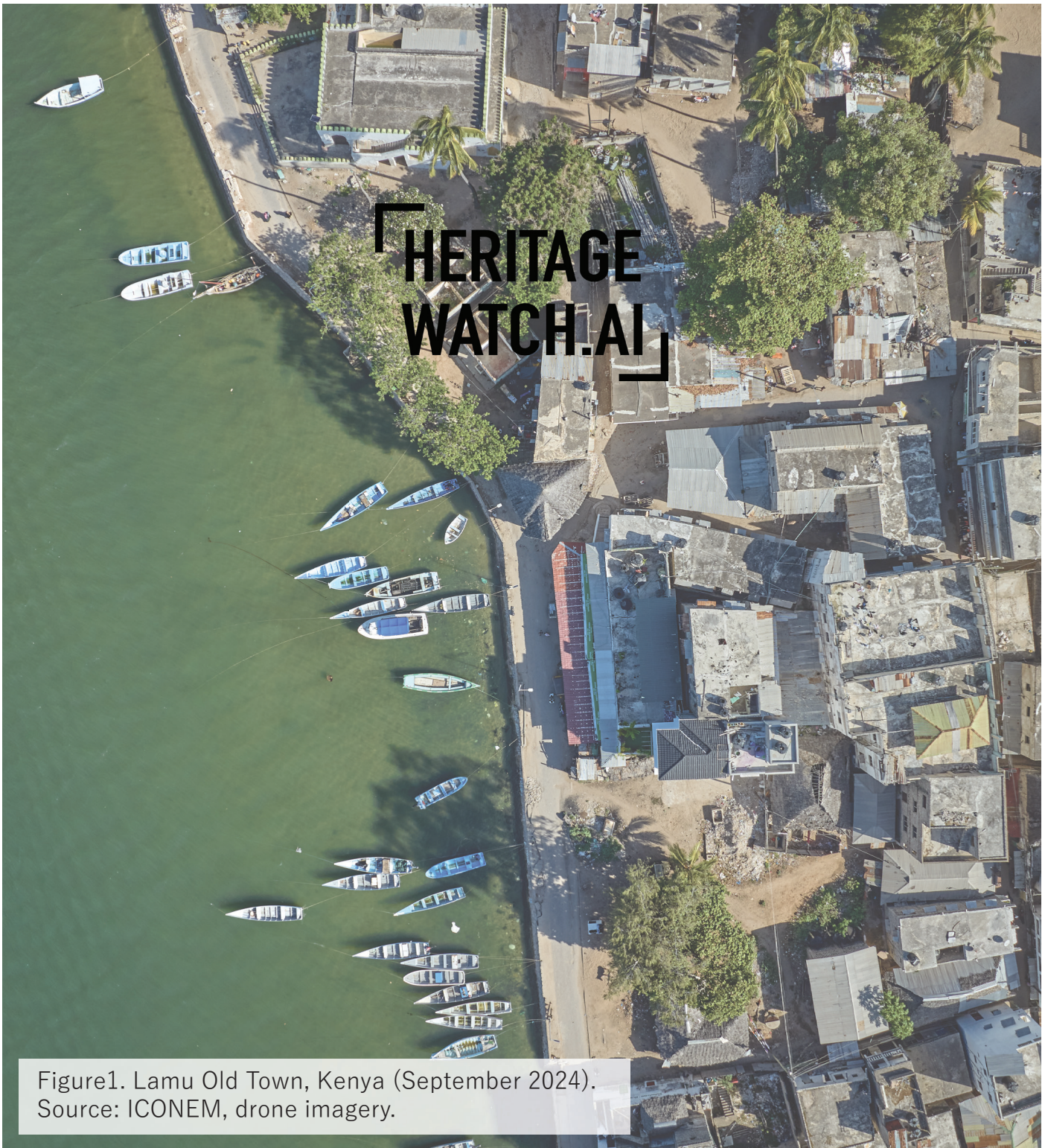




ENCROACHING SEAS AND HERITAGE AT RISK IN AFRICAN COAST



Encroaching Seas and Heritage at Risk in African coast
With Case Studies from Senegal, Mozambique, Kenya,
Tanzania.

Prepared by Heritage Watch AI

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TABLE OF CONTENTS

- 1 Key Messages**
- 2 Purpose and Use of This Report**
- 3 Regional Coastal Context: Why African Coastal Heritage Is at Risk**
 - 3.1 Regional Disaster Exposure (2002–2024)
 - 3.2 Why Regional Exposure Does Not Equal Site-Level Damage
- 4 Site Profiles: Coastal Heritage Under Environmental Stress**
 - 4.1 Gorée Island (Senegal)
 - 4.2 Mozambique Island (Mozambique)
 - 4.3 Zanzibar (Tanzania)
 - 4.4 Lamu (Kenya)
- 5 Cross-Site Patterns and Heritage Vulnerability Types**
- 6 What Can Be Done Now**
 - 6.1 Immediate Priorities for Risk Reduction
 - 6.2 Monitoring, Early Warning, and Decision Support
 - 6.3 Integrating Heritage into Coastal Adaptation Planning
- 7 Conclusions**
- 8 Annexes**
 - A. Data Sources and Methodology
 - B. Environmental Indicators and Thresholds
 - C. Supplementary Maps and Figures
 - D. Disaster History and Regional Hazard Records (to be updated)

1. Key Messages

Africa's coastal heritage sites are already experiencing material degradation driven by chronic environmental stress, not only by extreme disasters.

Salinity, persistent heat and humidity, and repeated wetting–drying cycles are the dominant drivers of damage to coral stone, lime mortars, and traditional coastal construction systems.

Shoreline stability does not imply low risk: even stable coastlines can sustain continuous marine exposure that accelerates long-term decay.

Global and regional hazard assessments are essential, but they do not capture how climate stress actually affects heritage materials on the ground.

Effective action requires preventive, materials-focused conservation strategies, aligned with dominant stress mechanisms rather than generic hazard categories.

time. This approach is particularly relevant for heritage sites, where damage often accumulates gradually and remains invisible until advanced stages of deterioration.

The report is intended for:

heritage authorities and site managers, coastal and urban planners, national agencies and international partners involved in climate adaptation and cultural heritage protection.

Technical methods, datasets, and analytical procedures are provided in annexes to ensure transparency and reproducibility, while the main report prioritises clarity, comparability, and action-oriented insights.

2. Purpose and Use of This Report

This report examines how climate-related coastal processes are affecting architectural and cultural heritage across selected African coastal sites. Its primary purpose is to support decision-making for heritage conservation, coastal management, and climate adaptation, by translating environmental data into heritage-relevant risk insights.

Rather than focusing solely on discrete hazards such as storms or flooding, the report adopts a stress-based approach, analysing how persistent environmental conditions, thermal regimes, salinity, marine exposure, and hydrological activation interact with historic building materials and urban form over

3. Regional Coastal Context: Why African Coastal Heritage Is at Risk

Africa's coastal heritage reflects centuries of maritime exchange, architectural adaptation, and cultural continuity. Many historic settlements developed in close relationship with the sea, often on low-lying islands, peninsulas, or estuarine margins. These same geographic advantages now place them among the most climate-exposed heritage environments on the continent.

At a regional scale, coastal heritage is increasingly affected by:

sea-level rise, which elevates baseline water levels and exacerbates flooding and salinity intrusion;

coastal flooding and storm surge, which cause episodic damage and activate stored salts within masonry;

shoreline instability, which can increase exposure even where direct erosion is limited.

Continental-scale assessments, including those produced by UNESCO and recent scientific studies, indicate that exposure to coastal hazards is projected to increase significantly across both the Atlantic and Indian Ocean coasts during the 21st century. Countries such as Mozambique and Tanzania show particularly high projected exposure due to long, low-lying coastlines, while Senegal and Kenya exhibit more spatially heterogeneous but locally acute risk.

However, regional and global assessments typically operate at coarse spatial resolutions and focus on hazard occurrence, rather than on how environmental conditions affect heritage materials and structures. As a result, they may underestimate risk at sites where degradation is driven by chronic stress rather than by dramatic events.

This report addresses that gap by combining

regional context with site-specific analysis, examining how global climate pressures translate into local patterns of material decay, exposure, and vulnerability at four emblematic coastal heritage sites.

3.1 Regional Distribution of Climate-Related Events (2002–2024)

Regional disaster records show that climate-related events in Senegal are concentrated along the coast, with the Dakar region, within which Gorée Island is located, among the most consistently affected areas due to recurrent flooding and urban hydrological stress. This indicates that Gorée is embedded within a region of persistent hydrological disturbance, even where site-scale analyses show limited shoreline retreat or permanent inundation.

Across East Africa, climate-related disasters are similarly concentrated along the western Indian Ocean coastline. Coastal districts in Tanzania, Mozambique, and Kenya show high cumulative exposure over the past two decades, driven mainly by flooding, extreme rainfall, and, in some areas, cyclonic activity. This situates Stone Town, Ilha de Moçambique, and Lamu Old Town within a broader zone of sustained coastal climate stress, despite variation in hazard frequency and type between countries.

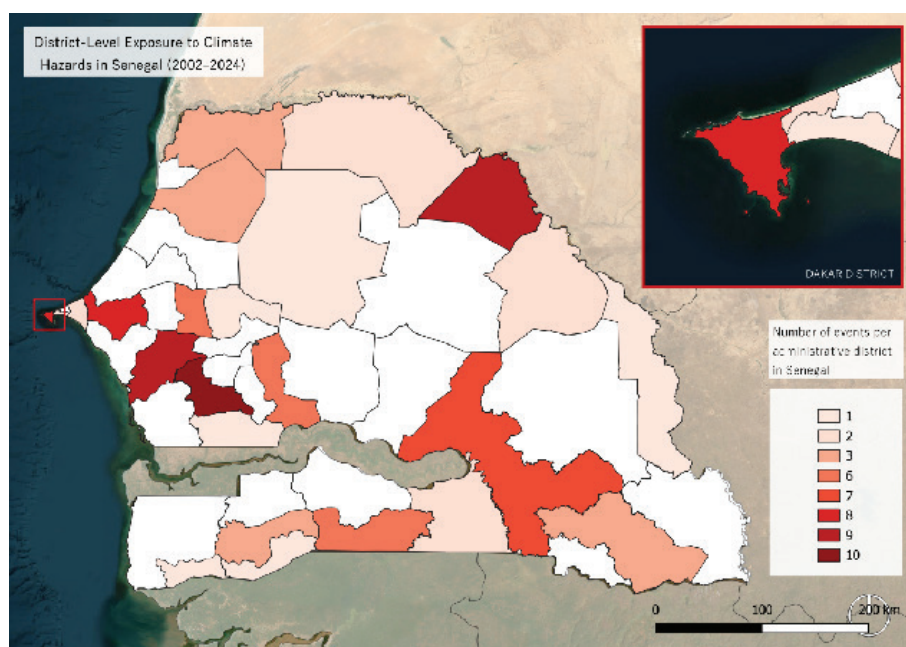


Figure 2: Regional exposure to climate-related hazards in West Africa (2002–2024).

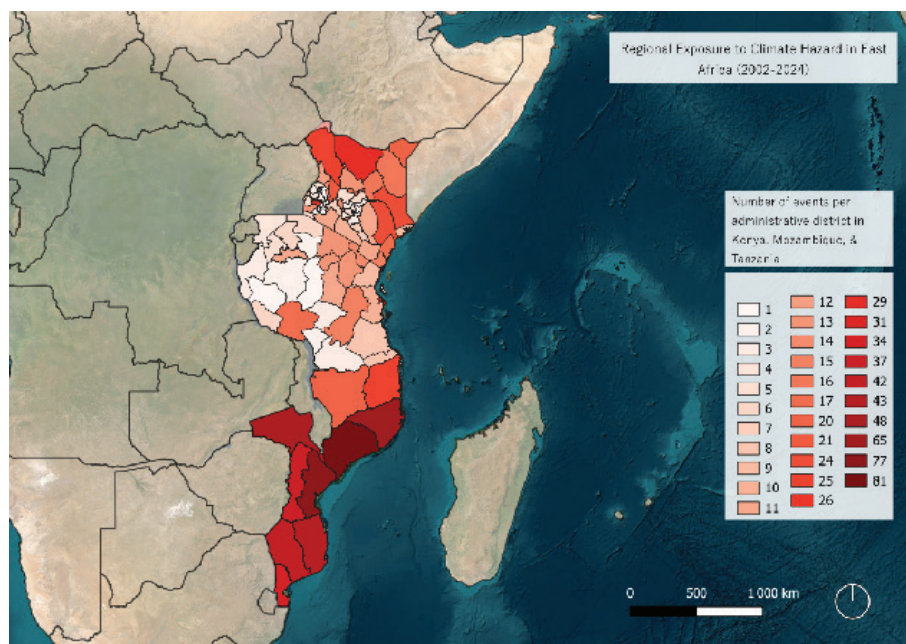


Figure 3: Regional exposure to climate-related hazards in East Africa (2002–2024).

3.2 Temporal Patterns of Climate-Related Events (2002–2024)

While regional maps illustrate where climate-related hazards are concentrated spatially, temporal analysis helps clarify how frequently these pressures recur. Disaster records show that coastal regions examined in this study experience repeated activation of hydrological stress, with limited hazard-free intervals over the past two decades. To illustrate these temporal patterns without overloading the main report, one representative graph is presented

for West Africa and one for East Africa. Country-specific breakdowns are provided in the annex.

West Africa:

Senegal’s disaster record between 2002 and 2024 shows regular recurrence of climate-related events, dominated by flooding. Although event frequency varies from year to year, there is no extended period without recorded hazards, indicating persistent background pressure rather than isolated extremes.

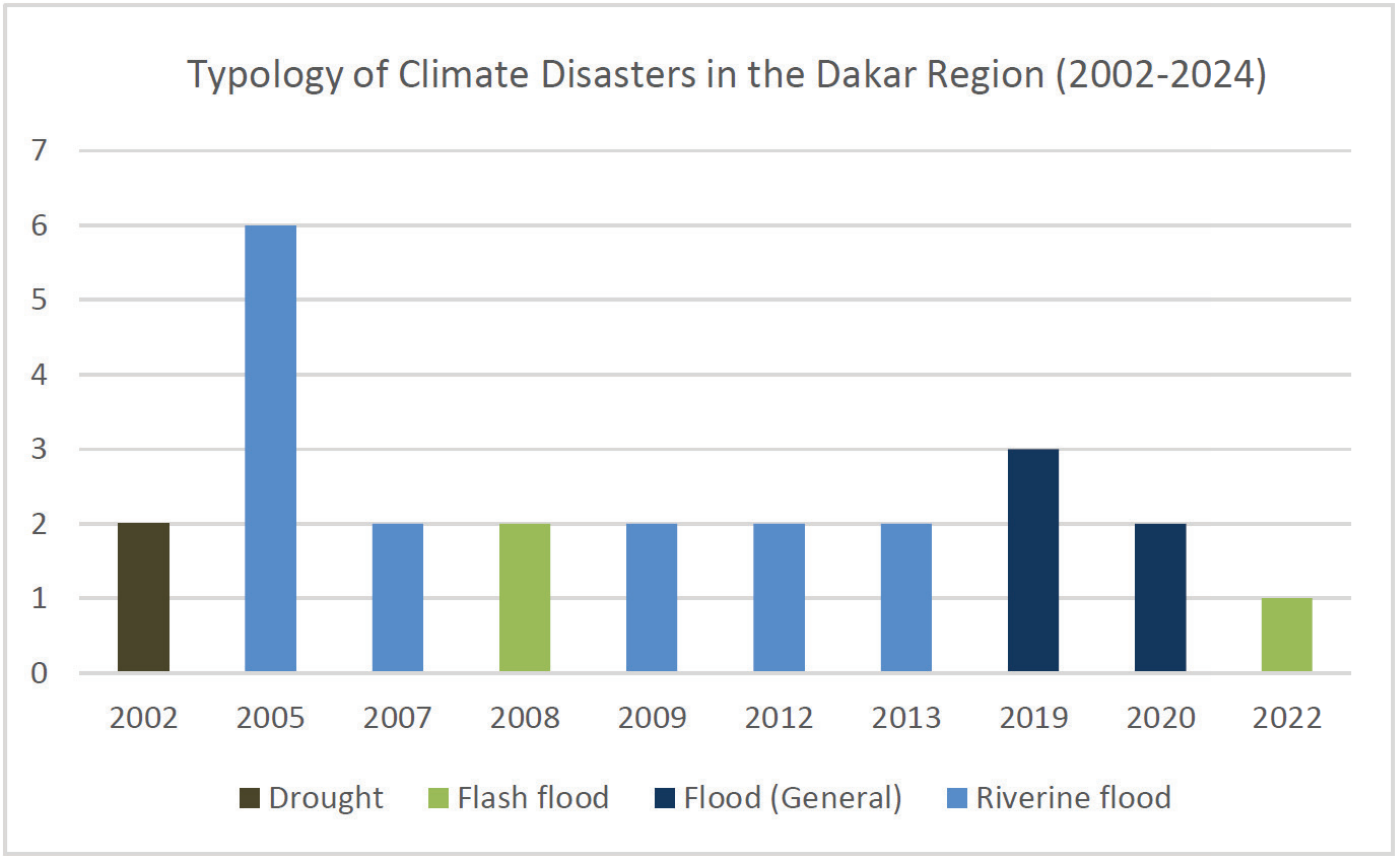


Figure 4: Number of recorded climate-related events per year in Senegal (2002–2024).

This pattern confirms that coastal heritage sites within the Dakar region, including Gorée Island, are subject to recurrent hydrological activation, which periodically elevates groundwater levels, prolongs moisture exposure, and reactivates salts within historic masonry. Even when individual events do not cause direct damage, their cumulative effect contributes to long-term material degradation.

East Africa (Kenya, Tanzania, Mozambique)

Across East Africa, disaster records indicate a similarly persistent pattern of hydrological stress, with flooding, extreme rainfall, and, in some areas, cyclone-related impacts occurring regularly over the past two decades. While the dominant hazard types and frequencies vary between countries, the regional signal is one of sustained exposure rather than isolated extremes.

Flooding, both riverine and coastal, emerges as the most frequent event type across Kenya, Tanzania, and Mozambique, with cyclones contributing episodically, particularly along

the Mozambican coast. Drought events further compound this pattern by weakening soils and urban drainage systems, increasing sensitivity to subsequent rainfall and flood events.

Taken together, this regional temporal profile situates Stone Town (Zanzibar), Ilha de Moçambique, and Lamu Old Town within climatic contexts characterised by repeated hydrological activation. These events intermittently intensify the thermal, salinity, and moisture-driven degradation processes identified in the site-level analyses, even where direct disaster impacts on heritage structures are not consistently documented.

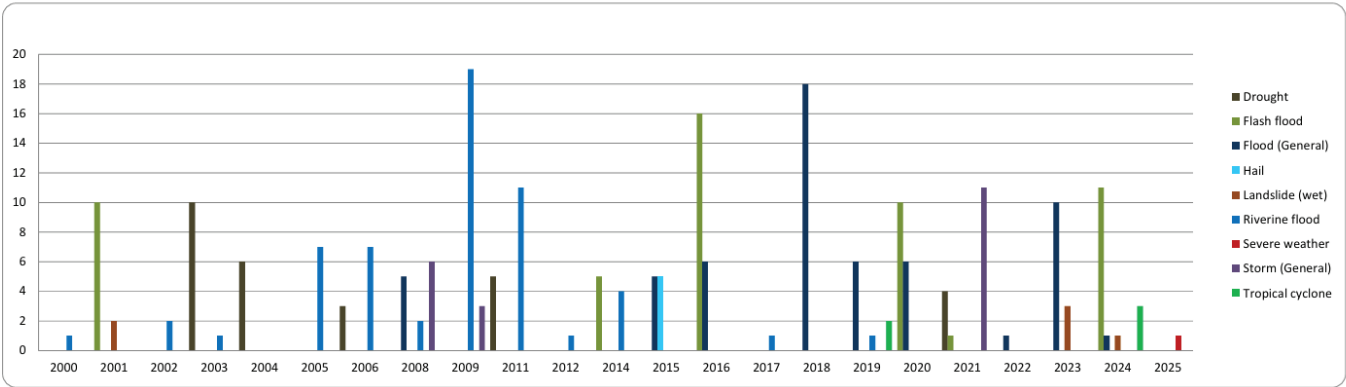


Figure 5: Number of recorded climate-related events per year in Tanzania (2002–2024).

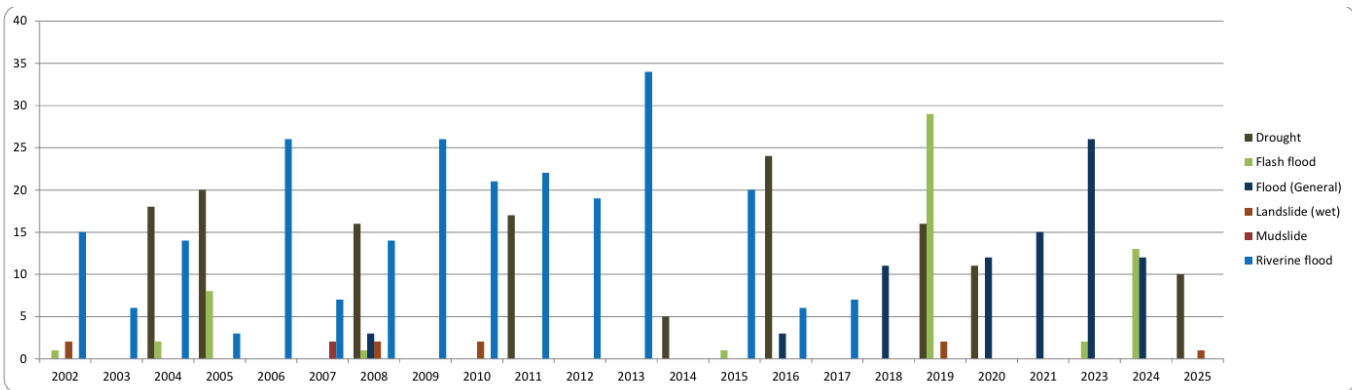


Figure 6: Number of recorded climate-related events per year in Kenya (2002–2024).

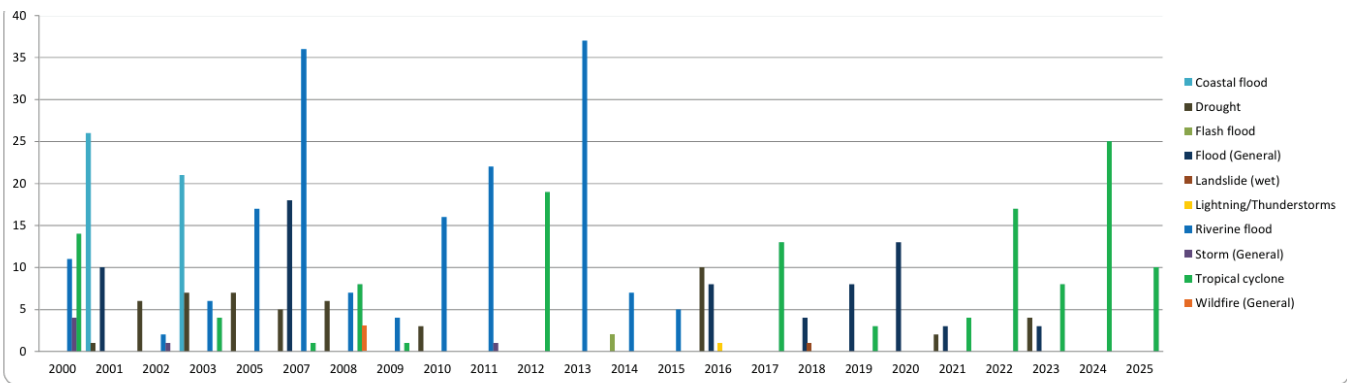


Figure 7: Number of recorded climate-related events per year in Mozambique (2002–2024).

3.3 Implications for Interpreting Coastal Heritage Risk

Regional disaster records demonstrate that Africa's coastal heritage sites are embedded within environments of recurrent climatic disturbance, particularly linked to flooding, extreme rainfall, and drought. However, these data also highlight the limitations of hazard-frequency metrics when used in isolation for heritage risk assessment.

At several of the case study sites, including Gorée Island and Stone Town, recorded disaster frequency does not align directly with observed patterns of material degradation or vulnerability. This apparent discrepancy reflects the fact that heritage risk is driven primarily by chronic environmental stress; salinity, moisture retention, and thermal conditions, rather than by the immediate physical impact of discrete disaster events.

In this context, disasters function mainly as episodic amplifiers. Flooding events re-saturate porous masonry and foundations, mobilise stored salts, and delay drying cycles, while droughts weaken soils and drainage systems, increasing sensitivity to subsequent rainfall. These processes intensify ongoing degradation trajectories without necessarily producing visible, event-specific damage.

The integration of regional disaster data with site-scale environmental and material analysis therefore supports a key finding of this report: the absence of frequent disasters, shoreline retreat, or catastrophic events does not equate to low heritage risk. Instead, vulnerability emerges from the interaction between recurring climatic disturbances and long-term exposure to marine and atmospheric stress.

This regional framing provides essential context for the site profiles that follow, ensuring that site-level observations are interpreted within the broader climatic regimes shaping coastal heritage across Africa.

The regional analysis highlights that Africa's coastal heritage is embedded within zones of recurrent climatic stress, shaped by flooding, extreme rainfall, and long-term coastal exposure. However, regional disaster frequency and shoreline trends alone do not explain how risk materialises at the scale of historic buildings and urban fabric.

To understand how these broad pressures translate into tangible heritage vulnerability, the following section presents detailed site profiles for four coastal Areas of Interest. Each case study integrates shoreline dynamics, environmental stress indicators, and architectural characteristics to examine how climate-related processes interact with specific materials, settlement forms, and coastal settings. Together, these profiles provide the empirical basis for identifying cross-site patterns and informing targeted conservation and adaptation strategies.

SITE PROFILES:

4.1. GORÉE ISLAND, SENEGAL

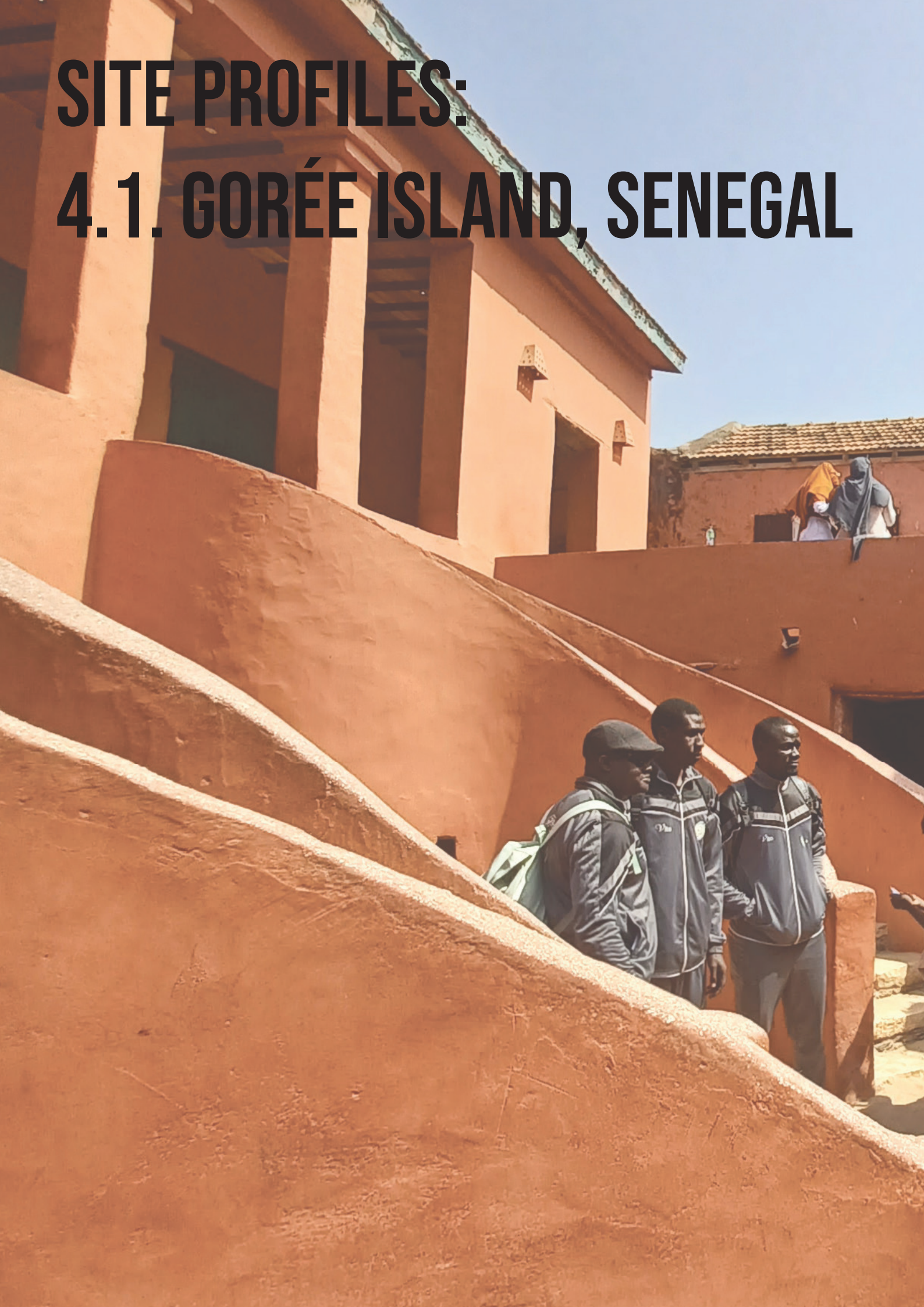




Figure 8: Source: Adjoajo, Wikimedia Commons (CC BY-SA 4.0), original work.

UNESCO World Heritage Site (1978), ID 26

Coordinates: 14° 40' 01"N, 17° 23' 54"W

Architectural and Material Profile

Gorée Island comprises a dense historic urban fabric of French colonial and Afro-European buildings constructed primarily from coral stone, basalt, lime-based plasters, clay tiles, and timber elements. Owing to the island's small size, low elevation, and direct marine exposure, environmental stressors affect the heritage fabric at a site-wide scale, with limited spatial buffering.



Figure 9: Gorée Island and its cultural heritage sites.



Figure 10: Gorée Island Museum

Source: Adjoajo, Wikimedia Commons (CC BY-SA 4.0), February 2025.



Figure11: Île de Gorée, Senegal.

Source: Elke Selter, ALIPH

Environmental–Heritage Stress Analysis

Thermal Stress (Sea Surface Temperature)

Seasonal sea surface temperature contrast is pronounced, with warm-season maxima averaging $\sim 28.9^{\circ}\text{C}$ and cool-season minima ranging between 16.2°C -- 18.9°C , producing a mean thermal amplitude of $\sim 11.7^{\circ}\text{C}$ (2014–2024). Although no persistent warming trend is observed, the recurrence of high seasonal amplitude indicates moderate–high thermal stress.

Heritage risk implication:

Repeated expansion–contraction cycles contribute to material fatigue, micro-cracking, and increased permeability in coral stone masonry and lime plasters, particularly on sun- and sea-exposed façades, facilitating subsequent chemical decay.

Chemical Stress (Marine Salinity)

Cool SST ($^{\circ}\text{C}$) and Warm SST ($^{\circ}\text{C}$)

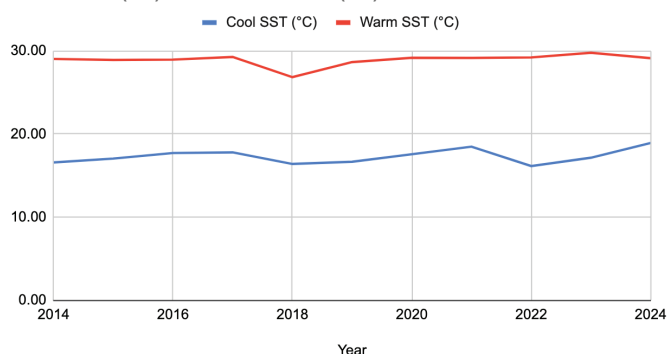


Figure 12: Sea surface temperature (cool and warm seasons) at Gorée Island, 2014–2024.
Source: Copernicus Marine Service.

Thermal Amplitude ($^{\circ}\text{C}$) vs. Year

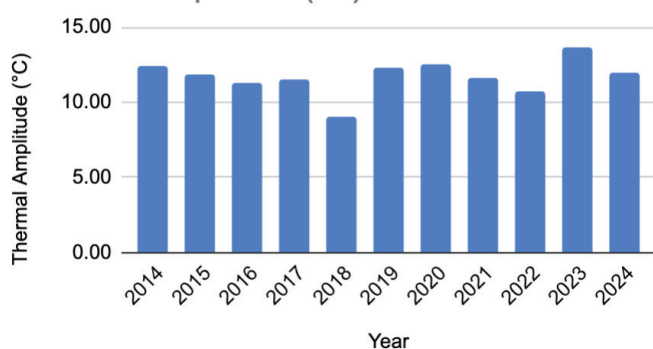


Figure 13: Thermal amplitude at Gorée Island, 2014–2024.
Source: Copernicus Marine Service.

Maximum salinity values remain consistently high (mean ~ 35.8 PSU), while variability in minimum salinity produces a mean seasonal amplitude of ~ 2.7 PSU, with several years exceeding 3 PSU. This defines a persistently saline exposure regime with active seasonal cycling.

Heritage risk implication:

Salinity constitutes the dominant driver of material degradation at Gorée. Repeated dissolution–crystallisation cycles lead to granular disintegration, surface powdering, plaster flaking, and loss of historic finishes, directly threatening the legibility and authenticity of architectural surfaces.

Min Salinity (PSU) and Max Salinity (PSU)

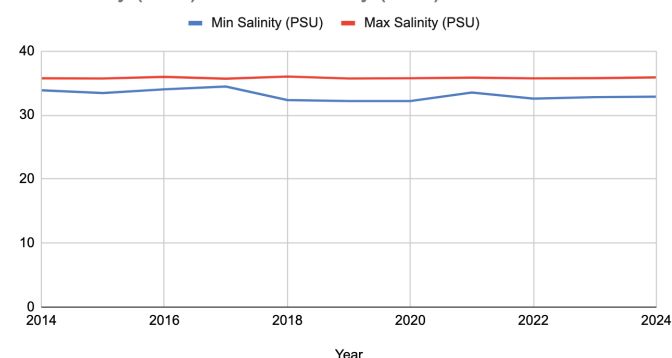


Figure 13: . Sea surface salinity (minimum and maximum) at Gorée Island, 2014–2024.
Source: Copernicus Marine Service.

Salinity Amplitude (PSU) vs. Year

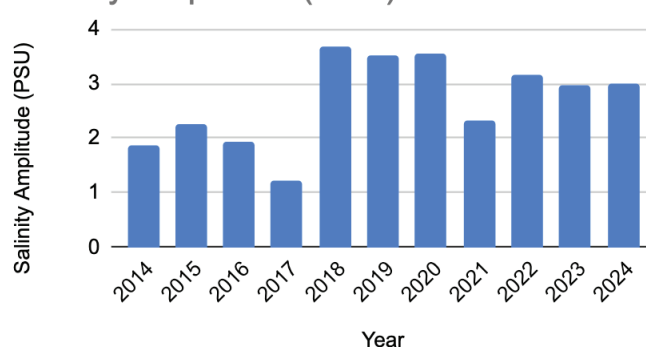


Figure 14: Salinity amplitude at Gorée Island, 2014–2024.
Source: Copernicus Marine Service.

Marine Energy Exposure (Wave Height)

The wave climate is moderate, with mean annual maximum significant wave heights of ~2.38 m, punctuated by isolated high-energy events (e.g. > 3.3 m in 2020). Interannual variability is otherwise limited.

Heritage risk implication:

Marine energy acts as a secondary, episodic stressor, increasing salt spray penetration, causing short-term saturation of coastal masonry, and locally affecting pavements and foundations during storm events. Its primary impact is the acceleration of existing chemical and moisture-driven decay rather than direct mechanical damage.

Max SWH (m) vs. Year

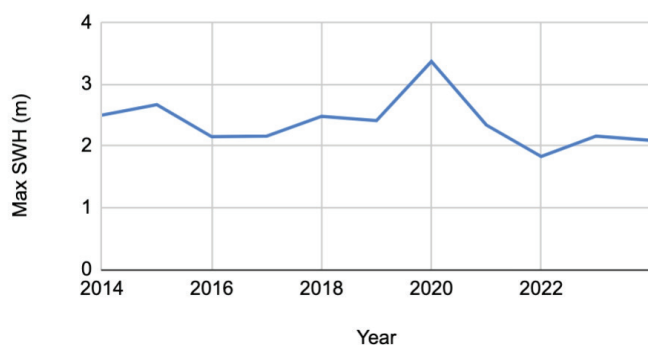


Figure 15: Maximum wave height at Gorée Island, 2014–2024.

Source: Copernicus Marine Service.

SWH Amplitude (m)

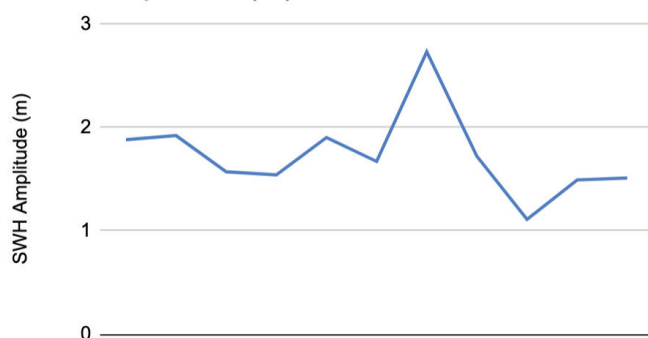


Figure 16: Wave height amplitude at Gorée Island, 2014–2024.

Source: Copernicus Marine Service.

Hydrological Stress (Rainfall and Humidity)

Annual rainfall is low to moderate but highly variable (~138–539 mm), while relative humidity remains persistently high (mean ~69–78%), with strong seasonal contrasts.

Heritage risk implication:

Rainfall and humidity function as stress multipliers, reactivating salts stored in porous materials and prolonging moisture residence time within walls. These processes intensify salinity-driven decay and contribute to foundation wetting during peak rainy periods, without constituting an independent dominant hazard.

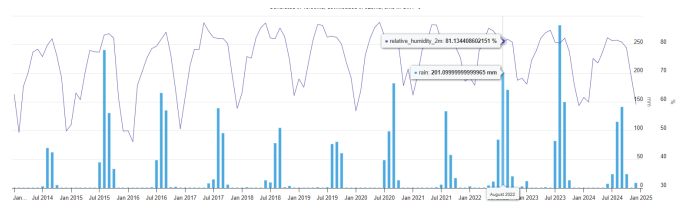


Figure 17: Rainfall and relative humidity at Gorée Island, 2014–2024.

Source: Copernicus Marine Service.

Integrated Heritage Risk Characterisation

Gorée Island’s vulnerability is governed by the interaction of persistent salinity stress and high seasonal thermal amplitude, modulated by episodic marine energy events and seasonally activated hydrological processes. Risk manifests primarily as slow, cumulative material degradation rather than abrupt damage or large-scale coastal loss, underscoring the importance of preventive, materials-focused conservation strategies.

Stress Type	Qualitative Level	Key Characteristics
Thermal stress (SST)	Moderate–High	Pronounced seasonal amplitude; recurrent material fatigue
Salinity stress (SSS)	High	Persistent salt availability; active dissolution–crystallisation
Wave exposure (SWH)	Moderate	Episodic storm-driven impacts; enhanced salt spray
Rainfall / hydrological stress	Moderate	Seasonal wetting; amplification of chemical decay

Table 1. Environmental stress summary for Gorée Island

Shoreline Change and Coastal Dynamics

A. Shoreline Position Through Time (2000–2021)

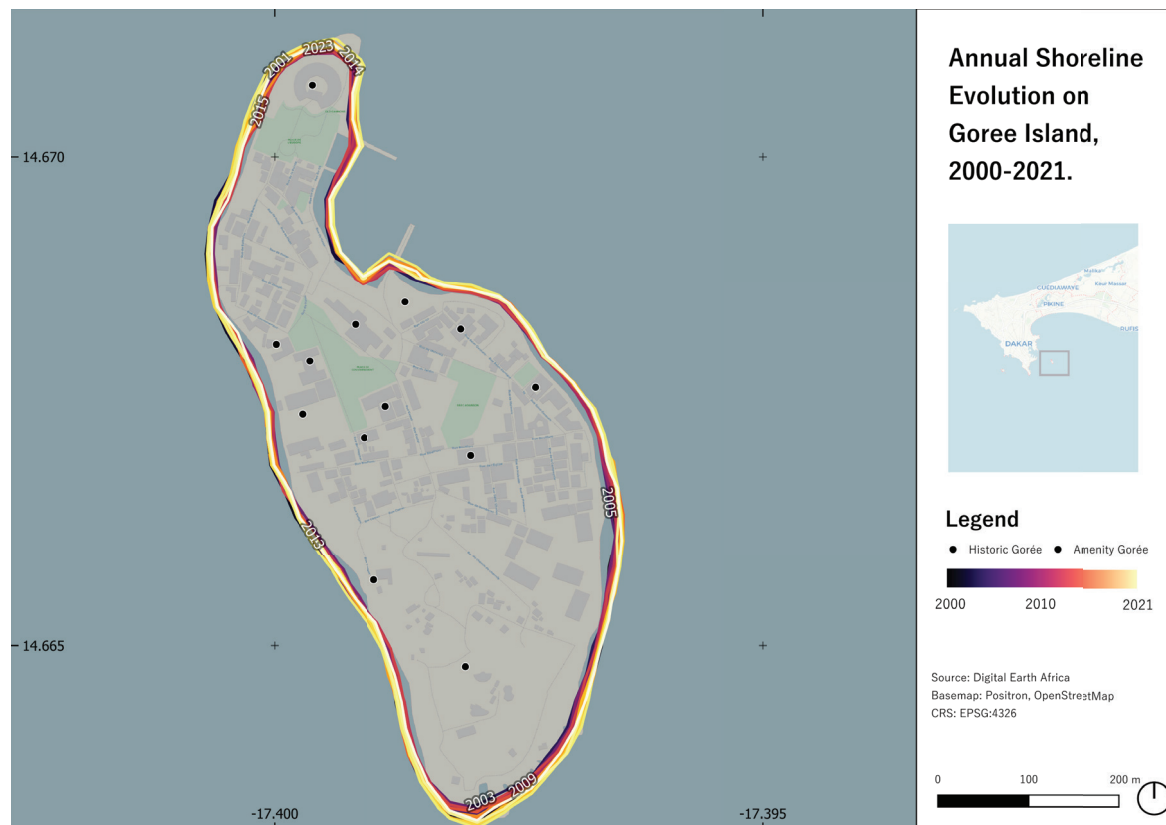


Figure 18. Shoreline position through time at Gorée Island, 2000–2021.
Source: Digital Earth Africa.

Observation

The annual shoreline position map indicates limited spatial displacement of the shoreline around Gorée Island over the period 2000–2021. Shoreline traces show minor oscillations between seaward and landward positions, with the most seaward extent recorded in 2001 and the most landward position around 2010. Overall, the median annual shoreline position has shifted by approximately 10 metres over the full observation period, with no consistent directional trend.

Analysis

These patterns indicate a net stable shoreline regime, characterised by short-term variability rather than sustained erosion or accretion. The oscillatory behaviour suggests sensitivity to interannual forcing (e.g. storms, sediment redistribution, tidal or seasonal effects), but the absence of progressive landward retreat implies that large-scale geomorphological destabilisation is not occurring at the island scale. Shoreline mobility remains constrained within a narrow envelope, consistent with Gorée's rocky volcanic base and partial shelter within the Cap-Vert Peninsula.

B. Rates of Shoreline Change (2000–2021)



Figure 19. Rates of shoreline change at Gorée Island, 2000–2021.
Source: Digital Earth Africa.

Observation

Shoreline change rate analysis shows that most coastal segments around Gorée fall within the “no change” to very low change category. Localised zones of slight accretion and minor retreat are present, but rates generally remain close to zero, with no extensive sections exhibiting sustained erosion (>-5 m/year) or rapid accretion (>5 m/year).

Analysis

The spatial pattern of near-zero change rates confirms that Gorée’s coastline has remained geomorphologically stable over the past two decades. Localised deviations likely reflect small-scale sediment redistribution or engineered shoreline modifications rather than systemic coastal retreat. Importantly, the absence of persistent erosional hotspots suggests that shoreline change is not currently a primary driver of exposure increase for the island’s built heritage.

C. Implications for Heritage Exposure

Integrated interpretation

Shoreline stability at Gorée Island indicates that coastal retreat is not a dominant risk factor for the historic fabric at present. However, this stability does not equate to low heritage vulnerability. A stable shoreline facilitates continuous marine exposure, maintaining salt spray delivery, saline groundwater conditions, and repeated wetting of lower wall zones and pavements. In this context, shoreline dynamics act as a background exposure condition, enabling chronic chemical and thermal stress to operate persistently rather than episodically.

For Gorée's coral stone masonry and lime-based plasters, the principal heritage risk arises not from shoreline displacement, but from long-term marine influence under stable coastal geometry, which sustains salt accumulation and material fatigue over time. Shoreline change therefore functions as a modulating factor, shaping the persistence of environmental stress rather than driving damage directly.

SITE PROFILES:

4.2. MOZAMBIQUE ISLAND, MOZAMBIQUE





Figure 20: Building on Mozambique Island (2011). Photo by USAID / U.S. Agency for International Development, uploaded by JotaCartas.
Source: Wikimedia Commons.

UNESCO World Heritage Site (1991), ID 599

Coordinates: 15° 02' 12" S, 40° 43' 58" E

Architectural and Material Profile

Ilha de Moçambique is a low-lying coral limestone island characterised by a dual urban structure: the stone-built Cidade de Pedra, comprising coral stone masonry, lime-based plasters, vaulted structures, and major monuments; and the vernacular Cidade de Macuti, composed primarily of adobe walls, timber elements, and thatched roofing. The island's very low elevation, coral substrate, and direct exposure to the Indian Ocean render both districts highly sensitive to marine, thermal, and hydrological stress, though through distinct material degradation pathways.



Figure 21: Mozambique Island and its cultural heritage sites.



Figure 22: Ilha de Moçambique seen from Fort São Sebastião, with the bridge to the mainland in the background (2007). Photo by Stig Nygaard, licensed under CC BY 2.0
Source: Wikimedia Commons.



Figure 23: Porta da Capitania, Ilha de Moçambique, Nampula Province (2011). Photo by USAID / U.S. Agency for International Development, Public Domain.
Source: Wikimedia Commons

Environmental–Heritage Stress Analysis

Thermal Stress (Sea Surface Temperature)

Sea surface temperatures remain consistently high throughout the year, with cool-season averages of ~25.6 °C and warm-season maxima of ~29.8 °C, producing a relatively low mean thermal amplitude of ~4.3 °C (2014–2024). This reflects a persistently warm tropical marine environment with limited seasonal relief.

Heritage risk implication:

Thermal stress at Mozambique island is chronic rather than cyclical. Sustained warmth promotes prolonged moisture retention within coral stone masonry and lime mortars, limiting drying periods and increasing susceptibility to salt crystallisation and chemical alteration. In the Cidade de Macuti, persistent heat accelerates biological degradation of thatch and timber, shortening material lifespan and

increasing maintenance demands.

Chemical Stress (Marine Salinity)

Salinity levels remain persistently high, with annual maximum values averaging ~35.2 PSU and limited interannual variation. Minimum salinity values also remain elevated, producing a relatively low mean salinity amplitude of ~1.3 PSU.

Heritage risk implication:

This pattern defines a constant saline exposure regime, in which building materials experience prolonged saturation rather than pronounced wet–dry cycling. Deep salt penetration weakens coral limestone, degrades lime mortars, and accelerates surface decay, particularly under conditions of sustained humidity. Salinity therefore acts as a background stressor, amplifying damage during storms and flooding rather than operating as an isolated decay mechanism.

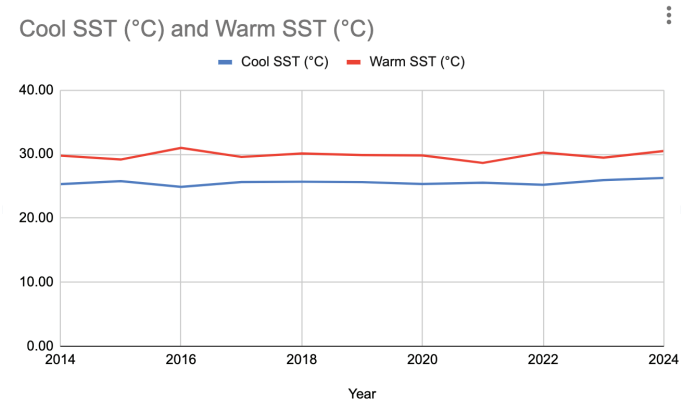


Figure 24: Sea surface temperature (cool and warm seasons) at Mozambique Island, 2014–2024. Source: Copernicus Marine Service.

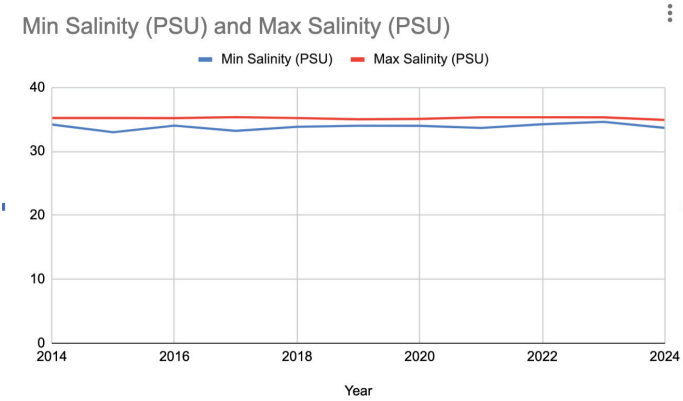


Figure 26: . Sea surface salinity (minimum and maximum) at Mozambique Island, 2014–2024. Source: Copernicus Marine Service.

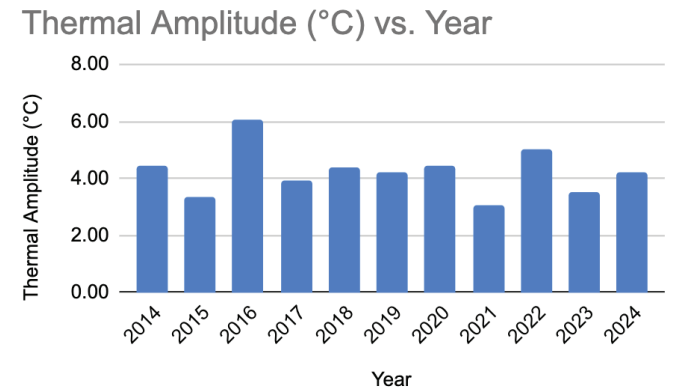


Figure 25: Thermal amplitude at Mozambique Island, 2014–2024. Source: Copernicus Marine Service.

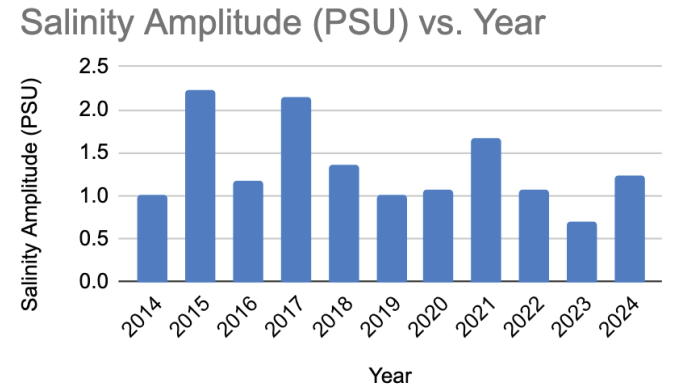


Figure 27: Salinity amplitude at Mozambique Island, 2014–2024. Source: Copernicus Marine Service.

Marine Energy Exposure (Wave Height)

Ilha de Moçambique experiences consistently high marine energy conditions. Annual maximum significant wave heights average ~2.55 m, with several years exceeding 2.8 m and a peak of ~3.06 m (2018). Minimum wave heights remain low (~0.31 m), producing a high mean wave height amplitude of ~2.24 m, the largest among the case study sites.

Heritage risk implication:

Marine energy represents a primary driver of heritage vulnerability. Recurrent high wave energy increases the frequency of coastal overtopping, wave-driven flooding, and foundation destabilisation, while also intensifying salt aerosol deposition on exposed façades. Limited recovery time between events results in cumulative structural weakening and accelerated material loss across both monumental and vernacular architecture.

Max SWH (m) vs. Year

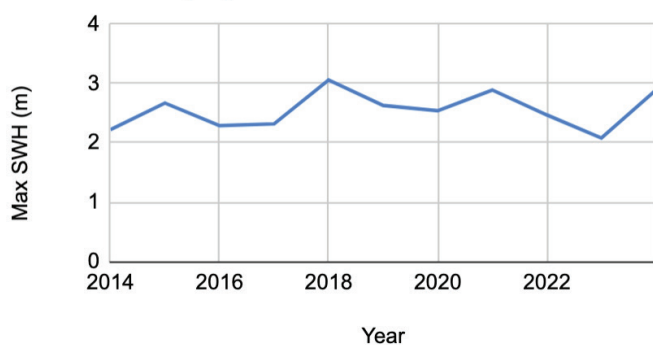


Figure 28: Maximum wave height at Mozambique Island, 2014–2024.
Source: Copernicus Marine Service.

SWH Amplitude (m) vs. Year

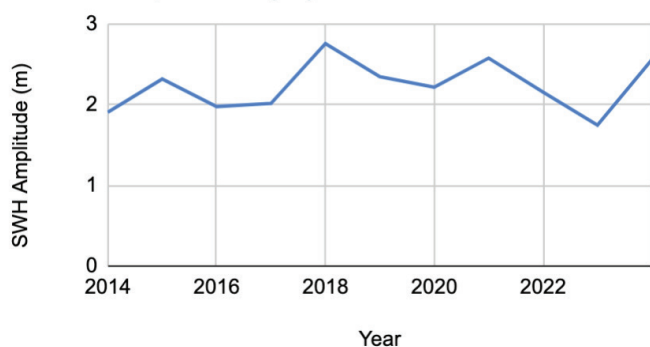


Figure 29: Wave height amplitude at Mozambique Island, 2014–2024.
Source: Copernicus Marine Service.

Hydrological Stress (Rainfall and Humidity)

Rainfall and near-surface relative humidity data (2014–2024) indicate a highly active hydrological stress regime. Annual rainfall totals average approximately ~987 mm, with strong interannual variability (~684–1,232 mm), concentrated in the December–March wet season. Relative humidity remains persistently high, with mean values of ~78.8%, maximum values approaching 100%, and elevated minimum values (mean ~39%), indicating limited drying potential even during the dry season.

Heritage risk implication:

This combination of intense seasonal rainfall and sustained atmospheric humidity produces prolonged wetting phases with minimal recovery time. In the Cidade de Pedra, repeated foundation saturation and slow drying accelerate salt mobilisation, mortar weakening, and surface decay of coral masonry. In the Cidade de Macuti, rainfall and waterlogging directly compromise adobe walls and thatch structures, driving recurrent damage and material loss. Hydrological stress therefore functions as both a direct damage mechanism and a multiplier of thermal, salinity, and marine energy stress.

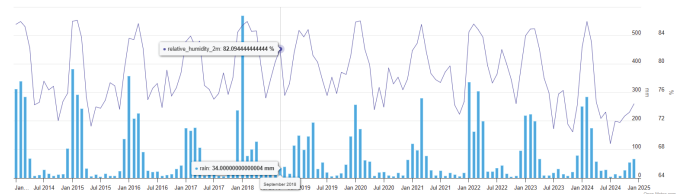


Figure 30: Rainfall and relative humidity at Mozambique Island, 2014–2024.
Source: Copernicus Marine Service.

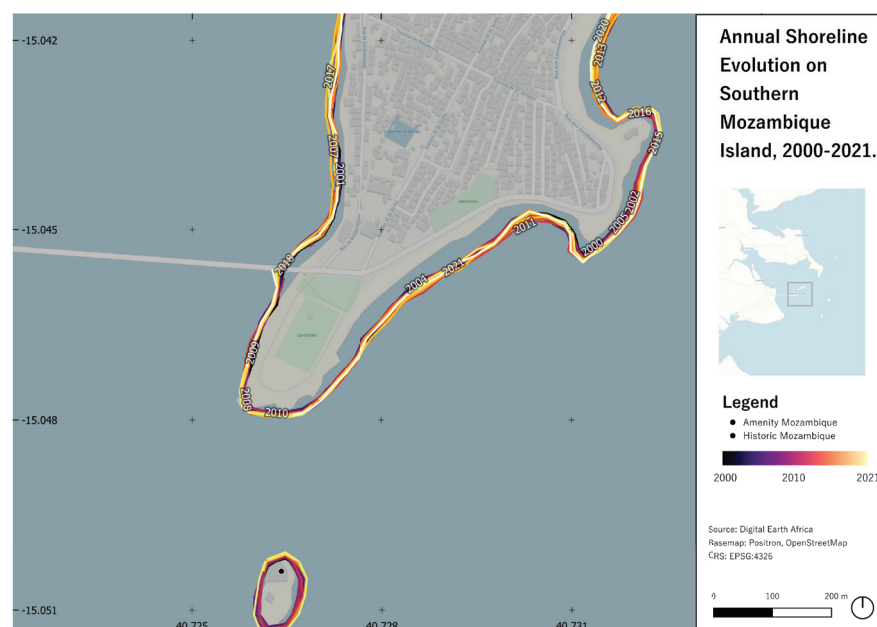
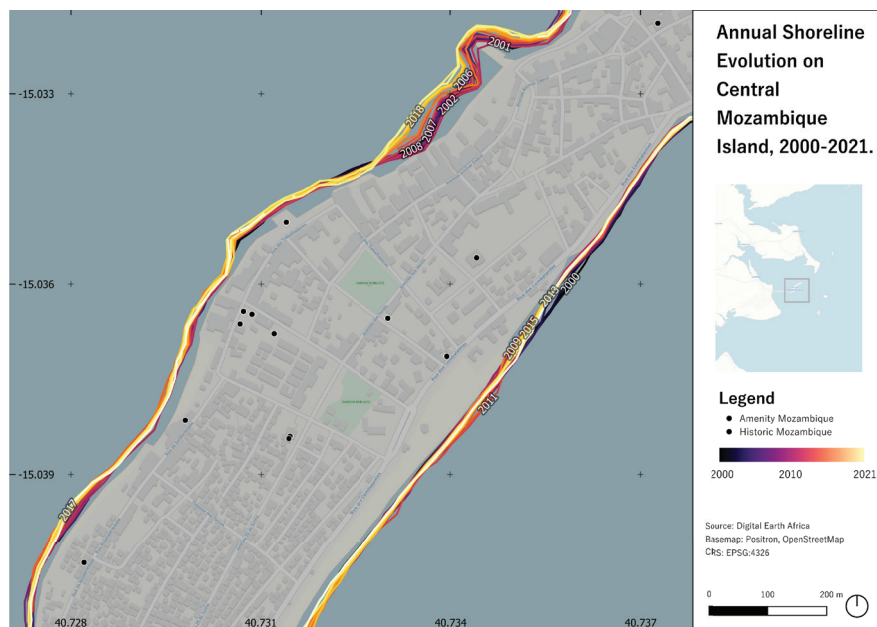
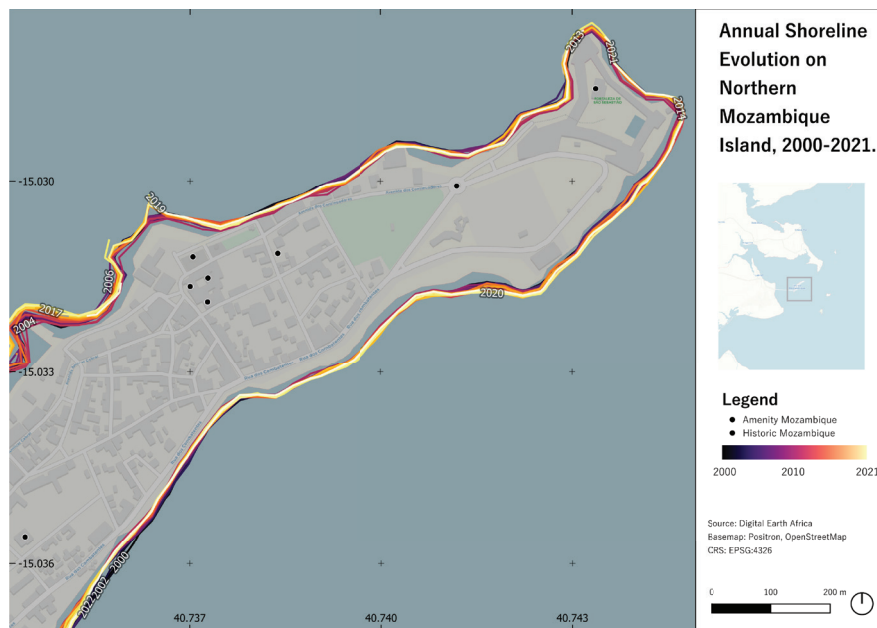
Integrated Heritage Risk Characterisation

Ilha de Moçambique’s vulnerability is defined by the convergence of chronic thermal and salinity stress with high marine energy and intense seasonal hydrological activation. Unlike sites dominated by slow material fatigue alone, risk here manifests through both cumulative degradation and recurrent acute damage, with limited recovery time between events. This creates a high likelihood of progressive fabric loss in the absence of sustained, adaptive conservation measures. Shoreline Change and Coastal Dynamics

Stress Type	Qualitative Level	Key Characteristics
Thermal stress (SST)	Moderate–High (chronic)	Persistently warm conditions; limited seasonal relief
Salinity stress (SSS)	Moderate	Constant saline exposure; prolonged material saturation
Wave exposure (SWH)	High	Frequent storm-driven wave energy; foundation destabilisation
Rainfall / hydrological stress	High	Intense rainy season; recurrent flooding and waterlogging

Table 2. Environmental stress summary for Mozambique Island

A. Shoreline Position Through Time (2000–2021)



Figures 31, 32, 33: Shoreline position through time at Mozambique Island, 2000–2021.
Source: Digital Earth Africa.

Observation

The annual shoreline position maps show pronounced spatial and temporal variability along the coastline of Ilha de Moçambique between 2000 and 2021. Shoreline traces indicate repeated landward and seaward shifts, with several sections—particularly along the eastern and southern flanks—showing noticeable landward displacement over time. In contrast to Gorée Island, shoreline positions do not cluster tightly, and interannual differences are visible across most segments of the island.

Analysis

These patterns indicate an actively mobile shoreline regime, reflecting the island's low elevation, coral limestone base, and exposure to open-ocean and lagoonal processes. The repeated landward shifts suggest episodic erosion and overtopping, likely associated with storm surge, high wave events, and seasonal hydrodynamic forcing. The lack of long-term positional convergence implies that the shoreline has not stabilised within a narrow envelope, increasing uncertainty in coastal boundary conditions and exposure for the built environment.

B. Rates of Shoreline Change (2000–2021)

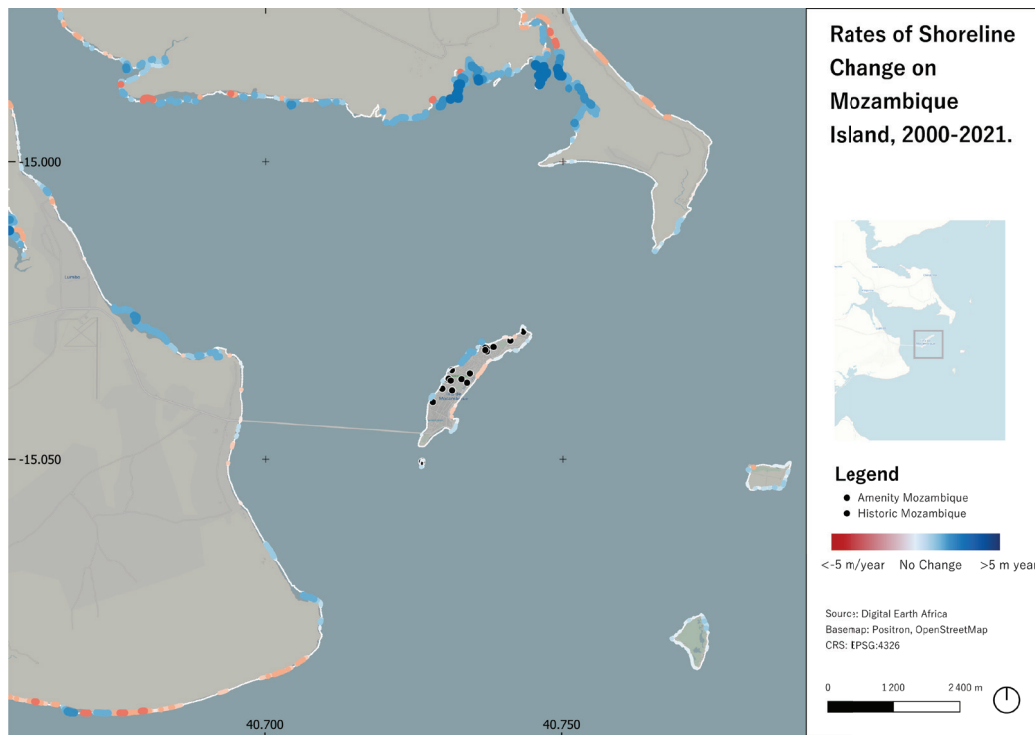


Figure 34: Rates of shoreline change at Mozambique Island, 2000–2021. Source: Digital Earth Africa.

Observation

The shoreline change rate map reveals marked spatial heterogeneity, with multiple coastal segments exhibiting moderate to high rates of both erosion and accretion. Several areas along the northern and eastern margins display positive change rates exceeding +5 m/year, while adjacent sections show localized retreat. Unlike Gorée, extended stretches of the coastline fall outside the “no change” category, indicating sustained geomorphological adjustment rather than short-term oscillation.

Analysis

The coexistence of high accretion and erosion rates suggests an energetic and redistributive coastal system, where sediment is frequently reworked rather than retained. This behaviour is consistent with strong wave energy, cyclone influence, and altered sediment supply linked to reef degradation and mangrove loss. From a heritage perspective, such spatially uneven shoreline change increases the likelihood of localized exposure hotspots, where erosion, inundation, or foundation undermining may intensify over relatively short timescales.

C. Implications for Heritage Exposure

At Ilha de Moçambique, shoreline dynamics represent a direct and significant driver of heritage exposure, rather than a background condition. Active shoreline mobility increases the frequency and extent of coastal overtopping, foundation saturation, and saltwater intrusion into soils and lower wall zones. These processes interact strongly with the island’s persistent thermal, salinity, and rainfall stress, reducing recovery time between damaging events and accelerating structural weakening of coral stone masonry and lime mortars.

Unlike sites with stable coastlines, the historic fabric of Ilha de Moçambique is subject to both chronic environmental stress and recurrent physical disturbance, amplifying long-term degradation pathways. Shoreline change therefore plays a central role in shaping vulnerability at this site, acting as a primary exposure mechanism that magnifies the impact of other environmental stressors on both monumental and vernacular heritage structures.



SITE PROFILES:

4.3. LAMU, KENYA



Figure 35: Lamu City, drone view (2024). Aerial photograph by Iconem.

UNESCO World Heritage Site (2001), ID 1055

Coordinates: 2° 16' 10" S, 40° 54' 08" E

Architectural and Material Profile

Lamu Old Town is located on a low-lying coral island within the Lamu Archipelago and represents one of the most complete surviving examples of traditional Swahili urbanism. The historic fabric is constructed primarily of coral stone masonry bonded with lime mortar, with mangrove poles (boriti) used extensively for roofing and structural support, alongside timber doors and decorative elements. The dense urban morphology limits rapid drainage and concentrates runoff, increasing exposure of foundations and lower wall zones to moisture-related stress. Close interaction with tidal channels and surrounding mangrove systems further intensifies sensitivity to salinity and humidity.



Figure 36: Lamu Old town and its cultural heritage sites.



Figure 37: Lamu Old Town, a World Heritage Site (2023). Photo by Almaddy2022, licensed under CC BY-SA 4.0

Source: Wikimedia Commons



Figure 38: Minaret of a mosque on Lamu Old Town's seafront, Kenya (2022). Photo by Ahmedshayo14, licensed under CC BY-SA 4.0

Source: Wikimedia Commons.

Environmental–Heritage Stress Analysis

Thermal Stress (Sea Surface Temperature):

Sea surface temperatures remain consistently warm throughout the year, with annual maxima averaging ~29.2 °C and exceeding 30.5 °C in recent years. Cool-season temperatures show limited variability, averaging ~25.8 °C, resulting in a moderate mean thermal amplitude of ~3.4 °C (2014–2024).

Heritage risk implication:

This regime reflects chronic heat and humidity rather than strong seasonal cycling. Persistent warmth limits drying of coral stone masonry and lime mortars, sustaining internal moisture, salt activity, and biological growth. Timber elements, particularly mangrove poles, are especially vulnerable to accelerated decay. Thermal stress therefore acts primarily as a background amplifier of salinity- and moisture-driven degradation rather than a dominant cyclic stressor.

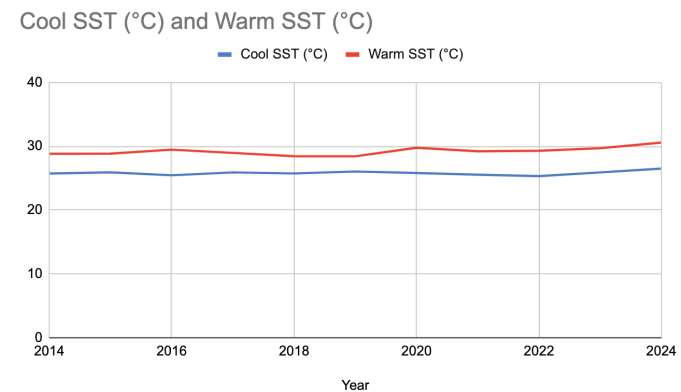


Figure 39: Sea surface temperature (cool and warm seasons) at Lamu, 2014–2024. Source: Copernicus Marine Service.

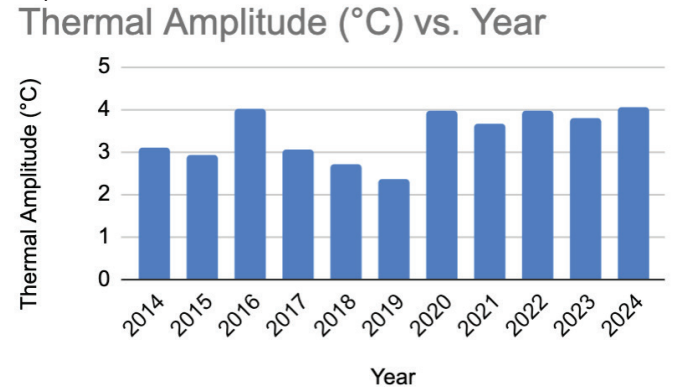


Figure 40 Thermal amplitude at Lamu, 2014–2024. Source: Copernicus Marine Service.

Chemical Stress (Marine Salinity):

Salinity levels remain persistently high, with annual maxima averaging ~35.0 PSU and minimum values remaining elevated throughout the period. Mean seasonal salinity amplitude is moderate (~2.16 PSU), with regular oscillation but no sustained long-term trend.

Heritage risk implication:

This salinity regime constitutes a chronic chemical stress on Lamu’s coral stone and lime-based materials. Continuous salt availability, combined with sustained moisture, promotes repeated dissolution–crystallisation cycles that drive surface scaling, granular disintegration, and loss of plaster finishes. Because seasonal dilution is limited, salt stress is continuous rather than episodic, increasing the likelihood of cumulative long-term damage. Timber elements are indirectly affected through saline aerosols and high ambient humidity, further accelerating biological degradation.

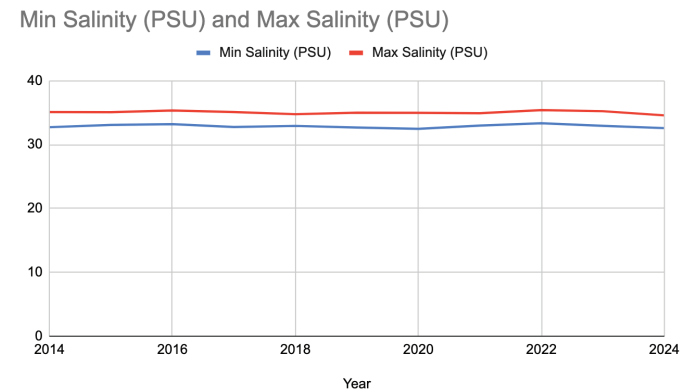


Figure 41: . Sea surface salinity (minimum and maximum) at Lamu, 2014–2024. Source: Copernicus Marine Service.

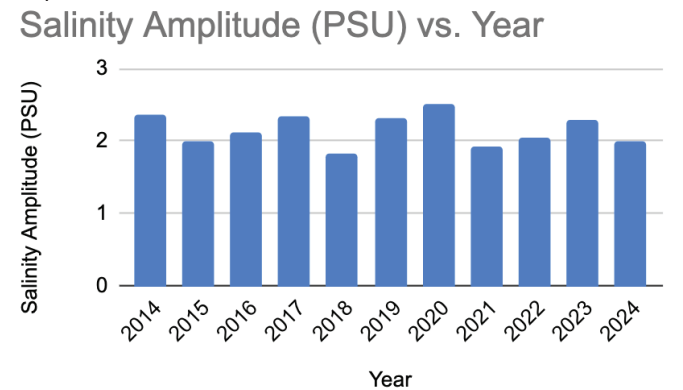


Figure 42: Salinity amplitude at Lamu, 2014–2024. Source: Copernicus Marine Service.

Wave conditions are generally moderate, with annual maximum significant wave heights averaging ~ 1.93 m and episodic peaks exceeding 2.3 m in several years. Minimum wave heights remain low (~ 0.35 m), producing a mean wave height amplitude of ~ 1.58 m.

Wave energy at Lamu operates primarily as an episodic triggering stress rather than a constant mechanical force. Seasonal storms increase salt spray and aerosol transport, accelerating façade weathering and surface erosion of coral stone and lime plaster. Wave-driven processes also contribute indirectly to coastal flooding and localised shoreline instability, particularly where mangrove buffers are degraded. Although not the dominant driver of degradation, wave energy amplifies salinity and rainfall impacts during storm periods, contributing to cumulative material fatigue.

Year	Max SWH (m)
2014	1.75
2015	1.60
2016	2.40
2017	1.55
2018	1.95
2019	1.95
2020	2.35
2021	2.15
2022	1.85
2023	1.65
2024	1.85

Source: Copernicus Marine Service.

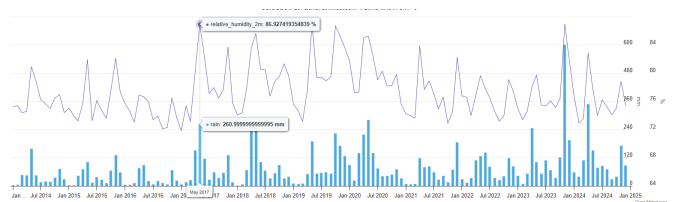
The line graph displays the SWH Amplitude in meters over a ten-year period from 2014 to 2023. The y-axis, labeled 'SWH Amplitude (m)', ranges from 0.0 to 2.5 with increments of 0.5. The x-axis, labeled 'Year', shows the years from 2014 to 2023. The amplitude starts at approximately 1.4m in 2014, dips to 1.3m in 2015, rises to a peak of 2.0m in 2016, falls to 1.2m in 2017, and then generally trends upwards to another peak of 2.0m in 2020. After 2020, the amplitude decreases to 1.5m in 2022 and 2023, with a slight recovery to 1.4m in 2024.

Year	SWH Amplitude (m)
2014	1.4
2015	1.3
2016	2.0
2017	1.2
2018	1.6
2019	1.65
2020	2.0
2021	1.8
2022	1.5
2023	1.4
2024	1.5

Source: Copernicus Marine Service.

Lamu experiences two rainy seasons (April–June and October–November), with high annual rainfall and recurrent coastal flooding and waterlogging affecting low-lying areas of the historic core.

Hydrological stress acts as both an activating and amplifying mechanism, saturating foundations, mobilising salts within porous masonry, and prolonging moisture retention in walls. Inadequate drainage exacerbates these effects, accelerating decay at ground level and weakening coral masonry over time. Rainfall and flooding therefore reinforce chemical and biological degradation processes rather than functioning as isolated hazards.



Source: Copernicus Marine Service.

Integrated Heritage Risk Characterisation

The environmental vulnerability of Lamu Old Town is defined by chronic, interacting pressures rather than extreme or rapidly escalating hazards. Persistent warmth and humidity, combined with continuously elevated salinity, make salt crystallisation and moisture retention the central drivers of decay in coral stone masonry and lime-based plasters. Moderate but episodic wave energy and recurrent rainfall events act as amplifiers, triggering accelerated deterioration during storm periods. Overall risk is long-term and cumulative, placing sustained strain on traditional materials and underscoring the importance of preventive maintenance, moisture management, and the protection of natural buffers such as mangroves and dunes.

Stress Type	Qualitative Level	Key Characteristics
Thermal stress (SST)	Moderate–High (chronic)	Consistently warm temperatures; high humidity
Salinity stress (SSS)	High	Elevated salinity with seasonal variability
Wave exposure (SWH)	Low–Moderate	Generally low energy; episodic storm-driven peaks
Rainfall / hydrological stress	Moderate–High	High annual rainfall; coastal flooding and waterlogging

Table 3. Environmental stress summary for Lamu

Shoreline Change and Coastal Dynamics

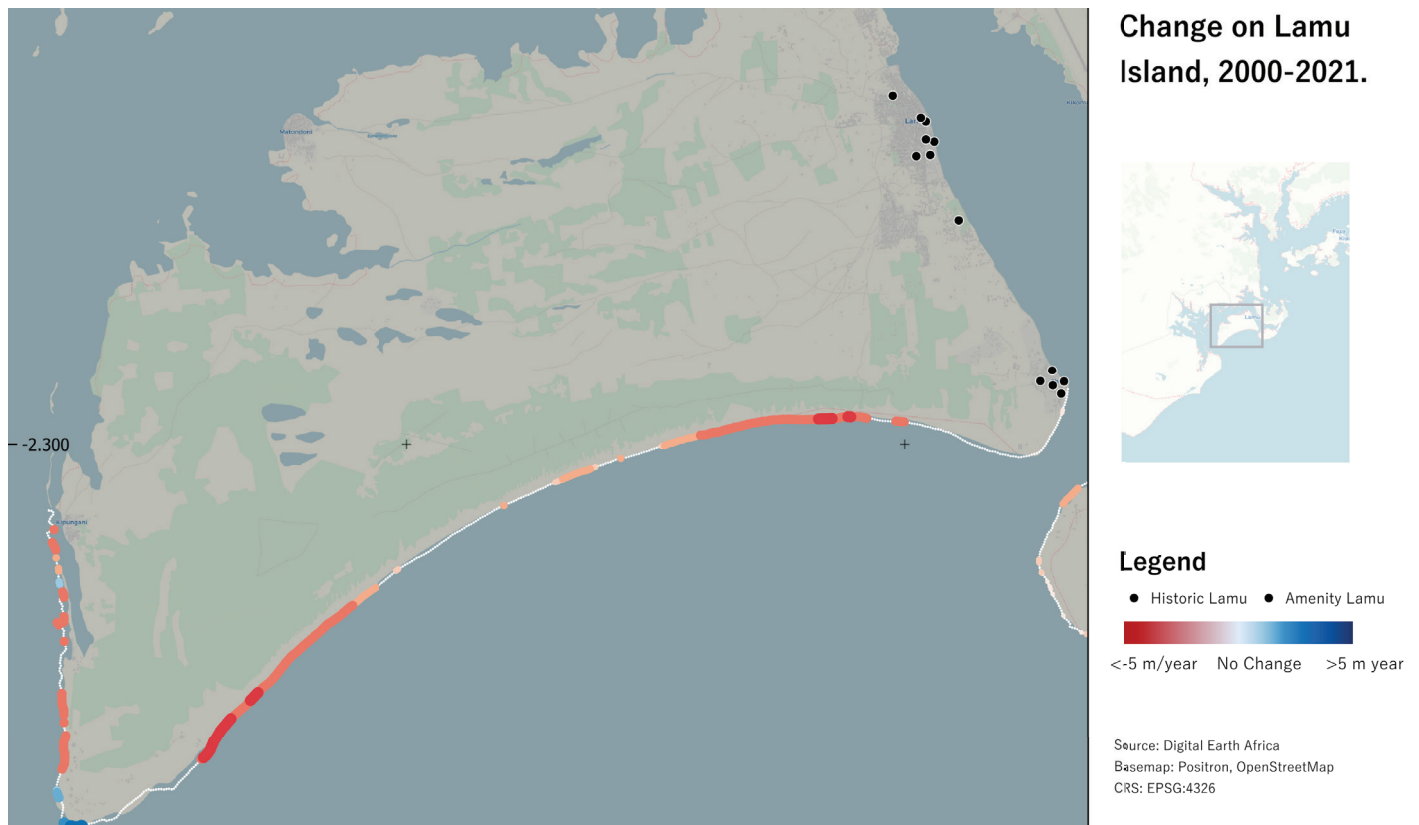


Figure 46 Rates of shoreline change at Lamu, 2000–2021.
Source: Digital Earth Africa.

A. Rates of Shoreline Change (2000–2021)

Observation

Shoreline change rate analysis for Lamu Island indicates spatially variable coastal behaviour, with pronounced erosion affecting several sections of the southern and western coastlines. These areas exhibit sustained negative change rates, locally exceeding -5 m/year, while other stretches of the island show limited change or localized accretion. The most pronounced shoreline retreat is concentrated away from the historic core of Lamu Old Town, particularly along exposed sandy shorelines.

Analysis

This pattern reflects the geomorphological diversity of Lamu Island, where sandy and dune-dominated coastlines experience higher mobility than sheltered urban and mangrove-fringed areas. The concentration of erosion along exposed margins suggests sensitivity to wave action, sediment redistribution, and the degradation of protective coastal ecosystems. However, the absence of strong erosion signals immediately adjacent to the historic core indicates that direct shoreline retreat is not currently the dominant exposure mechanism for Lamu Old Town.

B. Implications for Heritage Exposure

Integrated interpretation

Although shoreline change data do not directly capture conditions along the immediate perimeter of Lamu Old Town, island-scale erosion patterns provide important contextual insight. The erosion of peripheral shorelines can alter sediment dynamics, tidal exchange, and hydrodynamic conditions within the Lamu Archipelago, indirectly influencing flooding frequency, groundwater salinity, and mangrove stability near the historic settlement.

For the heritage fabric of Lamu Old Town, constructed primarily of coral stone, lime mortar, and mangrove timber, risk arises less from direct coastal retreat and more from chronic salinity, moisture retention, and episodic flooding, as previously identified in the environmental stress analysis. Shoreline dynamics therefore act as a secondary exposure modifier, shaping the broader coastal system in which the town is embedded rather than directly undermining its physical boundary.

This distinction underscores the importance of integrating geomorphological context with material-focused stress indicators, particularly in complex archipelagic settings where heritage vulnerability may not coincide spatially with zones of maximum shoreline change.

SITE PROFILES:

4.4. UNGUJA, TANZANIA





Figure 47: Stone Town of Zanzibar, United Republic of Tanzania (2009). Photo © UNESCO, licensed under CC BY-SA 3.0 IGO
Source: Wikimedia Commons.

UNESCO World Heritage Site (2000), ID 173

Coordinates: 6° 08' S, 39° 20' E

Architectural and Material Profile

Stone Town is located on the western coast of Unguja Island and represents a dense urban ensemble of Swahili stone architecture shaped by African, Arab, Persian, and Indian influences. The historic fabric is constructed primarily of coral stone masonry bonded with lime mortar, with lime-based plasters, timber elements, mangrove poles (boriti), and makuti roofing in associated structures. The compact urban morphology, coral rag substrate, and proximity to the shoreline limit drainage efficiency and increase exposure of lower wall zones and waterfront façades to moisture and salinity-related stress.



Figure 48: Zanzibar and its cultural heritage sites.

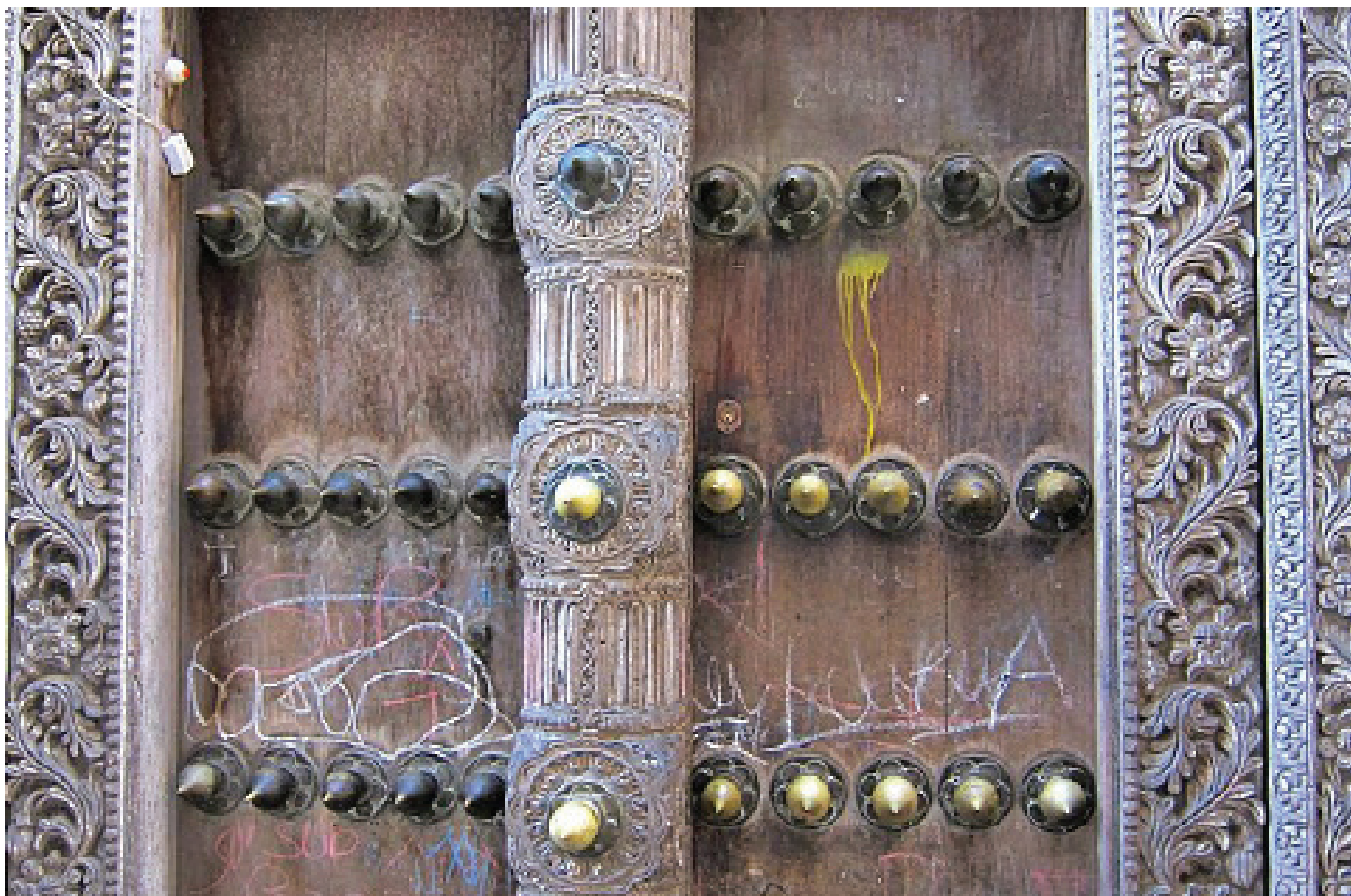


Figure 49: Zanzibar, Tanzania (2012). Photo by Martijn.Munneke, licensed under CC BY 2.0
Source: Wikimedia Commons



Figure 50: Waterfront of Stone Town, Zanzibar, Tanzania (2017). Photo by David Stanley, licensed under CC BY 2.0
Source: Wikimedia Commons

Environmental–Heritage Stress Analysis

Thermal Stress (Sea Surface Temperature)

Sea surface temperatures around Unguja remain persistently warm, with annual maxima averaging ~29.7 °C and exceeding 30 °C in multiple years after 2016. Cool-season temperatures remain high and stable, averaging ~25.9 °C, producing a moderate mean thermal amplitude of ~3.8 °C (2014–2024).

Heritage risk implication:

Persistent heat and humidity limit drying of coral stone and lime plasters, sustaining internal moisture, salt activity, and biological growth. Timber elements and makuti roofing are indirectly affected through accelerated decay. Thermal stress thus acts as a continuous background driver, amplifying salinity- and moisture-related degradation.

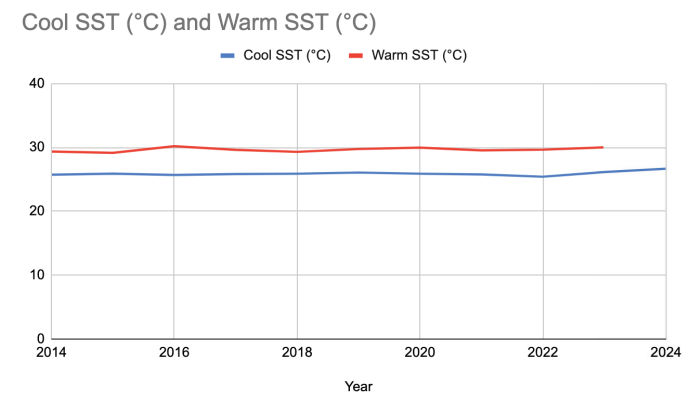


Figure 51: Sea surface temperature (cool and warm sesons) at Zanzibar, 2014–2024. Source: Copernicus Marine Service.

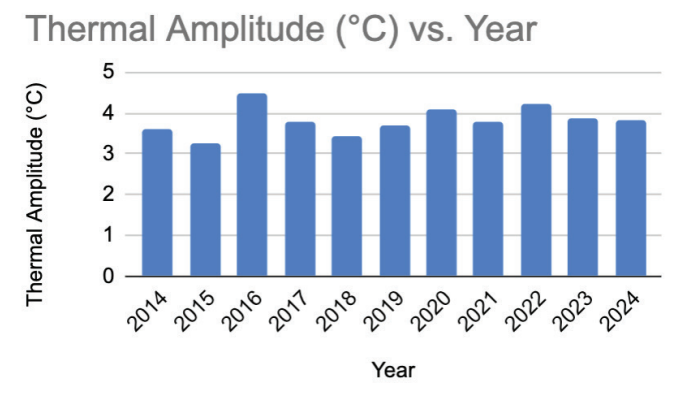


Figure 52: Thermal amplitude at Zanzibar, 2014–2024. Source: Copernicus Marine Service.

Chemical Stress (Marine Salinity)

Salinity levels remain consistently high, with annual maximum values averaging ~35.1 PSU and reaching ~35.4 PSU in several years. Minimum salinity values average ~33.1 PSU, but show increased interannual variability after 2019, with minima dropping below 32 PSU in 2024. Mean seasonal salinity amplitude is approximately ~2.0 PSU.

Heritage risk implication:

This salinity regime represents a high, persistent chemical stress on coral stone and lime-based finishes. Elevated salinity and seasonal dilution–reconcentration cycles promote repeated salt crystallisation, driving surface scaling, granular disintegration, and plaster loss, particularly on exposed façades and waterfront structures. Salinity therefore acts as a primary long-term driver of cumulative material decay, closely linked to thermal and hydrological stress.

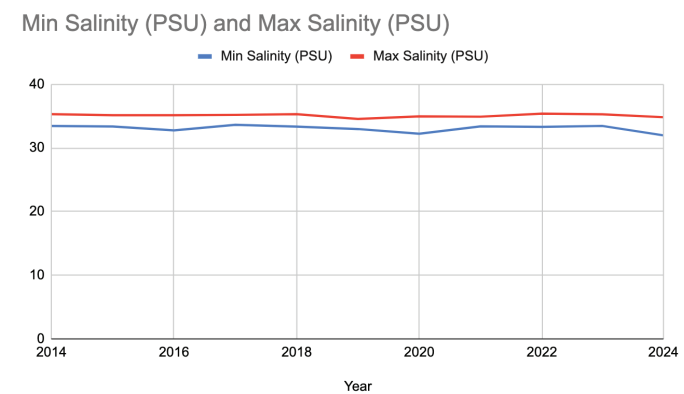


Figure 53: . Sea surface salinity (minimum and maximum) at Zanzibar, 2014–2024. Source: Copernicus Marine Service.

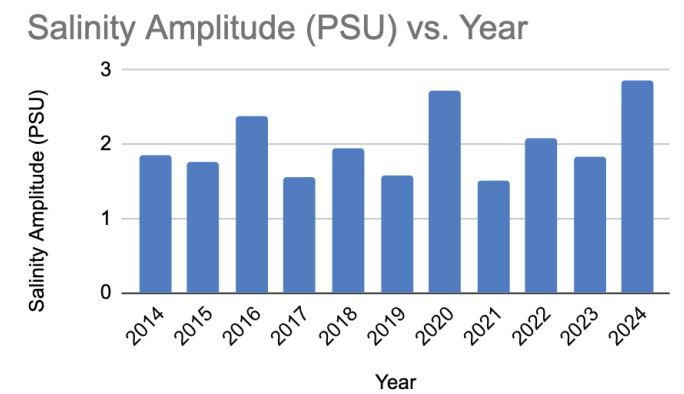


Figure 54: Salinity amplitude at Zanzibar, 2014–2024. Source: Copernicus Marine Service.

Marine Energy Exposure (Wave Height)

Wave conditions around Unguja are generally low to moderate, with annual maximum significant wave heights averaging ~ 0.92 m. Most years remain below 1.1 m, with an episodic peak of ~ 1.25 m recorded in 2024. Minimum wave heights are consistently very low (~ 0.07 m), resulting in a modest mean wave height amplitude of ~ 0.85 m.

Heritage risk implication:

Direct mechanical wave impact is not a dominant degradation driver for Stone Town. However, even moderate wave activity facilitates marine aerosol transport and salt spray deposition along the waterfront. Episodic wave peaks, particularly when coinciding with high tides or elevated sea levels, contribute to localised overtopping, splash erosion, and short-duration flooding. Wave energy thus acts as a secondary stressor, amplifying salinity- and moisture-driven decay rather than causing independent structural damage.

Max SWH (m) vs. Year

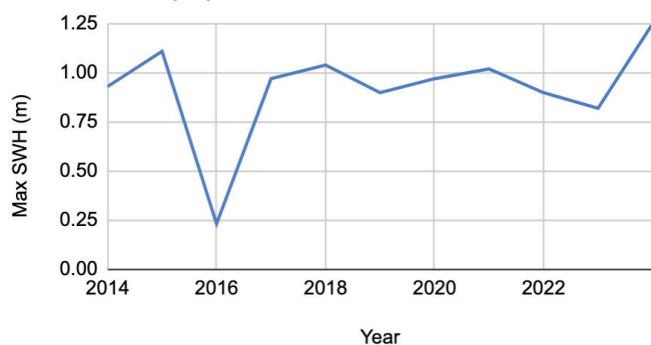


Figure 55: Maximum wave height at Zanzibar 2014–2024.

Source: Copernicus Marine Service.

SWH Amplitude (m) vs. Year

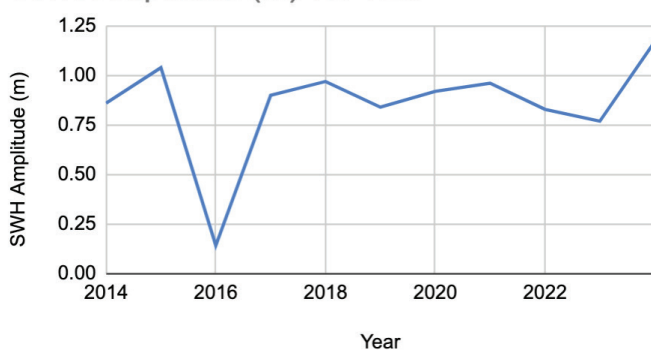


Figure 56: Wave height amplitude at Zanzibar, 2014–2024.

Source: Copernicus Marine Service.

Hydrological Stress (Rainfall and Humidity)

Rainfall and near-surface relative humidity data indicate a highly active hydrological stress environment, consistent with Unguja's tropical monsoon climate. Annual rainfall is high and seasonally concentrated, while relative humidity remains persistently elevated throughout the year, with limited dry-season relief.

Heritage risk implication:

The combination of intense seasonal rainfall and sustained atmospheric humidity promotes repeated wetting–drying cycles and prolonged moisture retention within walls. Rainfall mobilises salts stored in porous coral masonry, while slow drying prolongs crystallisation activity and biological growth. Inadequate drainage exacerbates foundation saturation and lower-wall deterioration, particularly in low-lying areas of Stone Town. Hydrological stress therefore acts as a key activating and amplifying mechanism, reinforcing salinity- and thermal-driven degradation rather than functioning as an isolated hazard.

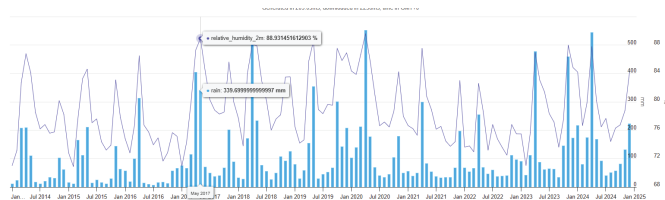


Figure 57: Rainfall and relative humidity at Zanzibar, 2014–2024.

Source: Copernicus Marine Service.

Integrated Heritage Risk Characterisation

The environmental vulnerability of Unguja (Stone Town) is defined by chronic, cumulative stress arising from the interaction of persistent warmth, high humidity, and elevated marine salinity within a generally low-energy wave environment. Salinity and moisture retention are the principal drivers of material degradation, while episodic wave activity and heavy rainfall act as secondary amplifiers during storm periods. Risk manifests primarily as progressive surface and material loss rather than abrupt structural failure, placing sustained pressure on coral stone architecture and lime-based finishes and underscoring the importance of moisture management, compatible repairs, and careful management of the historic waterfront.

Shoreline Change and Coastal Dynamics

Stress Type	Qualitative Level	Key Characteristics
Thermal stress (SST)	Moderate–High (chronic)	Persistently warm temperatures; high humidity
Salinity stress (SSS)	High	Elevated salinity with seasonal variability
Wave exposure (SWH)	Low–Moderate	Generally low energy; episodic increases
Rainfall / hydrological stress	Moderate–High	High rainfall; coastal flooding risk

Table 4. Environmental stress summary for Zanzibar

A. Shoreline Position Through Time (2000–2021)

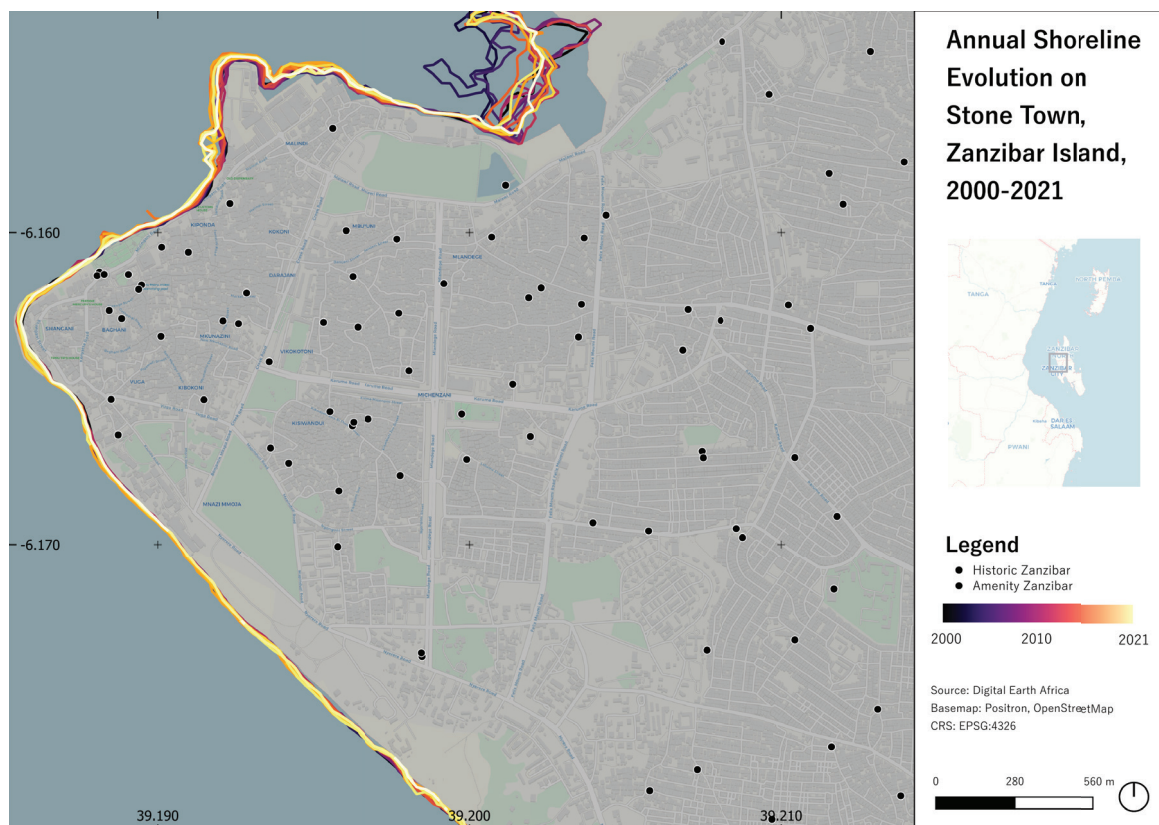


Figure 58 Shoreline position through time at Zanzibar, 2000–2021.
Source: Digital Earth Africa.

Observation

Annual shoreline position data indicate that the coastline around Unguja Island has undergone localized but persistent shoreline movement over the 2000–2021 period. At the island scale, many coastal segments show limited net displacement, with shoreline positions remaining relatively clustered. However, at the scale of Stone Town, the annual shoreline traces reveal clear positional variability, particularly along the western waterfront and harbour-facing sections. In these areas, successive shoreline positions display small but repeated landward and seaward shifts rather than convergence on a stable median line, indicating ongoing shoreline adjustment rather than long-term fixation.

Analysis

This pattern suggests a low-energy but dynamically responsive shoreline, where gradual processes such as tidal reworking, sediment redistribution, and sea-level rise interact with urban waterfront structures. While the magnitude of annual movement is modest compared to highly erosive systems, the persistence of positional variability at the historic core indicates that the shoreline is not static. This creates a setting in which even small changes in coastal position can influence flooding pathways, groundwater salinisation, and exposure of waterfront infrastructure over time.

B. Rates of Shoreline Change (2000–2021)

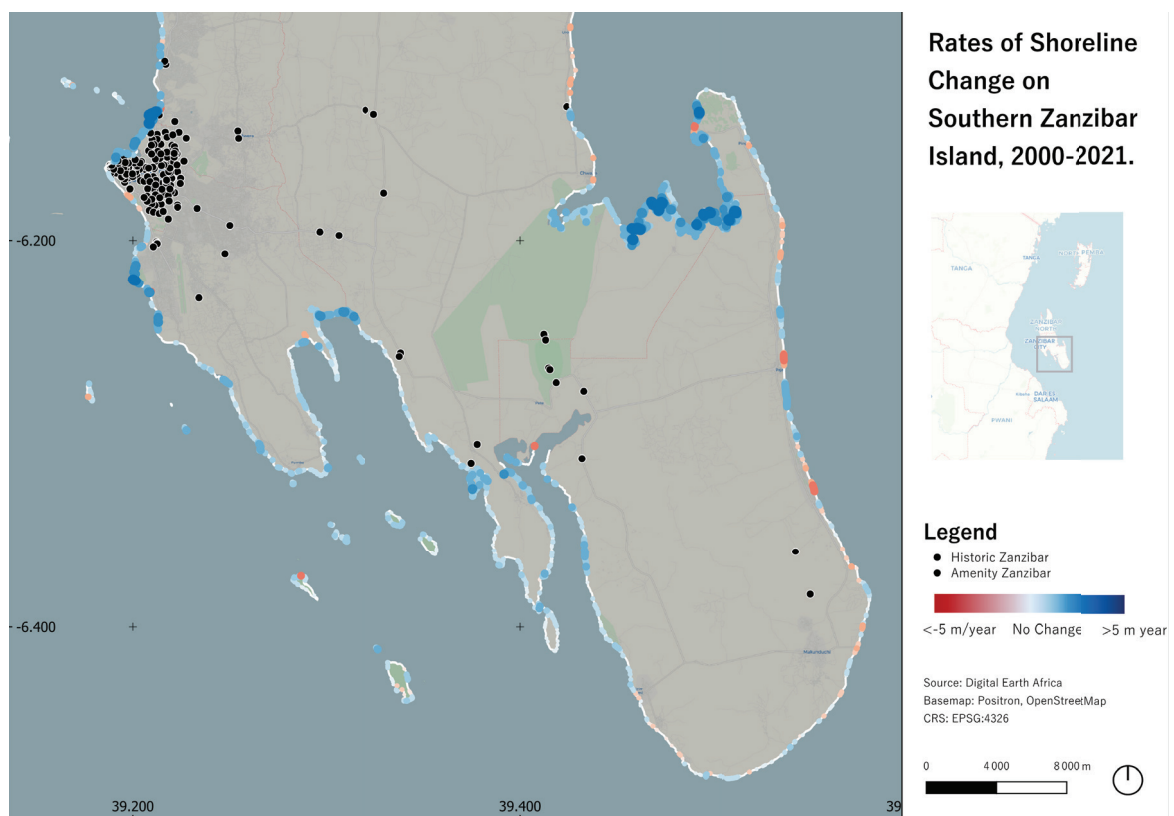
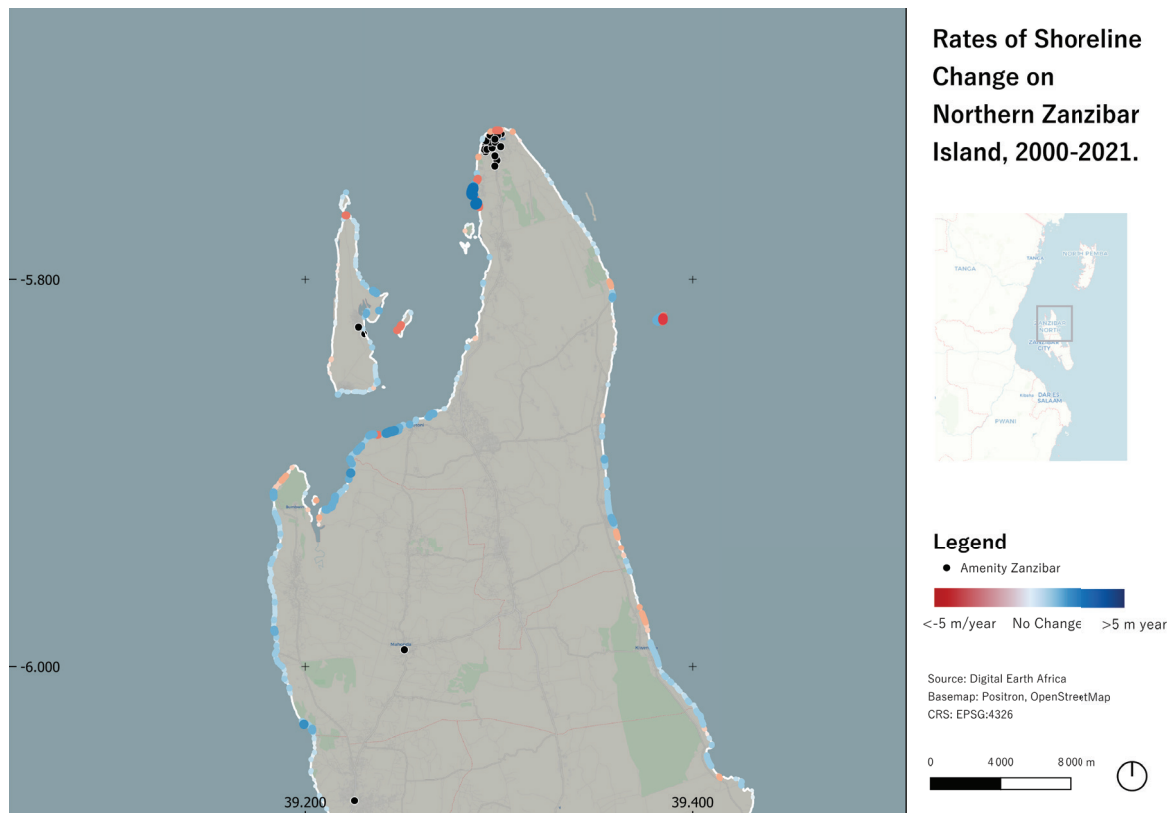


Figure 59 Rates of shoreline change at Zanzibar, 2000–2021.
Source: Digital Earth Africa.

Observation

The shoreline change rate maps show that much of Unguja's coastline falls within the "no change" to low-change categories, with limited stretches of pronounced erosion or accretion. Higher rates of accretion are visible along parts of the eastern and southern coasts, while isolated sections exhibit moderate erosion. Around Stone Town, shoreline change rates are generally low, with no extended segments showing sustained high retreat.

Analysis

The dominance of low shoreline change rates indicates that direct coastal erosion is not currently the primary exposure mechanism for Stone Town's heritage fabric. Instead, the shoreline appears to be constrained by a combination of coral geology, shallow nearshore bathymetry, and built waterfront structures. However, this apparent stability should not be interpreted as reduced vulnerability: low retreat rates can coexist with increasing flood frequency and saltwater intrusion, particularly in low-lying urban settings where even minor shoreline adjustments alter tidal and drainage dynamics.

C. Implications for Heritage Exposure

At Unguja, shoreline dynamics represent a secondary but enabling exposure pathway rather than a dominant driver of heritage loss. The relative stability of the shoreline around Stone Town limits the risk of rapid structural undermining by erosion, but persistent positional variability facilitates recurrent inundation, moisture retention, and saline groundwater interaction within the historic urban fabric.

In this context, shoreline behaviour amplifies chronic environmental stress, particularly salinity and humidity, by sustaining wet conditions along the waterfront and limiting natural drainage. Heritage vulnerability at Stone Town is therefore shaped less by shoreline retreat and more by the interaction between a low-energy, quasi-stable coastline and ongoing sea-level rise, tidal forcing, and urban hydrological constraints.

5. Cross-Site Patterns and Heritage Vulnerability Types

Comparison across the four case studies demonstrates that coastal heritage vulnerability is shaped primarily by the persistence, amplitude, and interaction of environmental stresses, rather than by the frequency of discrete disaster events or the presence of rapid shoreline retreat alone. Across all sites, sustained marine influence is evident; however, the structure and dominance of stress regimes vary markedly, producing different pathways of material degradation.

Thermal stress differentiates sites characterised by high seasonal thermal amplitude from those dominated by persistently elevated temperatures and humidity.

At Gorée Island, strong seasonal temperature contrasts promote repeated expansion–contraction cycles that contribute to material fatigue.

In contrast, Ilha de Moçambique, Unguja, and Lamu experience chronically warm conditions that limit drying, prolong moisture retention, and intensify chemical and biological decay processes.

Salinity emerges as a dominant and universal driver of heritage degradation across all sites, but with differing modes of action. Gorée and Unguja exhibit active seasonal salinity cycling, increasing the frequency of salt dissolution–crystallisation events and surface deterioration. Ilha de Moçambique and Lamu are characterised by near-continuous saline exposure, favouring deep salt penetration, long-term weakening of coral stone and lime mortars, and cumulative loss of material integrity.

Marine energy exposure varies substantially between sites. Ilha de Moçambique is distinguished by recurrent high wave energy, producing frequent overtopping, flooding,

and limited recovery time between damaging events. In contrast, Lamu and Unguja experience lower baseline wave energy, with wave action acting primarily as an episodic amplifier of salt spray and moisture ingress rather than as a dominant mechanical stressor. Hydrological stress plays a critical activating role across all sites. Seasonal rainfall and high humidity mobilise stored salts, extend wetting phases, and intensify decay processes, particularly where drainage capacity is limited. In all cases, degradation is cumulative, resulting from repeated stress activation rather than from isolated extreme events.

Taken together, these findings demonstrate that similar construction materials can experience fundamentally different degradation pathways, depending on how thermal, chemical, hydrological, and marine stresses interact locally. Hazard intensity alone is therefore insufficient to characterise heritage risk without consideration of long-term stress behaviour and material response.

Heritage Vulnerability Types:

Based on the cross-site analysis, four transferable coastal heritage vulnerability types are identified. These types represent generalised stress–material interaction profiles applicable beyond the study sites.

Type I — Thermo-Chemical Cycling Vulnerability

Characterised by strong seasonal thermal amplitude combined with active salinity cycling. Material decay is driven by repeated expansion–contraction and salt crystallisation, resulting in surface powdering, micro-cracking, and plaster loss.

Implication for action: prioritise salt management, surface protection, and preventive maintenance.

Type II — Chronic Multi-Stress Coastal Vulnerability

Defined by persistently high salinity, sustained warmth, intense rainfall, and recurrent high wave energy. Degradation occurs through cumulative chemical weakening combined with episodic structural disturbance, with limited recovery time between events.

Implication for action: address drainage, foundation stability, and material resilience in an integrated manner.

Type III — Moisture-Amplified Chemical Vulnerability

Dominated by chronic heat, high humidity, and continuous saline exposure under moderate wave conditions. Decay is driven by prolonged moisture retention, biological growth, and deep salt penetration rather than direct mechanical damage.

Implication for action: focus on moisture control, ventilation, and compatible repair materials.

Type IV — Low-Energy Urban Salinity Vulnerability

Occurs in relatively sheltered wave environments with high salinity and strong seasonal hydrological activation. Degradation is gradual but pervasive, affecting façades and lower wall zones through cumulative salt and moisture stress.

Implication for action: improve fine-scale monitoring and preventive conservation, as risk is often underestimated.

These vulnerability types provide a practical framework for prioritisation and intervention, enabling heritage managers and planners to align conservation strategies with dominant stress mechanisms rather than generic hazard categories.

6. What Can Be Done Now

From Risk Identification to Action-Oriented Heritage Management

The analyses presented in this report demonstrate that climate-related risk to coastal heritage is already materialising through slow, cumulative processes rather than sudden catastrophic events alone. While large-scale projections and disaster databases are essential for understanding future exposure, effective action on the ground depends on recognising early warning signals and intervening before degradation becomes irreversible.

This section translates the study's findings into practical guidance for heritage authorities, planners, and decision-makers. Rather than prescribing site-specific engineering solutions, it outlines near-term priorities, monitoring signals, and preventive strategies that can be applied across diverse coastal heritage contexts.

6.1 Likely Trajectories of Coastal Heritage under Current Conditions

Based on cross-site patterns observed in the case studies, three broad qualitative trajectories can be identified. These are not forecasts, but plausible pathways reflecting how heritage sites respond to sustained environmental stress under different levels of intervention.

Trajectory 1: Business-as-Usual (Chronic Degradation)

If current management practices remain unchanged, most coastal heritage sites are likely to experience gradual but accelerating material degradation. Persistent salinity exposure, thermal stress, and moisture retention will continue to weaken coral stone,

lime mortars, and earthen construction. Damage accumulates incrementally, through plaster loss, cracking, surface erosion, and biological growth, often remaining below emergency thresholds until conservation options become limited and costly.

Trajectory 2: Stress Amplification under Climate Intensification

Under conditions of increasing heat persistence, altered rainfall patterns, and episodic flooding, existing stress regimes intensify. Sites with limited drainage capacity, low elevation, or direct marine exposure become more vulnerable to compound effects, including foundation wetting, salt mobilisation, and structural instability. In this trajectory, damage accelerates not because of new hazards, but because recovery time between stress cycles diminishes.

Trajectory 3: Preventive Adaptation and Risk Containment

Where early warning signals are monitored and preventive measures are implemented, degradation can be slowed and, in some cases, stabilised. This trajectory relies on managing dominant stress mechanisms, particularly moisture and salinity, before visible damage escalates. While environmental exposure cannot be eliminated, heritage loss can be substantially reduced through targeted, low-regret interventions aligned with material behaviour.

6.2 Early Warning Signals and Monitoring Priorities

A key finding of this study is that heritage risk becomes visible well before structural failure or shoreline loss occurs. Monitoring a limited set of indicators can provide actionable insight into when intervention is needed.

The following signals are recommended as priority monitoring metrics for coastal heritage

Indicator	Signal of Concern	Interpretation for Heritage Risk
Persistent high salinity exposure	Recurrent seasonal salinity peaks with limited relief	High risk of salt crystallisation, plaster loss, and masonry weakening
Reduced drying periods	Sustained high humidity or rainfall	Prolonged moisture retention, biological growth, and salt mobilisation
Thermal persistence or strong seasonal amplitude	Chronic warmth or large seasonal temperature swings	Material fatigue, cracking, and increased permeability
Episodic flooding or overtopping	Flood events recurring within short intervals	Foundation wetting, erosion of pavements, and accelerated decay
Localised shoreline change near heritage clusters	Retreat or instability adjacent to built fabric	Increased exposure and loss of protective buffers

These indicators are deliberately simple and can be tracked using a combination of satellite data, site observations, and routine inspections. Importantly, none require high-resolution modelling or specialised instrumentation to be operationally useful.

6.3 Strategic Priorities for Immediate Action

Drawing on the comparative analysis and vulnerability typologies, five strategic priorities emerge for near-term action.

1. Shift from Hazard-Based to Stress-Based Management

Conservation planning should move beyond a focus on discrete hazards (e.g. floods or storms) and instead address the dominant stress regimes driving long-term material decay. Persistent salinity, moisture retention, and thermal stress are often more damaging than rare extreme events.

2. Prioritise Preventive Maintenance over Emergency Repair

Routine actions, such as improving drainage, managing salt accumulation, repairing compatible plasters, and ensuring ventilation, offer disproportionate benefits compared to post-damage reconstruction. Preventive measures are especially critical for coral stone and earthen heritage, where decay accelerates rapidly once protective layers are lost.

3. Integrate Heritage into Coastal Resilience Planning

Heritage sites should be explicitly included in coastal adaptation strategies alongside infrastructure and housing. This includes recognising historic urban cores as exposure zones, aligning heritage conservation with flood management and shoreline stabilisation, and avoiding protective measures that inadvertently trap moisture or salts in historic fabric.

4. Protect and Restore Natural Buffers

Mangroves, reef flats, beaches, and vegetated coastal margins play a critical role in moderating wave energy, moisture, and sediment dynamics. Their degradation increases stress on adjacent heritage structures. Where feasible, restoring or maintaining these buffers offers a low-regret adaptation option with co-benefits for ecosystems and communities.

5. Use Open-Access Geospatial Tools as Decision Support

Freely available satellite platforms provide sufficient resolution to detect changes relevant to heritage risk. Embedding these tools into routine heritage management—rather than treating them as research-only resources, can improve early detection, prioritisation, and accountability.

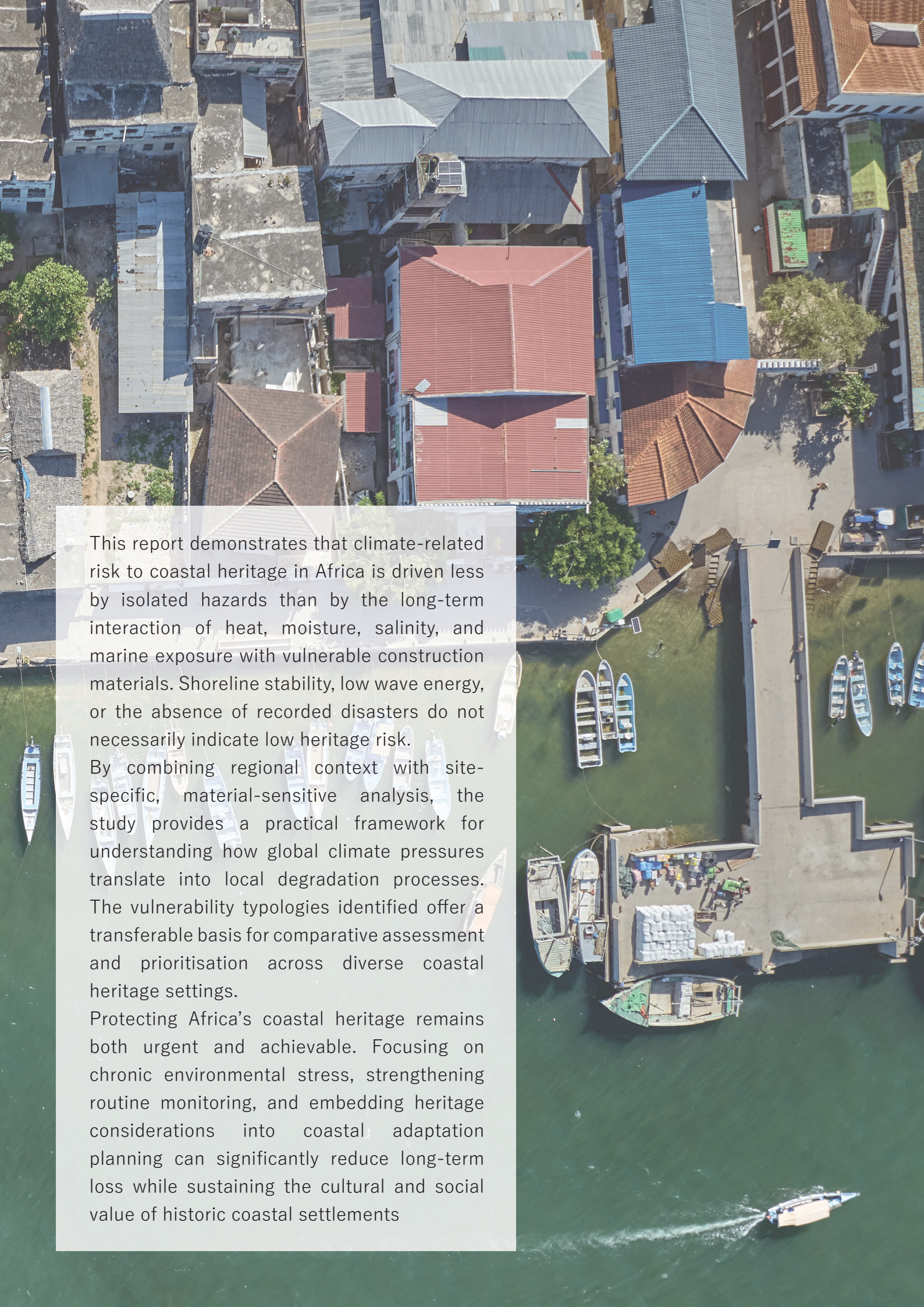
6.4 Positioning Disaster Risk within Long-Term Heritage Protection

While disaster events remain an important component of coastal risk, this study shows that disaster frequency alone is not a reliable proxy for heritage vulnerability. Many sites experience severe material degradation in the absence of frequent declared disasters, while others endure episodic shocks but recover due to favourable stress conditions or maintenance regimes.

Effective heritage protection therefore requires combining disaster preparedness with continuous monitoring of chronic environmental stress. This integrated perspective enables decision-makers to act before crises emerge, reducing both cultural loss and long-term intervention costs.

7. Conclusions



An aerial photograph of a coastal town. The top half shows a dense cluster of buildings with various roof colors: grey, blue, red, and brown. Some buildings have corrugated metal roofs, while others have tiled roofs. A few trees are scattered among the buildings. The bottom half shows a body of water with several small boats, mostly white and blue, moored along a concrete pier. A larger boat with a yellow and blue hull is moving through the water, leaving a white wake. The water is a deep green color. The overall scene depicts a vibrant coastal community.

This report demonstrates that climate-related risk to coastal heritage in Africa is driven less by isolated hazards than by the long-term interaction of heat, moisture, salinity, and marine exposure with vulnerable construction materials. Shoreline stability, low wave energy, or the absence of recorded disasters do not necessarily indicate low heritage risk.

By combining regional context with site-specific, material-sensitive analysis, the study provides a practical framework for understanding how global climate pressures translate into local degradation processes. The vulnerability typologies identified offer a transferable basis for comparative assessment and prioritisation across diverse coastal heritage settings.

Protecting Africa's coastal heritage remains both urgent and achievable. Focusing on chronic environmental stress, strengthening routine monitoring, and embedding heritage considerations into coastal adaptation planning can significantly reduce long-term loss while sustaining the cultural and social value of historic coastal settlements

ANNEX A — Data Sources and Analytical Framework

A.1 Site Selection and Areas of Interest (AOIs)

This report focuses on four coastal case studies selected for their cultural significance, architectural value, and exposure to climate-related coastal stress:

- Gorée Island, Senegal
- Ilha de Moçambique, Mozambique
- Lamu Old Town, Kenya
- Unguja / Stone Town, Zanzibar, Tanzania

Each Area of Interest (AOI) corresponds to a historic coastal island settlement, nationally or internationally recognised for its heritage value and situated within a highly exposed coastal environment. The selection reflects both geographical diversity—spanning the Atlantic and Indian Ocean coasts—and contrasting exposure regimes, allowing for comparative assessment of environmental stress affecting coastal heritage.

A.2 Environmental Stress Indicators

Environmental pressure on coastal heritage sites was assessed using a set of simple, physically interpretable stress indicators directly linked to marine dynamics and material behaviour. Indicators were selected based on their relevance to coral stone, lime-based mortars, masonry, timber elements, and traditional coastal construction systems common across the case studies.

The following indicators were analysed for each AOI:

- Sea Surface Temperature (SST) — to characterise thermal stress and seasonal temperature cycling
- Sea Surface Salinity (SSS) — to assess salt availability and crystallisation stress in porous materials

- Significant Wave Height (SWH) — as a proxy for marine energy, wave exposure, and salt aerosol production
- Rainfall and Relative Humidity — to capture hydrological activation and moisture residence time

Marine indicators were derived from Copernicus Marine (MyOcean) datasets and analysed through a custom interactive platform (Heritage Watch AI).

Rather than focusing on daily variability, the analysis prioritised seasonal extremes and annual amplitudes, allowing environmental stress to be interpreted in terms of recurrence and persistence rather than isolated events.

For each indicator, the following values were extracted annually over the period 2014–2024:

- seasonal minimum
- seasonal maximum
- stress amplitude (maximum minus minimum)

This approach captures chronic and cyclical environmental stress, which is particularly relevant for long-term material degradation processes in historic structures.

A.3 Shoreline Change Analysis

Shoreline dynamics were analysed separately to assess long-term exposure to coastal retreat or accretion, particularly where heritage structures are located close to the shoreline or depend on coastal stability.

Shoreline change was assessed using Digital Earth Africa (DEA) products derived from the Landsat archive, providing consistent continental-scale coverage. Analysis focused on:

- historical shoreline position
- rates of shoreline retreat or advance
- spatial variability along different segments of each island's coastline

Where relevant, analysis was conducted at two spatial scales:

- macro-scale, to identify overall shoreline trends at island level
- micro-scale, focusing on shoreline segments adjacent to heritage concentrations

Shoreline trends were interpreted in relation to marine stress indicators (wave energy, sea-level tendencies) and known human interventions, such as coastal infrastructure or land reclamation.

A.4 Supporting Sources

Satellite-derived analyses were cross-referenced with:

- UNESCO World Heritage documentation and State of Conservation reports
- national and local heritage records
- scientific literature and historical sources
- existing coastal and climate studies

This multi-layered approach enabled environmental stress patterns to be interpreted in relation to architectural materials, urban form, and site-specific conditions.

ANNEX B — Regional Hazard and Exposure Context

B.1 Continental-Scale Assessments of Coastal Heritage Risk

This annex summarises findings from continental-scale studies that assess exposure of African cultural and natural heritage sites to sea-level rise, coastal flooding, and shoreline change.

In particular, it draws on a large-scale geospatial assessment published in *Nature Climate Change* (Vousdoukas et al., 2022), which compiled an inventory of 284 coastal heritage sites across Africa and overlaid these with hydrodynamic flood models and shoreline projections under two climate scenarios:

- RCP 4.5 (moderate emissions)

- RCP 8.5 (high emissions)

Exposure was assessed for a baseline year (2010) and projected to mid-century (2050) and end-of-century (2100), providing a scenario-based understanding of future risk.

B.2 Projected Exposure by Country

Results from this regional assessment indicate that coastal heritage exposure increases markedly under higher-emission scenarios, with particularly strong signals along the Indian Ocean coastline.

Approximate projected exposure of coastal heritage sites to coastal hazards (flooding and erosion), based on Vousdoukas et al. (2022), is summarised below (rounded values):

Mozambique and Tanzania emerge as among the most exposed contexts due to their long, low-lying coastlines and frequent storm activity, while Senegal shows high exposure in specific coastal zones despite more heterogeneous national patterns.

Country	2010 (km ²)	2050 RCP 4.5	2050 RCP 8.5	2100 RCP 4.5	2100 RCP 8.5
Kenya	285	285	900	400	1000
Senegal	800	800	2200	1000	3000
Mozambique	0	1000	7000	1000	8500
Tanzania	0	0	700	0	850

B.3 Interpretation and Limitations

While continental-scale assessments provide essential insight into broad exposure trends, they operate at coarse spatial resolutions and primarily capture hazard occurrence rather than material-specific vulnerability.

As a result, such assessments may underestimate risk at sites where degradation is driven by chronic environmental stress (e.g. salinity, thermal cycling, humidity) rather than by episodic flooding or erosion. This limitation reinforces the need for site-level, material-sensitive analysis, as presented in the main report.

outside formal adaptation and risk planning mechanisms.

By integrating geospatial analysis with heritage-focused interpretation, this report contributes to bridging that gap and supports the incorporation of cultural heritage into national and regional climate adaptation strategies.

ANNEX C — Policy and Strategic Context

This study aligns with a range of international and regional frameworks that recognise climate change as a critical threat to cultural heritage.

Key reference frameworks include:

- UNESCO Priority Africa, which identifies climate change and heritage preservation as strategic action areas
- UN Sustainable Development Goals, particularly
- SDG11.4 (protecting cultural and natural heritage)
- SDG 13.1 (strengthening resilience to climate-related hazards)
- UNFCCC Global Goal on Adaptation, which emphasises protection of vulnerable systems
- African Union Agenda 2063, which places cultural identity and sustainable development at the heart of continental progress

The 2025 UNESCO Global Assessment of Climate Risks to World Heritage Sites highlights that a significant share of Africa's cultural sites face moderate to severe exposure to sea-level rise and coastal flooding, yet remain