exacerbated by land subsidence resulting from the over-

Software: Sara S. Fouad, Essam Heggy, Oula Amrouni, Abderraouf Hzami
Supervision: Sara S. Fouad, Essam Heggy, Udo Weilacher
Validation: Sara S. Fouad, Essam Heggy, Seifeddine Jomaa, Yasser Elsheshtawy, Udo Weilacher
Visualization: Sara S. Fouad, Essam Heggy, Abderraouf Hzami
Writing – original draft: Sara S. Fouad, Essam Heggy, Oula Amrouni, Abderraouf Hzami, Steffen Nijhuis, Nesma Mohamed, Ibrahim H. Saleh
Writing – review & editing: Sara S. Fouad, Essam Heggy, Oula Amrouni, Abderraouf Hzami

exploitation of coastal aquifers (Figure 1a) owing to the increase in the local population and the expansion of aridity conditions. This results in an increased structural instabilities, leading to the failure of buildings along the coast (Ohenhen & Shirzaei, 2022). This phenomenon is mainly observed in developing nations (Post et al., 2018), where increasing numbers of coastal building collapses are reported, averaging over 300 annual fatalities (Dada et al., 2023). However, the hydroclimatic drivers of this increase remain poorly understood owing to a lack of published case studies. Consequently, mitigation measures are out-phased by the magnitude and expansion of these collapses in several coastal cities suffering from the increase in relative sea level rise.

The IPCC's AR6 and MedECC reports designated the Southern Mediterranean Basin, with its expansive 4,600 km-long sandy, low-lying, and arid coastlines extending from northern Tunisia to the east of the Canal of Suez in Egypt, as a hotspot for relative 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, due to the lack of published reports, its impact on coastal building infrastructure remains widely unquantified, let alone understood. From 2014 to 2020, Alexandria topped Mediterranean cities, with 86 buildings that ultimately collapsed and 201 that partially collapsed, resulting in a death toll of 85 inhabitants (Helal, 2022). The origin and drivers of the increasing number of building collapses remain speculative.

Herein, we explore the hydroclimatic and anthropogenic drivers that accelerate building collapse in Alexandria. We offer insights that can be transferred to other low-lying, arid coastal cities that experience similar phenomena. In particular, we explore the correlation between the location and structural characteristics of collapsed buildings and their vicinity to coastal areas experiencing high rates of shoreline retreats. 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 representative of other similar regional coastal cities undergoing increasing shoreline retreats. The degradation of these coastlines has increased their vulnerability to devastating coastal hydroclimatic extremes (e.g., Storm Daniel in Derna in Libya in September 2023, with more than 11,300 life casualties), calling for the urgency of coastal transformation studies in these populous regions to ensure infrastructure resilience to ongoing hydroclimatic changes (Normand & Heggy, 2024). Our results identified several hotspots where adaptive coastal transformations are urgently needed. We propose cost-effective and nature-based solutions to mitigate the root cause of this problem that applies to Alexandria and other Southern Mediterranean cities facing similar climatic challenges, as further discussed in the implications of this study.

2. Study Area: Alexandria

Alexandria is the largest port city 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 if no substantial mitigation measures are undertaken (Hilmi et al., 2022). The urban area of the port city of Alexandria consists of a large town divided into six districts: (a) Al Amreya, (b) Gharb (West), (c) Al Gomrok, (d) Wasat (Middle), (e) Shark (East), (f) 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/km^2 (El-Mallakh, 2020), Alexandria is the most densely populated urban area in the Southern Mediterranean basin.

The Alexandrian coastline is constituted of a succession of sandy beaches and harbors with adjacent dense urban areas that separate the Mediterranean Sea from inland Lake Mariout (Figure 2). The city's total area is 1459.6 km^2, of which the built-up part is 336.3 km^{2,} with the highest concentration observed near the seafront, which is just 0.4 m above sea level (Abd El-Ghani et al., 2017; El-Hattab et al., 2018; Pagnoni et al., 2015). More than half of residential areas are informal settlements (Barakat, 2020). Starting in 2010, several storm surges exceeding 1.2 m above the mean sea level have caused severe coastal flooding and damage to seafront buildings and infrastructure. As medicanes are becoming more frequent due to the warming waters in the eastern Mediterranean Basin, storm surges with devastating impacts are increasingly observed (Abutaleb et al., 2018).

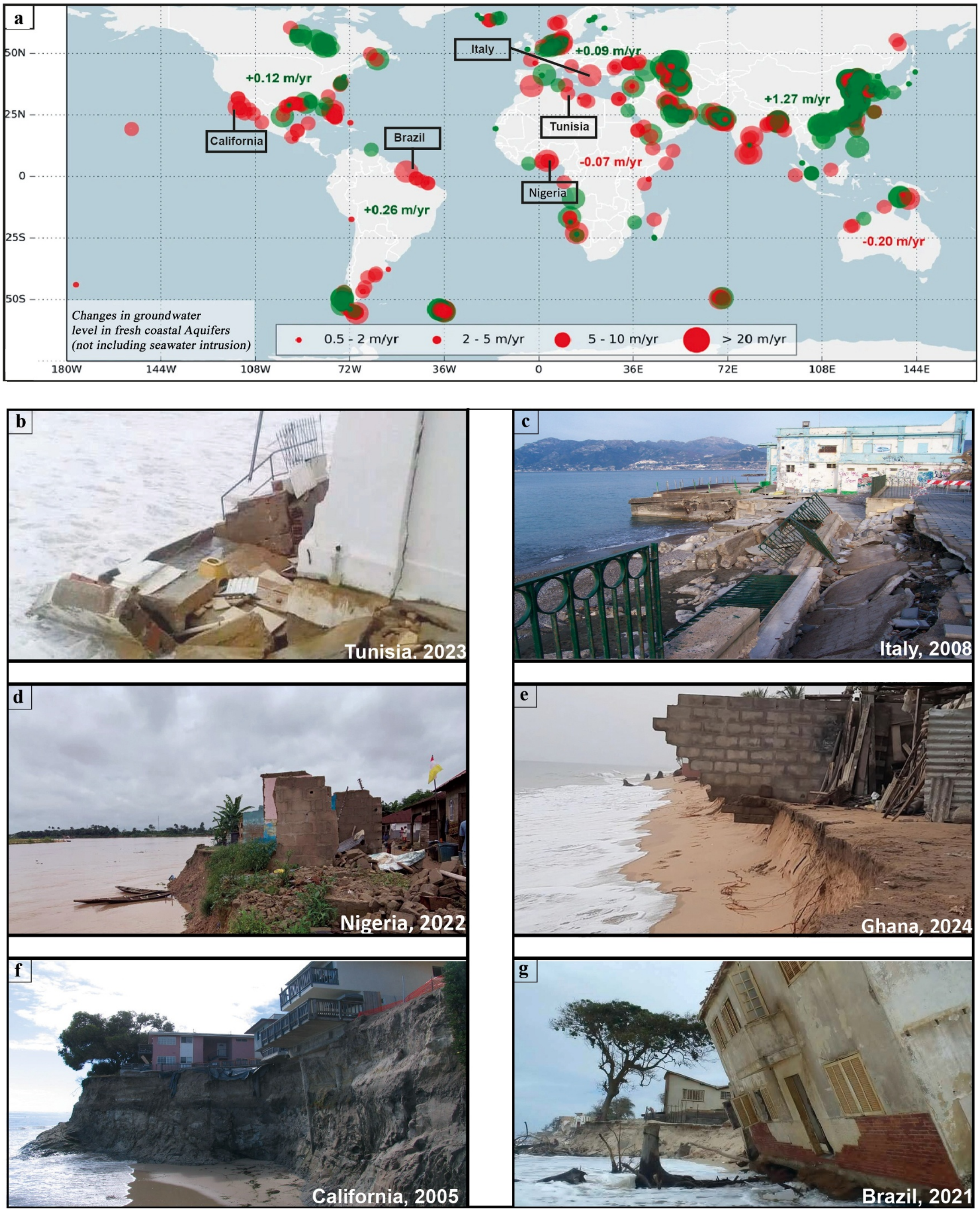

Figure 1. (a) Global map showing the recharge (in green) or discharge (in red) of groundwater level in coastal aquifers near urban areas (Post et al., 2018). Their dynamic resulted in significant structural instability, leading to globally observed damages in coastal buildings as in the cases of Tunisia (b), Italy (c), Nigeria (d), Ghana (e), California (f), Brazil (g) (Benassai et al., 2009; Francis, 2023; Sokpe, 2022; U.S. Geological Survey, 2005). The figure was created using Adobe Photoshop (2019).

3. Global Overview of Coastal Building Collapses

Building collapses on coastlines are globally associated with ground structural instabilities caused by the changes in groundwater levels in coastal aquifers, whether fresh or saline. Figure 1 summarizes the most recent up-to-date assessments of the changes in fresh groundwater levels in coastal aquifers. Notably, collapses in areas of elevated

10.1029/2024EF004883

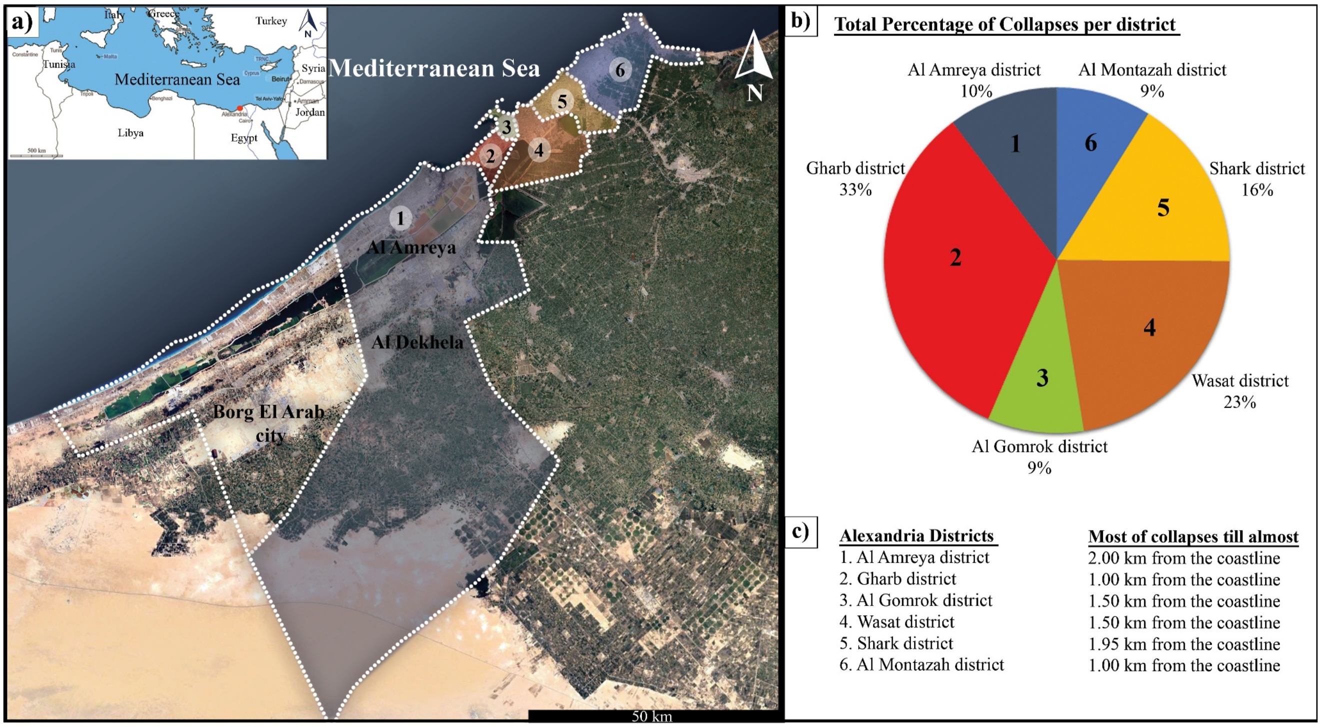

Figure 2. (a) The vulnerability of the six urban districts of the Alexandria Governorate has increased in the last 10 years, where most collapsed buildings are located at a maximum distance of ∼2 km from the coastline. (b) The percentage of buildings that collapse in Alexandria's six districts. A city 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 and 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 using Adobe Photoshop (2019).

changes in aquifer levels in Tunisia, Italy, Nigeria, Ghana, California, Florida, and Brazil are widely observed and summarized below.

In the Southern Mediterranean Basin, notably in Tunisia, coastal municipalities have observed severe structural damage to buildings associated with shoreline erosion (Figure 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, which face heightened erosion risk (Amrouni et al., 2019). A particular concern in these areas is the proximity of tourist structures to the shoreline, often violating regulatory guidelines, leading to 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). Similar patterns were observed in the central part of the Mediterranean Basin in Italy (Figure 1c). Notably, the collapse of coastal buildings in the nation's southern part increased by 9% from 1991 to 2001, when 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 countries such as Lagos in Nigeria, a notable coastal subsidence rate exceeding 4 mm/yr was observed using Interferometric Synthetic Aperture Radar (InSAR) observations from 2018 to 2021 (Ohenhen & Shirzaei, 2022). Land subsidence, associated with coastal aquifer discharge, results in frequent building collapses in the city, delineating an area with heightened susceptibility that affects between 255 and 4,050 structures (Figure 1d) (Ohenhen & Shirzaei, 2022). Similarly, coastal erosion in Accra, Ghana, is an ongoing concern for the stability of the 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 (Figure 1e) (Addo & Addo, 2016). Reports of coastal building collapses in Africa are difficult to assess due to the lack of accessible public records, unreported incidents, and the local authorities often being unable to identify the cause of these structural failures.

10.1029/2024EF004883

In California, San Francisco Bay, sea level rise poses a significant inundation risk to coastal urban areas and infrastructure, where subsidence rates are ~2 mm/yr along most coastal areas, with some locations reaching ~10 mm/yr due to artificial landfills and Holocene mud deposits (Figure 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; Ohenhen et al., 2024). Similar structural failures have been observed along the coastline of Florida. For instance, on 24 June 2021, Champlain Towers South, a 12-story condominium structure in Surfside, Florida, collapsed because of a structural failure. This catastrophic event ranks among the most fatal building collapses in the history of the United States, resulting in 98 confirmed deaths (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, aquifer and sea level records revealed a substantial rise in groundwater levels, exceeding the basement (Parkinson, 2021). Similarly, coastal erosion along the Brazilian resort town of Atafona, north of Rio de Janeiro in the Atlantic Ocean, averaging ~6 m/yr between 1984 and 2016, led to the collapse of 500 houses (Figure 1g) (Pearson, 2023; Valpassos & Cunha, 2023; Vassileva et al., 2021).

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

4. Materials and Methods

4.1. Building Collapse Data Set

Over the past two decades, the port city of Alexandria has experienced over 280 building collapses near its shorelines. Our study generated a holistic Geographical Information System (GIS) data set of the locations and structural characteristics of collapsed buildings in the six districts that form Alexandria's historic urban area (Figure 2). The database was compiled from site visits, government reports, private constructors' published statements, and numerous news archives. The data set assessed the total and partially collapsed buildings from 2001 to 2021.

4.2. Monitoring Long-Term Shoreline Evolution

We used a Digital Shoreline Analysis System (DSAS) to monitor long-term changes in coastline positions. The method is described in Thieler et al. (2009) and implemented using Sentinel 2A scenes for the year 2021 and digitized historical topographic maps (1887, 1959, and 2001). Using this approach, the DSAS algorithm generated cross-shore transects along the coastline of Alexandria. Each cross-shore transect had a length of 1,000 m and a spacing of 50 m. We used ArcGIS Pro to create a GIS-integrated time series with the calculated rate of change statistics, which allows us to visualize and assess how the geometry and position of the coastline have evolved over the last century. Our analysis uses two statistics from the DSAS model: (a) Net Shoreline Movement (NSM), which provides the reported overall separation between older (1887) and current (2021) coastline locations, and (b) End-Point Rate (EPR), which represents the annual rate of shoreline retreat averaged over the last century. The linear regression statistical method was used to quantify the georeferencing process's root mean square error (RMSE). The RMSE is used to quantify the error associated with manual digitization of the map and is not necessarily indicative of its resolution. The observed RMSE 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), that is, ±0.29 m/yr.

4.3. Land Subsidence Analysis

We used the vertical distribution of fallout cosmogenic ^{7}Be to assess the degree of ground relaxation in each of the city's districts. Seventy soil samples were collected from 14 sites to determine the ground mechanical stability across Alexandria. Five samples were collected from five successive vertical soil layers. Each sample was taken from an area of 0.5 m × 0.5 m at a depth of 5 cm.

The cosmogenic fallout radioisotope ^{7}Be was measured using its gamma energy photopeak of 477.6 keV (with a yield of 10.3) by a gamma-ray spectrometer system consisting of a p-type coaxial HPGe with an efficiency of

Table 1
Statistical Shoreline Evolution Analysis for the Beaches of Alexandria, Egypt, During the Periods 1887–2021, 1887–1959, 1959–2001, and 2001–2021

Study site (coast length)	Years	Max EPR	Min EPR	Average EPR	Median EPR	Error EPR	Max NSM	Min NSM	Average NSM	Median NSM	Error NSM
Alexandria (55 km)	1887–2021	−47.36	55.59	1.46	−0.41	0.18	−947.2	1591.09	30.67	−38.57	24.8
	1887–1959	−8.50	17.94	−0.57	−1.39	0.27	−696.75	1471	−46.94	−114.21	14.6
	1959–2001	−23.03	21.48	−0.13	−1.12	0.16	−967.00	902.34	−5.80	−47.08	6.0
	2001–2021	−41.43	56.47	−3.64	−1.9	0.18	−828.55	1129.42	72.97	−72.20	2.5

Note. Net shoreline movement rate (m). EPR: The End-Point 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.

24.5% and a resolution of 1.7 keV at 1.33 MeV. The detector was shielded using a 0.1 m thick cylindrical lead castle with an internal wall made of copper. Gamma-ray spectra were recorded using a PC-based 4096-channel analyzer and processed using Genie-2000 software. The surface distribution of radionuclide levels was used to show that the stability of the studied lands correlated with a high rate of building collapse.

5. Results

5.1. Rapid Shoreline Evolution

Recent changes in the coastal dynamics 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 & El-Magd, 2016). The latter increases salt intrusion into shallow coastal aquifers a few kilometers inland, negatively affecting soil quality and moisture levels (Zhongming et al., 2021). The shoreline retreat and excessive groundwater abstraction further aggravate seawater intrusion, leading to more saline intrusion into coastal aquifers and building foundations (Abd-Elhamid, 2010; Amrouni et al., 2019). Therefore, understanding the evolution of shorelines is crucial for assessing their impact on collapsed 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 in the 1950s, we can subdivide the temporal period assessment into natural and human-induced scales. As mentioned in Table 1, the calculated NSM based on the DSAS tool of Alexandria's districts varied from the eastern to the 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 EPR of −0.57 and −0.13 m/yr, respectively.

However, between 2001 and 2021, the Alexandria coast experienced a severe erosion rate with an average EPR of −3.64 m/yr, as shown in Table 1. The spatial extent of the impact of coastal erosion differs widely among the different urban districts (Figure 3). The most affected districts by the extreme erosion are localized on the western coast along the Gharb district with a maximum value of the EPR of −31.13 m/yr and on the eastern shore along the Al Montazah district with an EPR of −10.9 m/yr (Figures 4 and 5). 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 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 4.

5.2. Decadal Increase in Coastal Building Collapses

Coastal building collapses in Alexandria have been increasingly observed over the last two decades, with 117 collapses occurring between 2013 and 2015 compared to just one collapse between 2001 and 2004 (Figure 6) (Daftar Ahwal Cairo-based Research Institute (DADRI), 2020; Helal, 2022; Seif Eddin, 2021). Our mapping of these collapses shows that the most significant number occurred in an area of the Gharb district, ∼1 km from the coastline. The second is the Al Gomrok district, with the region witnessing collapses located ∼0.80–1.50 km from the coast. The third is the Wasat district, where areas undergoing collapse are located within the first 2 km of the coastline. The newly built residential communities in the Al Amreya district, ∼1–2 km away from the coastline,

10.1029/2024EF004883

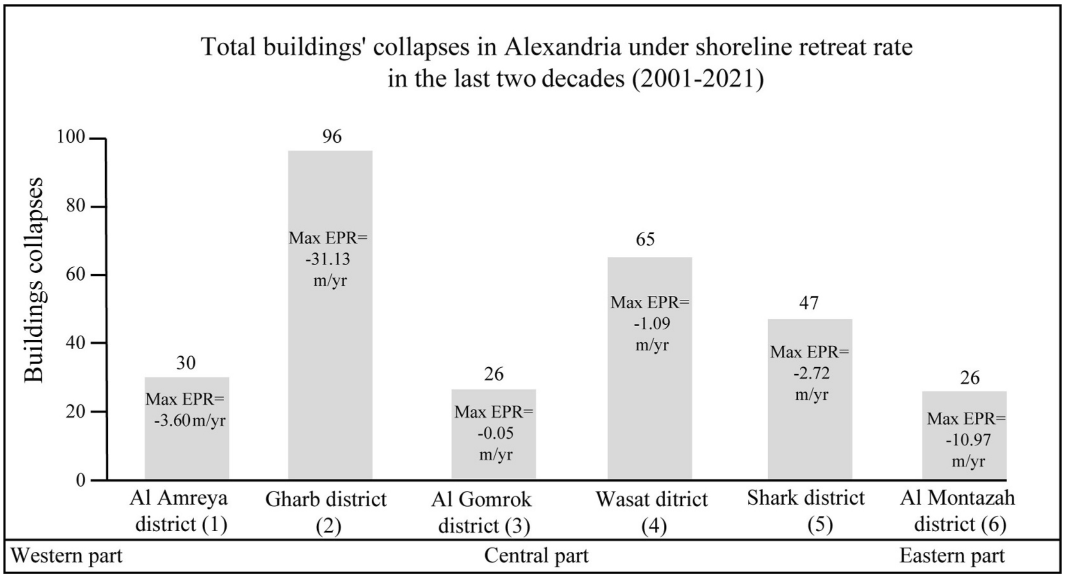

Figure 3. Relationship between building collapse and shoreline rates (Maximum End-Point Rate (EPR) = ±018 m/yr) during the 2001–2021 period in Alexandria, Egypt. The observed erosion rates are classified according to Esteves and Finkl (1998): accretion (>0.5 m/yr), stable (0.5 to −0.5 m/yr), erosion (−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. The figure was created in Adobe Photoshop (2019).

also witnessed several collapses, representing ∼11% of Alexandria's total building collapses over the last 20 years (Figure 2b).

Earlier studies have suggested that the lack of maintenance of old buildings, inefficient landscape transformation, urban expansion, and lack of wastewater infrastructure are the main factors accelerating the successive collapse of city buildings (Abd El Sabour, 2009; Abdelnaser, 2014). Moreover, deficiencies in construction regulations and legislation concerning the designation and execution of buildings are regarded as crucial reasons for property damage and consequent collapse (Abdelnaser, 2014). However, these factors are common to all city constructions and other cities across Egypt, where less collapses have been observed. Consequently, they cannot explain the geographical distribution of the collapse alone, as shown in Figure 3, where the vicinity of the coastline is correlated with the highest number of events. Therefore, the impact of decadal changes in coastal dynamics on the corrosion of building foundations is valid. We also observed that beach erosion enables seawater intrusion into 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 corrosion-induced failure (Setiawan et al., 2022). Furthermore, the increase in medicanes and their associated storm surges can also play an essential role in further corroding the foundations along Alexandria's coastline, ultimately increasing the risk of building collapses.

Another factor that can be considered is the continuous subsidence and ground settlement in some parts of the city, mostly land reclamation. This causes excessive differential deformation of the building foundations and infrastructure, thereby increasing the structural risk. Ohenhen et al. (2024) assess the vulnerability of coastal communities on the US East Coast to subsidence. Their findings indicate that significant portions of land, as well as populations, properties, and infrastructure, are exposed to subsidence rates ranging from 0.1 to 0.2 cm per year, necessitating proactive mitigation and monitoring strategies. The collapse of the Champlain Towers South in Surfside, Florida, highlighted various factors that can lead to coastal building failures, including structural design flaws and changing hydroclimatic conditions. The National Institute of Standards and Technology (NIST) pointed to water leaks from the pool deck as a significant issue. At the same time, finite element analysis uncovered other critical environmental factors (Zhu & Isobe, 2022). These incidents illustrate the complexity of coastal building failures and underscore the need to thoroughly examine structural weaknesses and environmental influences. A new comprehensive approach to building safety and maintenance is urgently needed to cope with the changing hydroclimatic conditions in several coastal areas (Simons et al., 2022).

Figure 4. (a) Spatio-temporal assessment of shoreline movement during the last century in years 1887, 2001, 1959, and 2021 on the western coast of Alexandria City; (1) Al Amreya district, (2) Gharb district, and (3) Al Gomrok district. (b, c) Degradation of the shoreline in Al Shatby on the western coast (from 1935 till 2022). The Integrated map and figure were created in Adobe Photoshop (2019) and ArcGIS Pro (2023).

Beyond the cases on the US East Coast, prolonged and often unnoticed ground subsidence threatens urban areas, as observed in Maceió, Brazil, where a ∼200 cm cumulative subsidence near the Mundaú Lagoon coast has been observed due to salt mining, emphasizing the need for long-term monitoring and numerical modeling integration (Vassileva et al., 2021). In Recife, Brazil, Persistent Scatterer Interferometry analysis identified subsidence rates of ∼1.5 cm/yr in areas with new construction, highlighting urban development's impact (Souza et al., 2023). Sentinel-1 IW InSAR data from 2014 to 2020 revealed subsidence rates of ∼4 cm/yr in Mexico City due to groundwater extraction, particularly in areas with compressible, clay-rich deposits, causing surface faulting and fracturing, endangering over 1.5 million inhabitants (Cigna & Tapete, 2021).

Environmental factors such as air pollution, waterway contamination, and changes in air humidity can also adversely affect the structural resilience of coastal buildings in the city. Furthermore, current inefficient management strategies for the Alexandria waterfront and institutional settings have limited contributions to urban resilience, and overlaps and conflicts between these institutions are due to ineffective management strategies (Fouad et al., 2023). However, the impacts of hydroclimatic change are potentially interwoven with the above factors and, if left unaddressed, would amplify the existing migration trends in urban areas (Czaika & Reinprecht, 2020).

Figure 5. (a) Spatio-temporal assessment of shoreline movement during the last century in the years 1887, 1959, 2001, and 2021 in the eastern coasts of Alexandria City. (4) Wasat district, (5) Shark district, (6) Al Montazah district, (b, c) Regression of the coastline in Sidi Bishr near the Al Montazah district (from 1935 till 2022). The Integrated map and figures were created using Adobe Photoshop (2019) and ArcGIS Pro (2023).

5.3. 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 essential role in assessing the causes of collapse. The primary building material for standing structures is concrete for contemporary structures and limestone blocks for older structures (Khalaf & Abdel-megeed, 2018). This is because both the construction materials are abundant, cost-effective, and easily accessible to the surrounding environment. For instance, the northern coast of the Egyptian western desert includes limestone collected from several locations close to the city. Limestone is also used in the cement industry as an essential component in concrete fabrication and building blocks for older bearing wall systems. Concrete residential buildings usually range from 6 to 15 floors, whereas load-bearing limestone wall structures typically range from 1 to 6 floors in height (Ali & Yang, 2014).

The old downtown area of Alexandria is composed of two districts, Gharb and Al Gomrok. The ground in these two districts comprises a historic silty, alluvial, and sandy layer overlying the limestone (Zayed et al., 2020). Significant seawater intrusion has been observed in these coastal areas because of increased groundwater extraction for irrigation and domestic supply (Mahmoud, 2019). Furthermore, owing to groundwater overexploitation, seawater intrusion into coastal aquifers has caused clayey alluvial soils to destabilize because of the rise in brackish water. This results in heightened land subsidences, local topographic deformations, and

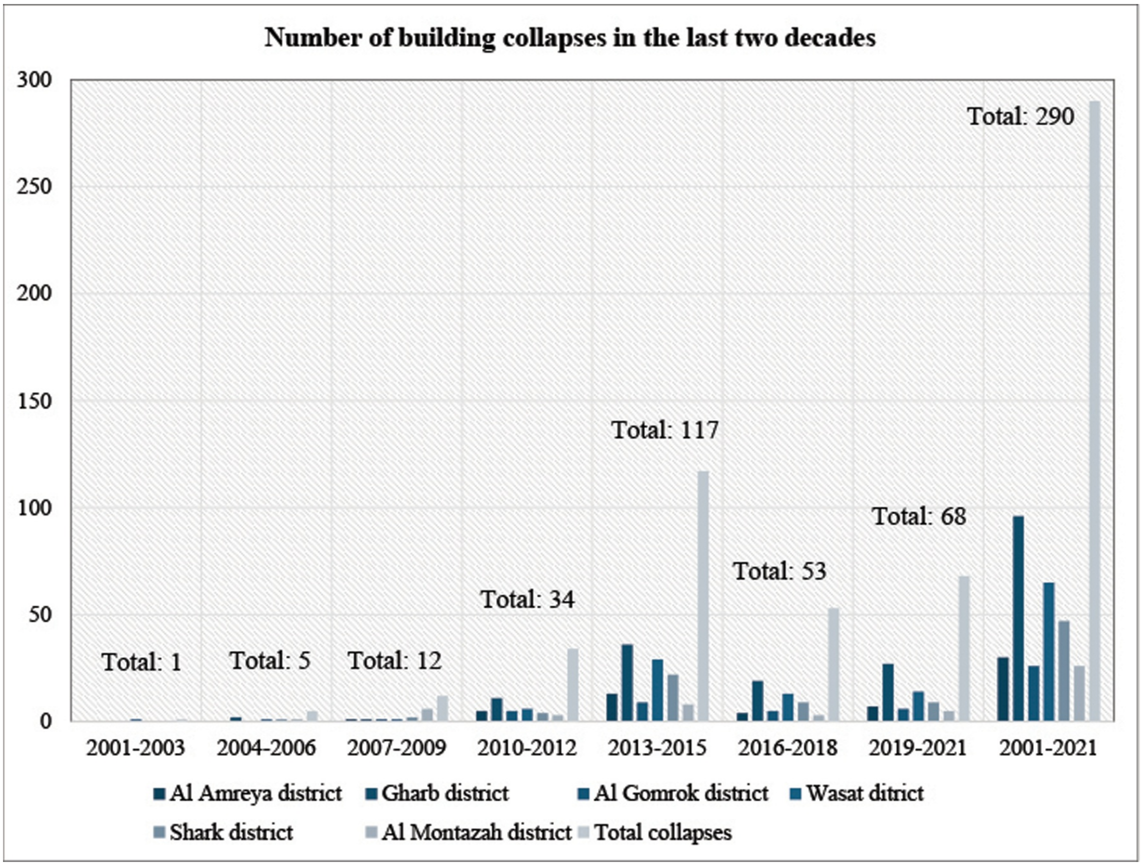

Figure 6. The evolution of building collapses in the last two decades has revealed anthropogenic and natural degradations, including a lack of management implementation and coastal erosion, and the impact of several storm surges of 1.2 m above = sea level (typical of the North coast: 0.4–0.5 m), resulting in coastal flooding and damage to coastal structures in December 2010, January 2011, and October 2015. The number of collapsed buildings in Alexandria indicates an increase in building collapse rates after 2011, which is equivalent to 96% of the total number of building collapses throughout the last two decades when the social unrest allowed numerous landowners to build houses without permission in slums and agricultural lands, violating constructions legislations. According to official reports, Alexandria is among the top cities with illegal buildings, with 14,521 without licenses. Source: (El-Sheikh, 2016; Daftar Ahwal Cairo-based research institute (DADRI), 2020; Helal, 2022). The figure was created in Microsoft Excel (2018).

karstifications, such as sinkholes and central cavities (Werner & Simmons, 2009), substantially damaging buildings and infrastructure. The multiplication of damaged buildings in these areas and the high cost of their rehabilitation have caused many inhabitants to abandon structurally damaged buildings and relocate to new urban areas further inland (Sušnik et al., 2015).

Foundation systems for low-rise concrete buildings often include shallow, isolated footings. Pile caps and raft systems are typically used in high-rise buildings. In contrast, bearing wall system foundations include isolated concrete footings for medium-rise buildings and block footings for shorter buildings (Magbool & El-Abbasy, 2021). As such, the increase in recently built multiple-story buildings in downtown areas exposes their deeper foundations 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 continuous landfilling to curb sea-level rise over the last 3,000 years. This is reflected in the fact that historic structures are always affected by the increase in underground water surrounding their foundations and its corrosive effect over time, which impacts the stability of the buildings (Figures 4 and 5). Thus, cracks were 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 has also been observed in recent higher buildings built illegally on shallow foundations. The case of these recent multiple-story buildings in the old downtown area is even more critical, as brackish groundwater continues to rise due to seawater intrusion, causing accelerated corrosion of the foundation by the chemical reactions between cement and seawater, leading to a quicker deterioration of such materials (Ragab et al., 2016).

5.4. 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 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). Over extended periods, ranging from centuries to millennia, land subsidence in Alexandria's coastal region is primarily driven by tectonic forces such as earthquakes and gravitational collapse resulting from fault movements. On shorter timescales spanning decades to centuries, subsidence rates are likely to be steady and moderate, aligning with the thickness of the sediment and compaction. Notably, the Nile Delta coastal plain should not be viewed as a single entity regarding land subsidence, mainly because of its pronounced northeast tilting (Wöppelmann et al., 2013).

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 (Hzami et al., 2021). The latter can be aggravated by potential flow reduction from upstream damming and prolonged droughts (Heggy et al., 2024). We observe a correlation between the coastline regression as caused by the sediment unbalance and the collapse of coastal buildings where the most affected Gharb district undergoes a maximum EPR of -31.13 ± 0.18 m/yr, account for ∼96% of the total number of building collapses in Alexandria between the years 2001–2021. As most of Alexandria's study zones are entirely managed by maritime structures, coastal sediment input driven by longshore drift, mainly from the northwest to southeast, has been completely trapped in 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.

Currently, Alexandria is experiencing one of the highest rates of ground subsidence in Africa (GNSS, 2024). Our study conducts a parallel investigation to assess the ground stability across the city by measuring the relaxation depth h_0 (cm), which is defined as the distance from the ground surface to the depth above which 63.2% of the total fallout radionuclide inventory resides. The relaxation depth is an indicator of the ground stability (Saleh et al., 2024). The latter, in turn, depends on the compressibility of the ground, which is affected by seawater intrusion due to shoreline retreat (Taylor et al., 2019). The h_o values are obtained by measuring the subsurface concentration of ^{7}Be isotope particles in each district. In each district, ^{7}Be levels for five subsurface ground layers were fitted using Equation 1 to calculate the h_o for each district.

$$C_X = C_O\, e^{-\alpha x} \tag{1}$$

where C_x (Bq/kg^{-1}) is the ^{7}Be concentration at relaxation depth (x, cm), C_o is the activity concentration in the top ground layer, and α (cm^{-1}) is the coefficient of the vertical distribution.

The relaxation depth h_0 (cm) is defined as:

$$h_o = 1/\alpha \tag{2}$$

The average relaxation values of the ground for each district are shown in Figure 7a. The relaxation values ranged from 2 cm in the Al Amreya and Al Montazah to the highest values of 7 and 6 cm in the Gharb and Wasat districts, respectively. In comparison, the Shark district recorded a relaxation of 4 cm. High relaxation values were observed in the districts with highly collapsed buildings.

The effects of ground erosion on construction are significant because they destabilize building foundations, increasing the need for repairs. The latter is increasingly unaffordable by inhabitants because of the worsening economy with increased inflation and the rising cost of building materials (Ghaly, 2022), which increases the number of abandoned houses and the homeless population once these buildings collapse or become uninhabitable (Gyamfi-Aidoo, 1987). Furthermore, during winter, rainwater drainage causes an increase in groundwater levels, in addition to the effect of seawater intrusion. The increased frequency and amplitude of eastern Mediterranean storms may lead to further shoreline recession and seawater intrusion, deteriorating the city' building foundations. For instance, studies conducted on Alexandria' ground stability using radioisotopes (^{7}Be and ^{137}Cs) in the short

10.1029/2024EF004883

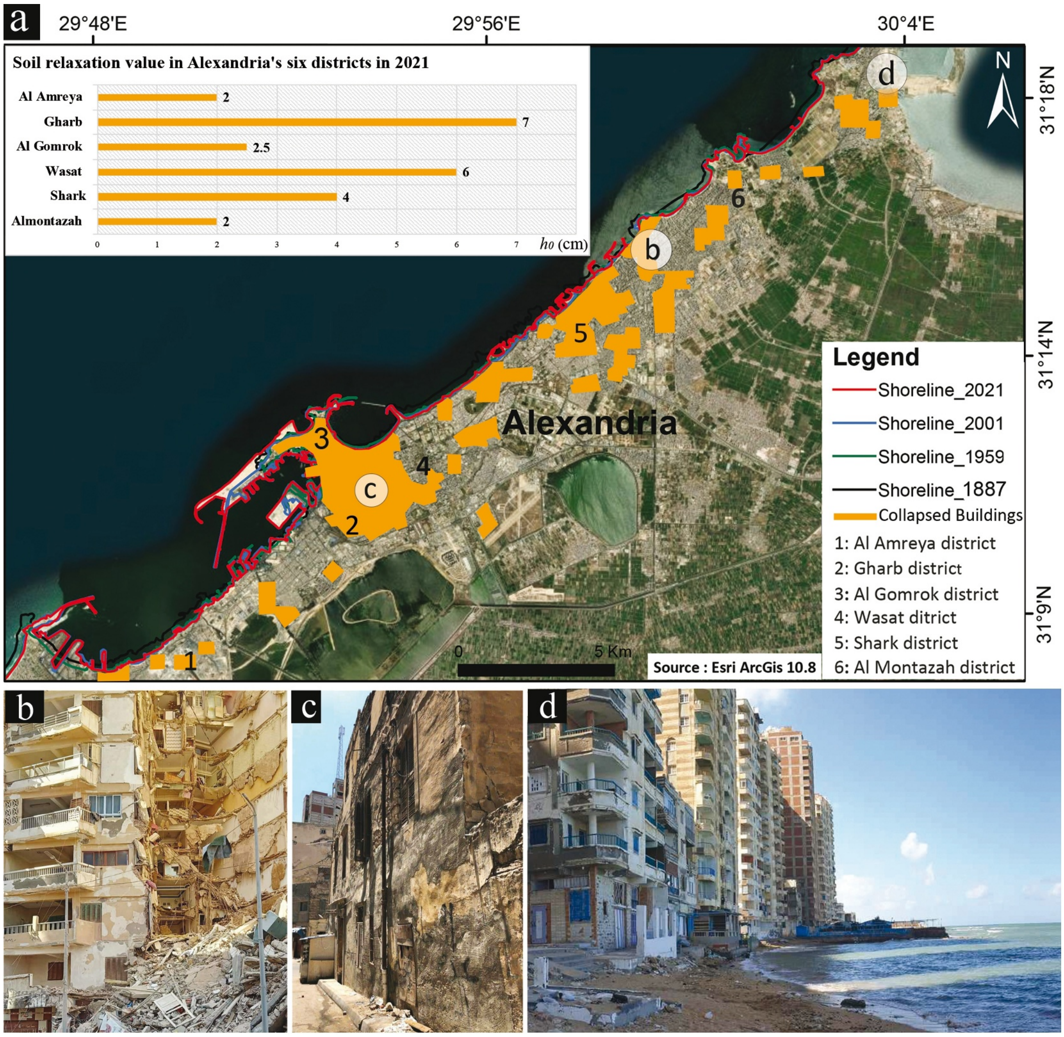

Figure 7. (a) Spatio-temporal assessment of the shoreline movement during the last century in 1887, 1959, 2001, and 2021 on the eastern coasts of Alexandria City and the locations of partially/totally collapsed buildings in the areas used for ground validation. The analysis showed differing ground relaxation measurements across the six districts. The Al Amreya and Al Montazah had the lowest values at 2 cm, whereas the Gharb and Wasat districts recorded the highest at 7 and 6 cm, respectively. The Shark district had an intermediate value of 4 cm. Importantly, districts with more collapsed buildings also had higher ground relaxation values. (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 and figure were created in Adobe Photoshop (2019), ArcGIS Pro (2023), and Microsoft Excel (2018).

and long term showed that most of the city's terrain suffers from severe erosion that exceeds the average of other coastal cities in Egypt (Saleh et al., 2024).

6. Discussion

As the port city of Alexandria is the most populous coastal urban area in the Mediterranean basin, its increased vulnerability to relative sea level rise and increased storm surges has local and regional socioeconomic consequences, including the disruption of maritime routes due to its proximity to the Suez Canal, one of the world's busiest shipping routes. As such, it is crucial to mitigate its coastal vulnerability induced by the rising hydro-climatic fluctuations in the eastern Mediterranean basin. The latter requires an adaptive, sustainable, and cost-effective coastal transformation along the city's 70-km-long waterfront with different risk levels, which must be considered in future planning processes. In the early 2000s, Egypt initiated an Integrated Coastal Zone

Management (ICZM) plan for the entire Mediterranean coast. The plan was 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 has never been implemented because of decision-makers' perception that hydroclimatic extremes are occasional and rare events, and therefore, such investment is not a priority (UNEP/MAP/PAP, 2008). This perception has been recently questioned due to the increased frequency of storm events in the Southern Mediterranean Basin over the last 20 years.

There are five main adaptation approaches for mitigating Alexandria's rising coastal erosion and submersion risks: hard protection, soft protection, accommodation, ecosystem-based adaptation, and managed retreat (Bongarts et al., 2021).

The first approach is the hard protection, or "gray infrastructure" advance responses, 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 because of their high cost, aesthetic attributes, and environmental impact (Esteban et al., 2019; Hinkel et al., 2018). However, hard protection also involves creating artificial land above sea level. It is particularly advantageous in densely populated areas, such as Alexandria, because it can provide accessible new sites for development that are already connected to the urban fabric (Alves et al., 2020). Nevertheless, this approach can be detrimental to coastal ecosystems and habitats (Warner et al., 2018), contributing to "ocean sprawl" and ecological disruption (Bishop et al., 2017).

The second approach involves soft protection, including dune rehabilitation and beach nourishment (Amrouni et al., 2024). It allows for a more dynamic coastal response (Van Rijn, 2011) and is considered an environmentally friendly alternative to hard protection. However, the cost of implementing sand nourishment can be prohibitive for large areas because 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 in most of Alexandria's seafronts.

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 various urban planning and architectural solutions such as elevating buildings, reinforcing foundations, and developing floating structures (Trang, 2016). However, these solutions require significant resources, are in the experimental phase for 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 using natural coastal ecosystems for protection (Cheong et al., 2013). Although this approach is cost-efficient and effective in attenuating waves and reducing the impacts of coastal hazards caused by increased storminess, its implementation in areas with high aridity and fluctuating hydroclimatic conditions, such as Alexandria, remains challenging (Gao et al., 2020). Additionally, ecosystem-based adaptation may pose risks of introducing invasive species that must be carefully evaluated, as they can affect fishing activity (Rinde et al., 2016), one of Alexandria's pillars of food security. Recent examples of ecosystem-based mitigation approaches in urban coastal environments have shown the potential to develop adaptive, social-ecological inclusive solutions (Nijhuis et al., 2023; van Bergen et al., 2021). These examples highlight the need for multiscale planning strategies and design principles that consider the natural landscape as a foundation for working with natural processes, fostering socially and ecologically inclusive and resilient urban coastal landscapes (Nijhuis, 2022).

Finally, managed retreat involves the strategic relocation of infrastructure and populations from high-risk coastal areas (Hauer, 2017; Hilmi et al., 2022). Although it is potentially the most effective method for submersion risk mitigation (Haasnoot et al., 2021), it is often socially controversial and involves 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 area is bordered to the south by Lake Mariout. Hence, any relocation will result in the distribution of a portion of the population and infrastructure, which may be socially unacceptable for city inhabitants who have a strong cultural attachment to the coastline.

10.1029/2024EF004883

Figure 8. Mitigation procedures are currently being implemented in Alexandria: (a) beach nourishment supported by dikes and groynes in the western port and Abou Qir port, with areas of 176,000 m^2 and 56,655 m^2, respectively. (c) In 2019, local authorities invested $14 million in dropping 4,700 concrete blocks around the historic fortress of the Gharb district to protect it from waves of coastal erosion. The figure was created using Adobe Photoshop (2019).

Various U.S. and European cities have successfully implemented managed retreat strategies with differing levels of public acceptance and execution (Bragg et al., 2021). For instance, French policies have successfully demonstrated the need for an anticipatory and learning approach to managing retreats (Rocle et al., 2021). A similar effort is urgently needed in Alexandria to anticipate unavoidable population displacements from high-vulnerability areas, where coastal damage may become irreversible given the currently available technical solutions and resources for implementation.

All the above adaptation strategies require the active and coordinated involvement of municipalities, landowners, citizens, and government entities, which is unfortunately absent in Alexandria and for most highly populated coastal cities in the Southern Mediterranean Basin. The participation of 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 also socioeconomically.

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 adaptation strategy. As such, an adaptative landscape-based coastal mitigation approach is paramount to address Alexandria's coastal challenges while considering the complex morphodynamic 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 varies substantially along the coastline from one district to another (Figure 7a), each localized mitigation approach must be weighted by the amplitude of the observed coastal degradation. Currently, the coastal rehabilitation of Alexandria is witnessing excessive implementation of hard protection responses, where wave breakers are installed along the coasts of the Wasat, Shark, and part of the Al Montazah districts (Figure 2a), where the highest rate of shoreline retreat and building degradation was observed, as shown in Figure 4a. Although hard protection offers immediate shoreline stabilization, it is relatively expensive and negatively affects the coastal environment and the city's 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 8b. Nevertheless, pursuing this option involves technical and financial commitments to beach nourishment for perpetuity (McDougall, 2017).

7. Adaptative Landscape Mitigations

In addition to ongoing hard and soft protection measures, the development of natural coastal landscape solutions should be encouraged, facilitating the design, planning, and management of public spaces that enhance public connectivity to the maritime environment (e.g., Fouad & Sharaf Eldin, 2021; Fouad et al., 2023), which, in turn, will increase awareness of hydroclimatic extremes and support efforts to address the multifaceted aspects of coastal degradation. In urban landscape development, living shorelines, sand engines, wave breakers, bioswales, rain gardens, infiltration and exfiltration trenches, and constructed wetlands can be tested, particularly in the

10.1029/2024EF004883

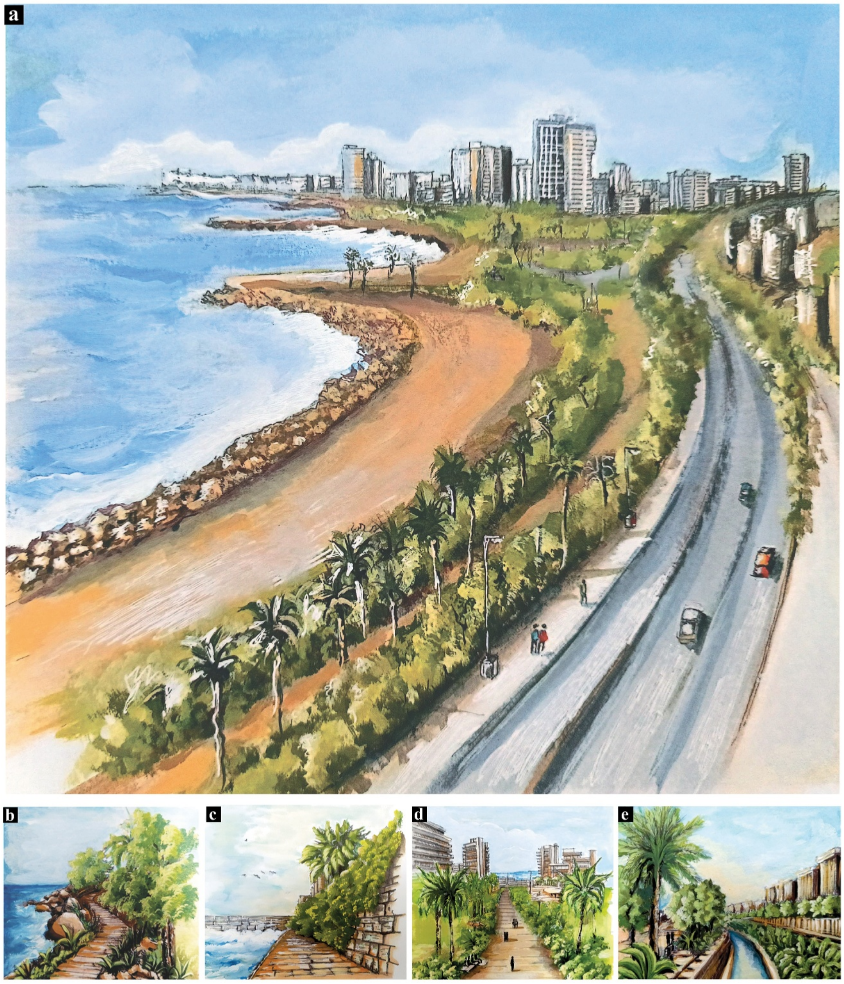

Figure 9. (a) The conceptualization of spatial hybridization approach for future adaptive coastal landscape mitigations, based on the criteria listed in Section 7, the strategy should include maintenance, enhancement, or restoration of a green belt along Alexandria's coastline. (b) Around 10 km of new coastal and waterfront parks stretching from the 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 is hand-drawn and assembled using Adobe Photoshop (2019).

coastal communities of Alexandria. Moreover, lessons learned from other port cities facing similar challenges demonstrate how systemic, integral, and multilayered solutions across scales can be achieved for coastal protection. This involves designing solutions that consider the morphodynamic 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 defense," "ecosystem-based adaptation," and "accommodation strategy" can be implemented (Figure 9a) (Climate Institute, 2019). A new green street system that includes high-tide gardens and salt-tolerant landscapes is proposed along the coastline of the city, as shown in Figure 9. During high tides, these saltwater landscapes serve as "bio pumps" as long-rooted, phreatophytic trees transport significant amounts of water, thereby controlling hydraulics, 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 the building foundation. Consequently, it is essential to connect the main coastline green street to the inner-city fabric through green-blue infrastructure and enhance the quality and functionality of waterways by connecting the inner city to the seashore (Fouad et al., 2022). Implementing these ecological principles and green solutions will enhance stormwater infiltration and better control the 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, thereby improving their awareness of the risks associated with sea level rise and hydroclimatic fluctuations (Figure 9). Currently, only those living on seafronts have this awareness (Fouad et al., 2023). Implementing soft defense in the Gharb district efficiently decreases seawater intrusion, as the district witnessed the highest decadal value of shoreline retreat and the highest record of building collapses in the last two decades. The accommodation strategy should be applied in densely populated the Al Gomrok, Shark, and Wasat districts by adapting existing infrastructure to mitigate rising sea levels. The Al Amreya can employ a managed retreat strategy as a newly urbanized district. This process includes soft-engineered solutions that can be gradually applied as part of a "rewilding" design approach for public and private properties. It involves redesigning infrastructure, streets, and buildings, as well as implementing major infrastructure upgrades. As a result of the transition to more water-based transportation systems, new building typologies featuring raised platforms for living and submerged living units can be developed.

A comprehensive and transformative foresight of Alexandria's waterfront, as shown in Figure 9a, is required to create an open and accessible space that promotes urban resilience against hydroclimatic fluctuations. 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 against storms, and connect Alexandria's inner-city fabric to its parks and waterfront assets. These solutions, shown in Figures 9b–9e, 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 defense 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 resist breaking waves. Wooden pillars must support the first ridge of the coastal buildings to enhance the coastal dynamics under the structures. They should be constructed along the entire waterfront, from the Al Amreya to Al Montazah. The risks of coastal flooding in lowlands in the Gharb and Al Gomrok districts can be mitigated by using ~2 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, thereby avoiding groundwater level rise to buildings' foundations in these districts, which account for 40% of the total building collapse in the city.

Furthermore, a managed retreat is the most sustainable soft management in the Shark and Wasat districts. For this purpose, green and blue spaces can be integrated with recreational areas and waterfront living concepts to create multifunctional 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 scenic and functional spaces for the community.

Future research incorporating the temporal dimensions of the architectural structures in Alexandria promises to refine the results of this study. Furthermore, a proper understanding of the ground 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 focused on Alexandria, the lessons learned to mitigate the increase in coastal building collapses as a consequence of sea level rise can be applied to several Mediterranean cities in North Africa, as well as within the eastern coastlines of the Arabian Peninsula, thereby offering a broader perspective on mitigating the risks associated with building collapses through informed coastal engineering and coastal landscape adaption planning strategies.

8. Limitations and Path Forward

While our study provides an initial assessment of the hydroclimatic drivers contributing to the rise in coastal building collapses in the Southern Mediterranean basin, there are limitations regarding the data insufficiency, which constrains the ability to fully resolve ambiguities in the observed trends. In particular, the limited availability of GIS urban databases, InSAR assessment of subsidences, and groundwater monitoring wells, which are not currently available but would further improve the confidence in our analysis. Furthermore, available governmental data are scarce on the precise numbers and locations of collapsed buildings in Alexandria and the associated fatalities. Additional measurements of coastal erosion rates across various timescales are necessary to modulate building collapses throughout the city.

Future investigation should focus on improving hydroclimatic data's spatial and temporal resolution across the Southern Mediterranean coasts. Establishing more comprehensive monitoring networks, particularly for sea level rise, storm surge, and coastal erosion, would enhance the accuracy of predictions and facilitate better identification of vulnerable regions. Building a coastal urban structural model that accurately forecasts future collapsing risks under different sea level rise and coastal erosion scenarios is crucial for understanding the future implications of climate change on coastal infrastructure in this area. Future research should prioritize short and mid-term projections, particularly regarding sea level rise, increased storm intensity, and other hydroclimatic factors, to develop more robust adaptive strategies for building resilience. Prospect studies should also explore methods to integrate community engagement in adaptive landscape strategies. Educating coastal populations about the risks posed by hydroclimatic factors and involving them in mitigation planning could enhance resilience efforts and support the sustainability of the interventions.

9. Conclusion

The coastal city of Alexandria is a fundamental case study that is representative of the rising hardship of Southern Mediterranean cities under the continuous rise in coastal erosion, sea levels, and increases in hydroclimatic changes. Cities with substantial informal coastal settlements, unstable buildings, and inefficient infrastructure rapidly deteriorate and collapse near the shoreline due to the increased corrosion in their foundations due to continuous seawater intrusion and its impacts on rising groundwater levels in coastal aquifers. Our assessment of the amplitude of shoreline retreats along the city's 70-km long coastline reveals that districts with higher rates of building collapse over the past two decades are closer to the coastline. Severe shoreline retreat has been observed to increase seawater intrusion in these areas, triggering a rise in groundwater levels in coastal aquifers, reaching building foundations, accelerating their bottom-up corrosion, generating ground structural instability, and causing their collapse. Incorporating a hybrid coastal mitigation approach that combines landscape and nature-based solutions will be crucial for tackling the impacts of increased extreme hydroclimatic events and sea level rise in Alexandria and the Southern Mediterranean that, if unaddressed, can cause more alarming building collapse patterns. The adaptive landscape approach has considerable potential to meet the rising challenges of low-lying coastal cities while meeting environmental, economic, and social constraints at local scales. The lessons learned in this analysis apply to other port cities in developing nations in North Africa and other arid areas that share the same hydroclimatic and socioeconomic setup as Alexandria and call for more detailed studies to meet their national commitments to address the ongoing rapid coastal degradation associated with climate change impacts.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

This study synthesizes published reports on building collapse. All data used in this investigation are openly available in 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 is made available in the Center for Open Science Repository Fouad (2024). Figures were generated using the Adobe Inc. (2019), Esri (2023), and Microsoft Corporation (2018).

Acknowledgments

This research was funded by the Zumberge Research and Innovation Fund of the University of Southern California, which is allocated to the Arid Climates and Water Research Center (AWARE). Part of this work was also funded by the National Aeronautics and NASA Jet Propulsion Laboratory. Graduate student Sara Fouad was partially supported for this research by the Alexander Von Humboldt Foundation and the Technical University of Munich, Germany.

References

Abd El-Ghani, M. M., Huerta-Martínez, F. M., Hongyan, L., & Qureshi, R. (2017). *Plant responses to hyperarid desert environments* (pp. 473–501). Springer International Publishing.

Abd-Elhamid, H. F. (2010). *A simulation-optimization model to study the control of seawater intrusion in coastal aquifers* (PhD Thesis). University of Exeter.

Abdelnaser, A. (2014). Criminal responsibility for construction workers: A comparative study. Dar Al-Faker and Law.

Abd El Sabour, M. (2009). *Maintenance of residential buildings in Egypt: The current situation and the future* (Ph.D. Thesis). Faculty of Engineering: Ain Shams University.

Abutaleb, K. A. A., Mohammed, A. H. E.-S., & Ahmed, M. H. M. (2018). Climate change impacts, vulnerabilities and adaption measures for Egypt's Nile delta. *Earth Systems and Environment*, *2*(2), 183–192. https://doi.org/10.1007/s41748-018-0047-9

Addo, K. A., & Addo, I. A. (2016). Coastal erosion management in Accra: Combining local knowledge and empirical research. *Jàmbá: Journal of Disaster Risk Studies*, *8*(1), 1–10. https://doi.org/10.4102/jamba.v8i1.274

Adobe Inc. (2019). Adobe Photoshop [Software]. https://www.adobe.com/products/photoshop.html

Ali, E. M., & El-Magd, I. A. (2016). Impact of human interventions and coastal processes along the Nile Delta coast, Egypt during the past twenty-five years. *The Egyptian Journal of Aquatic Research*, *42*(1), 1–10. https://doi.org/10.1016/j.ejar.2016.01.002

Ali, M. A. M., & Yang, H.-S. (2014). A study of some Egyptian carbonate rocks for the building construction industry. *International Journal of Mining Science and Technology*, *24*(4), 467–470. https://doi.org/10.1016/j.ijmst.2014.05.008

Alves, B., Angnuureng, D. B., Morand, P., & Almar, R. (2020). A review on coastal erosion and flooding risks and best management practices in west Africa: What has been done and should be done. *Journal of Coastal Conservation*, *24*(3), 38. https://doi.org/10.1007/s11852-020-00755-7

Amrouni, O., Heggy, E., & Hzami, A. (2024). Shoreline retreat and beach nourishment are projected to increase in Southern California. *Communications Earth & Environment*, *5*(1), 274. https://doi.org/10.1038/s43247-024-01388-6

Amrouni, O., Hzami, A., & Heggy, E. (2019). Photogrammetric assessment of shoreline retreat in North Africa: Anthropogenic and natural drivers. *ISPRS Journal of Photogrammetry and Remote Sensing*, *157*, 73–92. https://doi.org/10.1016/j.isprsjprs.2019.09.001

Ballinger, R. C. (2003). Coastal defences: Processes, problems and solutions. *Environmental Conservation*, *29*(4), 540–546. https://doi.org/10.1017/S0376892902270393

Barakat, P. N. (2020). Remodeling informality into sustainable housing prototype, Alexandria case, Egypt. Paper presented at the second Arab land conference, Cairo.

Bellert, F., Fila, K., Thoms, R., Hagenlocher, M., Harb, M., Cotti, D., et al. (2021). Application of remote sensing and GIS for risk assessment in Monastir, Tunisia. In F. Khebour Allouche & A. M. Negm (Eds.), *Environmental remote sensing and GIS in Tunisia* (pp. 191–210). Springer International Publishing.

Benassai, G., Celentano, P., & Sessa, F. (2009). Coastal storm damage reduction program in Salerno Province after the winter 2008 storms. *WIT Transactions on Ecology and the Environment*, *126*, 119–128.

Bishop, M. J., Mayer-Pinto, M., Airoldi, L., Firth, L. B., Morris, R. L., Loke, L. H. L., et al. (2017). Effects of ocean sprawl on ecological connectivity: Impacts and solutions. *Journal of Experimental Marine Biology and Ecology*, *492*, 7–30. https://doi.org/10.1016/j.jembe.2017.01.021

Bongarts, L. T., Rey-Valette, H., Chaumillon, É., Camus, G., Almar, R., Cazenave, A., et al. (2021). Designing coastal adaptation strategies to tackle sea level rise. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.740602

Bragg, W. K., Gonzalez, S. T., Rabearisoa, A., & Stoltz, A. D. (2021). Communicating managed retreat in California. *Water*, *13*(6), 781. https://doi.org/10.3390/w13060781

Brechwald, D., & Resilience Planner, M. (2018). Bay Area Earthquake residential building damage & displacement white paper. Retrieved from https://abag.ca.gov/sites/default/files/bay_area_earthquake_residential_building_damage_white_paper_jan2018_1.pdf

Cheong, S.-M., Silliman, B., Wong, P. P., Van Wesenbeeck, B., Kim, C.-K., & Guannel, G. (2013). Coastal adaptation with ecological engineering. *Nature Climate Change*, *3*(9), 787–791. https://doi.org/10.1038/nclimate1854

Cigna, F., & Tapete, D. (2021). *Sentinel-1 InSAR assessment of present-day land subsidence due to exploitation of groundwater resources in Central Mexico*. Institute of Electrical Electronics Engineers. https://doi.org/10.1109/igarss39084.2020.9323247

Climate Institute. (2019). Soft vs hard engineering for coastal defense adaptation. Retrieved from http://climate.org/soft-vs-hard-engineering-for-coastal-defense-adaptation/

Czaika, M., & Reinprecht, C. (2020). Drivers of migration: A synthesis of knowledge. *International Migration*, *163*, 1–45.

Dada, O., Almar, R., Morand, P., Bergsma, E., Angnuureng, D., & Minderhoud, P. (2023). Future socioeconomic development along the West African coast forms a larger hazard than sea level rise. *Communications Earth & Environment*, *4*(1), 150. https://doi.org/10.1038/s43247-023-00807-4

Daftar Ahwal Cairo-based research institute. (2020). Incidents of building collapses in Egypt over three years - Daftar Ahwal [Dataset]. https://docs.google.com/spreadsheets/d/1NVUuEW8Hty2LNmTk2lNTf4evPkKTx5no26nbJMCvswo/edit#gid=618555603

Dolce, M., Prota, A., Borzi, B., da porto, F., Lagomarsino, S., Magenes, G., et al. (2021). Seismic risk assessment of residential buildings in Italy. *Bulletin of Earthquake Engineering*, *19*(8), 2999–3032. https://doi.org/10.1007/s10518-020-01009-5

El-Hattab, M. M., Mohamed, S. A., & El Raey, M. (2018). Potential tsunami risk assessment to the city of Alexandria, Egypt. *Environmental Monitoring and Assessment*, *190*, 1–13.

El-Mallakh, N. (2020). *Internet job search, employment, and wage growth: Evidence from the Arab republic of Egypt (English)*. Policy Research working paper; no. WPS 9196. World Bank Group.

Elsawy, A. A., Ayad, H. M., & Saadallah, D. (2019). Assessing livability of residential streets – Case study: El-Attarin, Alexandria, Egypt. *Alexandria Engineering Journal*, *58*(2), 745–755. https://doi.org/10.1016/j.aej.2019.06.005

El-Sheikh, S. (2016). 4 officials referred to prosecution for Sharqeya building collapse. Retrieved from https://www.dailynewsegypt.com/2016/01/13/4-officials-referred-to-prosecution-for-sharqeya-building-collapse/

Environmental Sector Programme Strategy for Implementing Integrated Coastal Zone Management Process in Egypt (EEAA). (2008). Framework program for developing national ICZM plan for Egypt. *Ministry of State for the Environment, Egyptian Environmental Affairs Agency*.

Esri. (2023). ArcGIS Pro 3.2 Patch 1 (3.2.1) [Software]. https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview

Esteban, M., Jamero, M. L., Nurse, L., Yamamoto, L., Takagi, H., Thao, N. D., et al. (2019). Adaptation to sea level rise on low coral islands: Lessons from recent events. *Ocean & Coastal Management*, *168*, 35–40. https://doi.org/10.1016/j.ocecoaman.2018.10.031

Esteves, L. S., & Finkl, C. W. (1998). The problem of critically eroded areas (CEA): An evaluation of Florida beaches. *Journal of Coastal Research*, (26), 11–18.

Fegley, S. R., Smith, J. P. S., Johnson, D., Schirmer, A., Jones-Boggs, J., Edmonds, A., & Bursey, J. (2020). Nourished, exposed beaches exhibit altered sediment structure and meiofaunal communities. *Diversity*, *12*(6), 245. https://doi.org/10.3390/d12060245

Fouad, S. S. (2024). Soaring building collapses in southern Mediterranean coasts: Hydroclimatic drivers & adaptive landscape mitigations [Dataset]. https://osf.io/98pyu

Fouad, S. S., Heggy, E., Abotalib, A. Z., Ramah, M., Jomaa, S., & Weilacher, U. (2022). Landscape-based regeneration of the Nile Delta's waterways in support of water conservation and environmental protection. *Ecological Indicators*, *145*, 109660. https://doi.org/10.1016/j.ecolind.2022.109660

Fouad, S. S., Heggy, E., & Weilacher, U. (2023). Waterways transformation in the vulnerable port city of Alexandria. *Cities*, *141*, 104426. https://doi.org/10.1016/j.cities.2023.104426

Fouad, S. S., & Sharaf Eldin, S. (2021). Public perception influence on the reshaping urban heritage: A case study of port said historic quarters. *Space and Culture*, *26*(4), 579–597. https://doi.org/10.1177/12063312211018397

Francis, T. (2023). Bayelsa community Obogoro faces extinction while awaiting Govt's erosion prevention Project foundation for investigative journalism.

Frihy, O. E. (1994). Nile delta shoreline changes: Aerial photographic study of a 28-year period. *Journal of Coastal Research*, *4*(4), 597–606.

Gao, J., Kennedy, D. M., & Konlechner, T. M. (2020). Coastal dune mobility over the past century: A global review. *Progress in Physical Geography: Earth and Environment*, *44*(6), 814–836. https://doi.org/10.1177/0309133320919612

Ghaly, B. S. (2022). Demand-side determinants of inflation in Egypt: A dynamic analysis. *Scientific Journal of Business Research and Studies*, *36*(3), 31–70.

GNSS station. (2024). Station ALX2. Nevada geodetic laboratory. Retrieved from http://geodesy.unr.edu

GOPP. (2011). *General planning of Alexandria city, second part. Alexandria, general organization for physical planning (GOPP)*. Ministry of Housing, Infrastructures, New Constructive Societies.

Gyamfi-Aidoo, J. (1987). Application of GIS to the assessment of land degradation and associated hazards in the Upper East Region of Ghana. Paper presented at the 2nd International Conference, Extracts and Workshop on GIS, San Francisco, 26-30 October 1987.

Haasnoot, M., Lawrence, J., & Magnan, A. (2021). Pathways to coastal retreat. *Science*, *372*(6548), 1287–1290. https://doi.org/10.1126/science.abi6594

Hauer, M. E. (2017). Migration induced by sea-level rise could reshape the US population landscape. *Nature Climate Change*, *7*(5), 321–325. https://doi.org/10.3886/E100413V3

Heggy, E., Abotalib, A. Z., You, J., Hanert, E., & Ramah, M. (2024). Grand Ethiopian Renaissance Dam can generate sustainable hydropower while minimizing downstream water deficit during prolonged droughts. *Communications Earth & Environment*, *5*(1), 1–15. https://doi.org/10.1038/s43247-024-01821-w

Helal, I. (2022). Death under the rubble in Egypt. Shadows of death looms over occupants of buildings at risk of collapse. https://raseef22.net/english/article/1086120-death-under-the-rubble-in-egypt-shadows-shadows-of-death-looms-over-occupants-of

Hilmi, N., Ali, E., Carnicer Cols, J., Cramer, W., Georgopoulou, E., Le Cozannet, G., & Tirado, C. (2022). IPCC AR6 WGII cross-chapter paper 4: Mediterranean region. Paper presented at the EGU General Assembly Conference Abstracts.

Hinkel, J., Aerts, J. C. J. H., Brown, S., Jiménez, J. A., Lincke, D., Nicholls, R. J., et al. (2018). The ability of societies to adapt to twenty-first-century sea-level rise. *Nature Climate Change*, *8*(7), 570–578. https://doi.org/10.1038/s41558-018-0176-z

Hino, M., Field, C. B., & Mach, K. J. (2017). Managed retreat as a response to natural hazard risk. *Nature Climate Change*, *7*(5), 364–370. https://doi.org/10.1038/nclimate3252

Huber, J. E., Van de Riet, K., Sandell, J., & Scarpa, L. (2017). Salty urbanism: Towards an adaptive coastal design framework to address sea level rise. *The Plant Journal*, *2*(2), 389–414. https://doi.org/10.15274/tpj.2017.02.02.06

Hzami, A., Heggy, E., Amrouni, O., Mahé, G., Maanan, M., & Abdeljaouad, S. (2021). Alarming coastal vulnerability of the deltaic and sandy beaches of North Africa. *Scientific Reports*, *11*(1), 2320. https://doi.org/10.1038/s41598-020-77926-x

Khalaf, M. K., & Abdelmegeed, M. (2018). Assessment of physical and mechanical characteristics of masonry building materials in historic military towers in Alexandria-Egypt: A case study. *International Journal of Conservation Science*, *9*, 677–688.

Kong, X., & Smyl, D. (2022). Investigation of the condominium building collapse in Surfside, Florida: A video feature tracking approach. In *Structures* (Vol. 43, pp. 533–545). Elsevier. https://doi.org/10.1016/j.istruc.2022.06.009

Magbool, H. M., & El-Abbasy, A. A. (2021). Finite element verification of the unreliability of using structural plain concrete footing under reinforced concrete footing. *Case Studies in Construction Materials*, *15*, e00734. https://doi.org/10.1016/j.cscm.2021.e00734

Mahmoud, M. A. (2019). Impact of climate change on the agricultural sector in Egypt. In A. M. Negm (Ed.), *Conventional water resources and agriculture in Egypt* (pp. 213–227). Springer International Publishing.

McDougall, C. (2017). Erosion and the beaches of Negril. *Ocean & Coastal Management*, *148*, 204–213. https://doi.org/10.1016/j.ocecoaman.2017.08.008

Microsoft Corporation. (2018). Microsoft Excel [Software]. https://office.microsoft.com/excel

Nagati, O., & Stryker, B. (2020). Formal-informal interfaces: Comparative analysis between three Egyptian cities. In N. Marrengane & S. Croese (Eds.), *Reframing the urban challenge in Africa knowledge Co-production from the south* (pp. 42–81). Routledge.

Nijhuis, S. (2022). Landscape-based urbanism: Cultivating urban landscapes through design. In R. Roggema (Ed.), *Design for regenerative cities and landscapes: Rebalancing human impact and natural environment* (pp. 249–277). Springer International Publishing.

Nijhuis, S., Sun, Y., Cannatella, D., & Xie, G. (2023). A landscape-based regional design approach for sustainable urban development in the Pearl River Delta, China. In S. Nijhuis, Y. Sun, & E. Lange (Eds.), *Adaptive urban transformation: Urban landscape dynamics, regional design and territorial governance in the Pearl River Delta, China* (pp. 81–114). Springer International Publishing.

Normand, J. C., & Heggy, E. (2024). Assessing flash flood erosion following storm Daniel in Libya. *Nature Communications*, *15*(1), 6493. https://doi.org/10.1038/s41467-024-49699-8

Ohenhen, L. O., Barnard, P. L., Shirzaei, M., & Romanowicz, B. (2024). Slowly but surely: Exposure of communities and infrastructure to subsidence on the US East Coast. *PNAS Nexus*, *3*(1). https://doi.org/10.1093/pnasnexus/pgad426

Ohenhen, L. O., & Shirzaei, M. (2022). Land subsidence hazard and building collapse risk in the coastal city of Lagos, west Africa. *Earth's Future*, *10*(12), e2022EF003219. https://doi.org/10.1029/2022ef003219

Pagnoni, G., Armigliato, A., & Tinti, S. (2015). Scenario-based assessment of buildings' damage and population exposure due to earthquake-induced tsunamis for the town of Alexandria, Egypt. *Natural Hazards and Earth System Sciences*, *15*(12), 2669–2695. https://doi.org/10.5194/nhess-15-2669-2015

Parkinson, R. W. (2021). Speculation on the role of sea-level rise in the tragic collapse of the surfside condominium (Miami Beach, Florida USA) was a bellwether moment for coastal zone management practitioners. *Ocean & Coastal Management*, *215*, 105968. https://doi.org/10.1016/j.ocecoaman.2021.105968

Pearson, S. (2023). Rising Atlantic Ocean Engulfs Fishing Town in Brazil: The coastline is receding as much as 18 feet a year at the mouth of a river in Atafona. Retrieved from https://www.wsj.com/articles/rising-atlantic-ocean-engulfs-fishing-town-in-brazil-b1d69c2d

Post, V. E., Eichholz, M., & Brentführer, R. (2018). Groundwater management in coastal zones. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR). German Federal Institute for Geosciences and Natural Resources.

Ragab, A. M., Elgammal, M. A., Hodhod, O. A., & Ahmed, T. E. (2016). Evaluation of field concrete deterioration under real conditions of seawater attack. *Construction and Building Materials*, *119*, 130–144. https://doi.org/10.1016/j.conbuildmat.2016.05.014

Rinde, E., Tromsland, T., Kempa, M., Norling, P., & Kolluru, V. (2016). Increased spreading potential of the invasive Pacific oyster (Crassostrea gigas) at its northern distribution limit in Europe due to warmer climate. *Marine and Freshwater Research*, *68*, 252–262. https://doi.org/10.1071/MF15071

Ritchie, H., Samborska, V., & Roser, M. (2024). Urbanization. Retrieved from https://ourworldindata.org/urbanization

Rocle, N., Dachary-Bernard, J., & Rey-Valette, H. (2021). Moving towards multi-level governance of coastal managed retreat: Insights and prospects from France. *Ocean & Coastal Management*, *213*, 105892. https://doi.org/10.1016/j.ocecoaman.2021.105892

Saleh, I. H., Ibrahim, N. M., Hassaan, M. A., Ghatass, Z. F., Arayro, J., Mezher, R., et al. (2024). Using 7Be and 137Cs for assessing the land stability of Alexandria region, Egypt. *Sustainability*, *16*(4), 1692. https://doi.org/10.3390/su16041692

Salhi, A., Larifi, I., Salhi, H., & Heggy, E. (2024). Flooding in semi-unformal urban areas in North Africa: Environmental and psychosocial drivers. *Science of the Total Environment*, *929*, 172486. https://doi.org/10.1016/j.scitotenv.2024.172486

Seif Eddin, S. (2021). Crumbling city: Why does Alexandria account for over half of all building collapses in Egypt. Retrieved from https://www.madamasr.com/en/2021/04/01/feature/politics/crumbling-city-why-does-alexandria-account-for-over-half-of-all-building-collapses-in-egypt/

Setiawan, I., Morgan, L., Doscher, C., Ng, K., & Bosserelle, A. (2022). Mapping shallow groundwater salinity in a coastal urban setting to assess exposure of municipal assets. *Journal of Hydrology: Regional Studies*, *40*, 100999. https://doi.org/10.1016/j.ejrh.2022.100999

Shirzaei, M., & Bürgmann, R. (2018). Global climate change and local land subsidence exacerbate inundation risk to the San Francisco Bay Area. *Science Advances*, *4*(3), eaap9234. https://doi.org/10.1126/sciadv.aap9234

Simons, R., Xiao, Y., Evenchik, A., & Barreto, A. (2022). Champlain Towers South collapse: Frequency, governance and liability issues. *Journal of Sustainable Real Estate*, *14*(1), 57–74. https://doi.org/10.1080/19498276.2022.2104346

Sokpe, S. (2022). Residents of Keta and Agavedzi call for help after being displaced by tidal waves again on Sunday. *Better Ghana Digest*. Retrieved from https://betterghanadigest.com

Souza, W., Ruiz-Armenteros, A., & Cabral, J. (2023). Monitoring of land subsidence in the city of Recife/Brazil using Sentinel-1 SAR interferometry. In *5th joint international symposium on deformation monitoring (JISDM 2022)* (pp. 439–445). Editorial Universitat Politècnica de València.

Sušnik, J., Vamvakeridou-Lyroudia, L. S., Baumert, N., Kloos, J., Renaud, F. G., La Jeunesse, I., et al. (2015). Interdisciplinary assessment of sea-level rise and climate change impacts on the lower Nile delta, Egypt. *The Science of the Total Environment*, *503–504*, 279–288. https://doi.org/10.1016/j.scitotenv.2014.06.111

Taylor, A., Blake, W. H., Iurian, A. R., Millward, G. E., & Mabit, L. (2019). The use of Be-7 as a soil and sediment tracer. Assessing Recent Soil Erosion Rates through the Use of Beryllium-7 (Be-7). 1–13. https://doi.org/10.1007/978-3-030-10982-0_1

Thieler, E. R., Himmelstoss, E. A., Zichichi, J. L., & Ergul, A. (2009). *The digital shoreline analysis system (DSAS) version 4.0-an ArcGIS extension for calculating shoreline change (No. 2008-1278)*. US Geological Survey.

Trang, N. T. T. (2016). Architectural approaches to a sustainable community with floating housing units adapting to climate change and sea level rise in Vietnam. World Academy of Science, Engineering and Technology. *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering*, *10*(2), 168–179.

UNEP/MAP/PAP. (2008). Protocol on integrated coastal zone management in the Mediterranean. *UN Environmental Programme*.

U.S. Geological Survey. (2005). Homes along the edge of the coast in Isla Vista, California, Pacific coastal and marine science center.

Valpassos, C. A., & Cunha, J. B. (2023). Atafona: Records of a world in Ruins1. *8*, 1–20.

van Bergen, J., Mulder, J., Nijhuis, S., Poppema, D. W., Wijnberg, K. M., & Kuschnerus, M. (2021). Urban dunes: Towards BwN design principles for dune formation along urbanized shores. In J. van Bergen, S. Nijhuis, N. Brand, & M. Hertogh (Eds.), *Building with Nature perspectives: Cross-disciplinary BwN approaches in coastal regions* (pp. 101–128). TU Delft.

Van Rijn, L. (2011). Coastal erosion and control. *Ocean & Coastal Management*, *54*(12), 867–887. https://doi.org/10.1016/j.ocecoaman.2011.05.004

Vassileva, M., Al-Halbouni, D., Motagh, M., Walter, T. R., Dahm, T., & Wetzel, H. U. (2021). A decade-long silent ground subsidence hazard culminating in a metropolitan disaster in Maceió, Brazil. *Scientific Reports*, *11*(1), 7704. https://doi.org/10.1038/s41598-021-87033-0

Warner, J. F., van Staveren, M. F., & van Tatenhove, J. (2018). Cutting dikes, cutting ties? Reintroducing flood dynamics in coastal polders in Bangladesh and The Netherlands. *International Journal of Disaster Risk Reduction*, *32*, 106–112. https://doi.org/10.1016/j.ijdrr.2018.03.020

Werner, A. D., & Simmons, C. T. (2009). Impact of sea-level rise on seawater intrusion in coastal aquifers. *Ground Water*, *47*(2), 197–204. https://doi.org/10.1111/j.1745-6584.2008.00535.x

Wöppelmann, G., Le Cozannet, G., De Michele, M., Raucoules, D., Cazenave, A., Garcin, M., et al. (2013). Is land subsidence increasing the exposure to sea level rise in Alexandria, Egypt? *Geophysical Research Letters*, *40*(12), 2953–2957. https://doi.org/10.1002/grl.50568

Zayed, A. A., El-Tapey, H. M., & Al-Toukhy, A. A. (2020). Study of some soils South El-Amiria, Alexandria Governorate, Egypt using two soil classification systems. *Egyptian Journal of Agricultural Research*, *98*(4), 548–558. https://doi.org/10.21608/ejar.2020.146386

Zhongming, Z., Linong, L., Xiaona, Y., Wangqiang, Z., & Wei, L. (2021). *AR6 climate change 2021: The physical science basis*. Intergovernmental Panel on Climate Change.

Zhu, J., & Isobe, D. (2022). Numerical investigation on the collapse of the Champlain Towers South in Florida. *The Proceedings of The Computational Mechanics Conference*, *35*, 24–06. https://doi.org/10.1299/jsmecmd.2022.35.24-06