African Journal of Advanced Pure and Applied Sciences (AJAPAS)
Online ISSN: 2957-644X
Volume 4, Issue 4, 2025
Page No: 123-129
Website: https://aaasjournals.com/index.php/ajapas/index

ISI 2025: 1.126 SJIFactor 2024: 6.752 معامل التأثير العربي: 1.62

The Effects of Climate Change on Geological Structures in coastline Regions

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تأثيرات تغير المناخ على الهياكل الجيولوجية في المناطق الساحلية

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Received: August 07, 2025	Accepted: October 08, 2025	Published: October 12, 2025

Abstract:
Climate change is reshaping coastal zones by altering geomorphology and undermining geological stability. This article synthesizes evidence on three interlinked pathways—coastal erosion, seawater intrusion, and geohazard amplification—and explains how sea-level rise, intensifying storms, and anthropogenic pressure accelerate shoreline retreat, topsoil loss, and habitat degradation. We show that salinization of coastal aquifers reduces freshwater availability, degrades soil structure, and compromises agricultural output and critical infrastructure, thereby heightening risks of landslides, liquefaction, and structural failure. Cross-regional cases from the Niger Delta, Pakistan, and the Mediterranean demonstrate both the breadth of these impacts and the local specificities that shape exposure and vulnerability. The paper also evaluates intervention options spanning hard-engineering works, groundwater control, and GIS-supported risk mapping, alongside nature-based measures such as mangrove and wetland restoration. Finally, we outline adaptation and policy priorities to safeguard ecosystems and settlements, arguing for integrated coastal management that couples spatial planning with scenario-led monitoring to build resilience under ongoing climatic change.

Keywords: Coastal erosion, saltwater intrusion, sea-level rise, geological instability, climate change adaptation.

الملخص
يشكّل تغيّر المناخ عاملًا حاسمًا في إعادة تشكيل المناطق الساحلية من خلال التأثير على الخصائص الجيومورفولوجية وزعزعة الاستقرار الجيولوجي. يستعرض هذا البحث ثلاثة مسارات مترابطة ـ التعرية الساحلية، تسرب مياه البحر، وتفاقم المخاطر الجيولوجية ـ موضحًا كيف يؤدي ارتفاع مستوى سطح البحر وتزايد شدّة العواصف والضغوط البشرية إلى تسارع تراجع الشواطئ وفقدان التربة السطحية وتدهور النظم البيئية. كما يبيّن أن تملّح الخزانات الجوفية الساحلية يحد من توافر المياه العذبة ويؤدي إلى تدهور البنية الترابية وانخفاض الإنتاج الزراعي وتعريض البنى التحتية الحيوية لمخاطر الانهيارات والانزلاقات والسيولة الرملية وفشل الهياكل. وتوضح دراسات حالة من دلتا النيجر وباكستان وحوض البحر الأبيض المتوسط اتساع هذه التأثيرات وتفاوتها تبعًا للخصوصيات المحلية في التعرض والهشاشة. كما يتناول البحث استراتيجيات التدخل التي تشمل الحلول الهندسية التقليدية، وضبط المياه الجوفية، ورسم خرائط المخاطر بدعم نظم المعلومات الجغرافية، إلى جانب الحلول القائمة على الطبيعة مثل استعادة غابات المانغروف والأراضي الرطبة. وأخيرًا، يحدد الأولويات اللازمة للتكيّف والسياسات، مؤكدًا على أهمية الإدارة المتكاملة للمناطق الساحلية من خلال الدمج بين التخطيط المكاني والرصد القائم على السيناريوهات لبناء القدرة على الصمود في مواجهة التغيرات المناخية المستمرة.

الكلمات المفتاحية: تآكل السواحل، تسرب المياه المالحة، ارتفاع مستوى سطح البحر، عدم الاستقرار الجيولوجي، التكيف مع تغير المناخ.

1. Introduction

Global climate change is a multifaceted process that exerts significant influence on both natural ecosystems and human society. Among its most evident manifestations are the transformations in geological formations along coastlines. These areas, characterized by intense interactions between land and sea, exhibit heightened sensitivity to climatic variations [1]. Rising sea levels and intensifying storm surges trigger challenges such as shoreline erosion, saltwater flooding, and alterations in soil chemistry, thereby threatening both ecological balance and built infrastructure [2].

The geological transformations in coastal regions generate considerable environmental and economic repercussions. Elevated sea levels and storm activity accelerate erosion and soil depletion, jeopardizing natural habitats and man-made structures [3]. Concurrently, saltwater intrusion contaminates freshwater aquifers, undermining agricultural production and disrupting ecological stability [4]. Such developments directly impact local livelihoods and broader economic sustainability.

The adaptive capacity of coastal ecosystems to climate stressors is closely linked to the dynamic characteristics of their geological foundations. Variations in sea level influence sediment transport and deposition, reshaping coastal morphology and altering shoreline boundaries [1]. Empirical studies from the Baltic Sea demonstrate that climate change intensifies erosion and drives shoreline retreat, posing severe risks to both ecosystems and coastal communities [5].

Furthermore, geological alterations heighten the risks of groundwater salinization and freshwater scarcity. Intrusion of saline water into aquifers diminishes the quality of potable and irrigation water, thereby aggravating socio-economic vulnerabilities [4]. This reduction in freshwater availability further undermines regional stability and living conditions.

Addressing these challenges requires accurate assessment and monitoring. Advanced technologies such as remote sensing and Geographic Information Systems (GIS) have proven effective in mapping and analyzing climate-related impacts on coasts [3]. Nonetheless, findings indicate that additional research grounded in climate scenario modeling is needed to better anticipate future risks.

Accordingly, this study investigates the geological consequences of climate change in coastal zones and evaluates their long-term implications. The ultimate aim is to support the development of strategies that mitigate risks and foster resilience in the face of ongoing environmental change.

2. Coastal Erosion and Sea-Level Rise

2.1. Mechanisms of Coastal Erosion

Coastal erosion is a multifactorial process that reflects alterations in shoreline shape and structural integrity. These transformations are primarily influenced by natural dynamics such as wind, waves, currents, and rising sea levels. Climate change acts as an accelerator, intensifying these forces and disturbing the equilibrium of coastal ecosystems, thereby amplifying erosion risks [6]. Among the key drivers, sea-level rise plays a dominant role in initiating erosional activity. Research by Rasmussen, Sonnenborg, Goncear, and Hinsby demonstrated that higher sea levels, combined with drainage networks, promote saltwater intrusion and degrade coastal aquifers, threatening the long-term resilience of geological formations and ecosystems [7]. Additionally, greater storm intensity and wave energy accelerate sediment displacement along coasts, disrupting geological balance. Findings from Kont, Jaagus, and Aunap show that the Estonian coastline has undergone rapid morphological changes due to sea-level rise, with low-lying shores proving most susceptible [8].

2.2. Geological Transformations

Coastal geological transformations are the outcome of both natural drivers and anthropogenic pressures. Rising sea levels induced by climate change significantly alter sediment deposition and erosion patterns. Padmalal et al. investigated Holocene tropical lagoons and revealed that fluctuations in climate and sea levels reshaped coastal morphology in profound ways [9]. Another dimension of transformation is the salinization of aquifers. Ferguson and Gleeson highlighted how increased groundwater extraction, compounded by climate impacts, intensifies salinity in coastal aquifers, undermining freshwater sustainability [10]. Deltaic environments are particularly vulnerable; Abija, Abam, Teme, and Eze documented that the Niger Delta faces severe coastline retreat and long-term threats to agriculture and settlements as a result of rising seas and erosion [11].

2.3. Case Studies

Empirical studies worldwide illustrate the severe implications of erosion and sea-level rise, particularly in low-lying regions. For instance, Rabbani et al. analyzed Pakistan's coastline and found significant land loss, with socio-economic consequences for local populations, reinforcing the urgency of adaptive strategies [12]. In Morocco, Snoussi, Niazi, Khouakhi, and Raji employed GIS-based assessments to show that erosion imperils both urban and agricultural zones, underlining the necessity of robust planning frameworks [13]. Similarly, Danladi, Kore, and Gül identified that in Nigeria's Niger Delta, the combined effects of sea-level rise and anthropogenic activity drive shoreline retreat, requiring sustainable management measures [14]. A Mediterranean case study by

Rizzetto emphasized the threats posed to coastal tourism, advocating for a mix of engineering defenses and ecosystem-based approaches [15]. Finally, research on Indian lagoons by Ghorai and Sen revealed how heightened storm frequencies under climate change exacerbate ecological vulnerabilities, demanding immediate policy action [16].

Collectively, these studies underscore the acute vulnerability of coastal zones to climate stressors. Effective mitigation necessitates integrating engineering interventions with ecosystem-based protections to reduce the pace and impact of erosion.

3. Saltwater Intrusion and Soil Degradation

3.1. Processes Driving Saltwater Intrusion

Saltwater

Saltwater intrusion refers to the encroachment of seawater into groundwater reserves in coastal regions, driven by a combination of natural processes and human pressures [7]. Key factors such as rising sea levels, climate change, and overextraction of groundwater accelerate this phenomenon, undermining the quality of freshwater resources [10].

Sea-Level Rise: Rising sea levels elevate hydraulic pressure, forcing saltwater to penetrate deeper into freshwater aquifers. This accelerates salinization and diminishes the potability of groundwater, particularly in deltas and low-lying coasts [8].

Groundwater Overuse: Excessive withdrawal of groundwater for irrigation and industrial purposes decreases freshwater pressure in aquifers, creating favorable conditions for inland saltwater encroachment [6], [10]. This has been identified as a major factor disrupting ecological stability.

Storms and Flooding: Climate-driven increases in storm frequency and intensity trigger sudden inflows of seawater onto coastal lands, salinizing agricultural soils and altering their structural properties [17].

Drainage Canals and Infrastructure: Artificial channels and agricultural drainage systems act as conduits for saline water to migrate inland. Infrastructure expansion therefore compounds the threat of intrusion [7].

Table 1: Drivers of Saltwater Intrusion in Coastal Areas.

Driver	Mechanism
Sea-level rise	Increases hydraulic pressure, pushing seawater into aquifers [8]
Groundwater overuse	Reduces aquifer pressure, allowing saltwater to migrate inland [6], [10]
Storms and flooding	Storm surges transport seawater onto land, salinizing soils [17]
Drainage canals	Artificial channels provide pathways for inland saltwater migration [7].

3.2. Impact on Geological and Soil Composition

The intrusion of saltwater not only degrades groundwater quality but also fundamentally alters soil chemistry and structure.

- **Chemical Deterioration:** Saline infiltration drives ion exchange processes that lead to clay mineral dispersion and salt accumulation. This reduces soil permeability and restricts plant water absorption, thereby curtailing crop productivity [4].
- **Physical Deterioration:** Salinity causes soil compaction and hardening, lowering water retention and restricting plant growth. Flood-driven salt emergence can erode topsoil and deplete organic matter [13], [14].
- **Groundwater Aquifer Changes:** Aquifers exposed to prolonged salinization undergo chemical changes that are often irreversible, particularly when coupled with anthropogenic overuse and engineered drainage [10].
- **Ecological Impacts:** Saltwater encroachment diminishes biodiversity in sensitive ecosystems, leading to vegetation loss and faunal decline [16].

Table 2: Effects of Saltwater Intrusion on Soil and Aquifers.

Impact Type	Description
Chemical deterioration	Ion exchange and salt accumulation reduce soil permeability
Physical deterioration	Soil compaction and topsoil erosion reduce fertility
Aquifer degradation	Long-term chemical changes reduce freshwater drinkability
Ecological decline	Loss of vegetation and biodiversity in sensitive ecosystems

3.3. Regional Examples

Case studies worldwide demonstrate that saltwater intrusion is a global hazard:

- **Niger Delta, Nigeria:** Groundwater resources have become increasingly saline, with severe impacts on agriculture and food security [11].
- **Pakistan Coast:** Sea-level rise has accelerated aquifer salinization, threatening both drinking water and irrigation systems [12].
- **Moroccan Coast:** GIS-based vulnerability mapping revealed sharp declines in water quality, projecting worsening conditions under future climate change [13].
- **Mediterranean Coast:** Soil salinization has damaged tourism infrastructure and caused economic setbacks [15].
- **Indian Coastal Lagoons:** Vulnerability to salinity has persisted since the Holocene, reshaping lagoon morphodynamics [9].
- **Estonian Coast:** Rising seas and saltwater intrusion have degraded long-term groundwater reserves [8].

These examples underscore the global scale of saltwater intrusion and the urgency of integrating adaptation and mitigation strategies into coastal management.

Table 3: Regional Examples of Saltwater Intrusion.

Driver	Mechanism
Niger Delta (Nigeria)	Rapid aquifer salinization, agricultural losses
Pakistan Coast	Sea-level rise causing freshwater scarcity
Morocco Coast	GIS mapping shows declining water quality
Mediterranean Coast	Soil degradation impacts tourism infrastructure
Indian Coastal Lagoons	Salinity vulnerability observed since Holocene
Estonian Coast	Groundwater reserves deteriorating due to intrusion

4. Coastal Stability and Geohazards

4.1. Increased Geohazard Risks

Climate

Climate change magnifies geohazard risks by intensifying both the frequency and magnitude of destabilizing geological processes in coastal regions. Rising seas, more powerful storm waves, accelerated erosion, landslides, and soil liquefaction collectively endanger ecosystems and human settlements [17]. In particular, the rapid pace of erosion results in shoreline retreat and ecological degradation [6].

- **Storms and Hurricanes:** Global warming is closely tied to an upsurge in extreme weather phenomena, particularly tropical storms and hurricanes. These events amplify coastal erosion, accelerate soil loss, and jeopardize infrastructure [12].
- **Landslides:** Shifting precipitation patterns and sea-level rise elevate groundwater levels, destabilizing soils and increasing the likelihood of landslides in coastal zones. Shores with unconsolidated sediments are particularly vulnerable [8].
- **Liquefaction:** In earthquake-prone coastal regions, saturated soils are prone to liquefaction, resulting in building collapse and widespread structural damage [10].
- **Infrastructure Threats:** Sea-level rise undermines the functionality of coastal dams, dikes, and protective barriers. Structures designed to resist storm waves may prove ineffective under changing climatic conditions [13].

Table 4: Climate Change–Driven Geohazards in Coastal Areas.

Hazard	Mechanism
Storms & hurricanes	Intensify wave action, accelerate erosion, damage infrastructure
Landslides	Sea-level rise & rainfall saturation reduce soil stability
Liquefaction	Saturated soils collapse during seismic activity
Infrastructure risk	Rising seas weaken dams, seawalls, and breakwaters

4.2. Geological Instability and Structural Damage

Instability in coastal geology undermines both natural landscapes and human developments. Sea-level rise weakens coastal foundations, making them more prone to erosion and ground subsidence [9].

- **Landslides and Subsidence:** Elevated groundwater levels reduce ground strength, triggering landslides and surface subsidence, especially in densely populated coastal zones [14].
- **Infrastructure Damage:** Ports, bridges, roads, and drainage systems are acutely exposed to instability risks. GIS- and AHP-based assessments have highlighted critical vulnerabilities in infrastructure exposed to flooding and erosion [18].
- **Weakening of Foundations:** Saltwater intrusion accelerates soil salinity and waterlogging, weakening building foundations and increasing corrosion risks for reinforced concrete structures [4].
- **Ecosystem Collapse:** Decline of vegetation cover, combined with erosion, disrupts ecological stability. This contributes to agricultural losses, water stress, and long-term socio-economic consequences [16].

Table 5: Impacts of Coastal Geological Instability.

Impact	Description
Landslides & subsidence	Triggered by groundwater rise, leading to surface collapse
Infrastructure damage	Bridges, roads, ports, drainage at risk of collapse
Foundation weakening	Soil salinization corrodes concrete, destabilizing buildings
Ecosystem collapse	Vegetation loss disrupts ecological and agricultural systems

4.3. Risk Management and Adaptation Strategies

Efforts to mitigate coastal geohazards integrate both engineered defenses and ecological restoration. These approaches aim to enhance resilience and ensure long-term stability [15].

- **Engineering Solutions:**
  - *Breakwaters and Seawalls:* Built to dissipate wave energy and slow erosion, but costly and often unsustainable [13].
  - *Groundwater Control Systems:* Drainage networks regulate aquifer pressure and limit saline intrusion [7].
  - *Artificial Beach Nourishment:* Replenishing coasts with sand or gravel to restore natural barriers [6].
- **Nature-Based Solutions:**
  - *Mangrove and Vegetation Restoration: Strengthens natural defenses against erosion and storm surges [17].*
  - *Wetland Protection: Maintains water absorption, reduces flooding, and sustains ecological balance [9].*
- **Adaptation and Planning Strategies:**
  - *GIS and Remote Sensing: Enable detailed risk assessments and long-term planning [18].*
  - *Hazard Mapping: Identifies vulnerable zones to support early warning systems [14].*
  - *Settlement Restrictions: Urban planning regulations should limit construction in high-risk zones [15].*

Overall, ensuring coastal stability under climate stress requires integrating engineering, ecosystem-based, and policy-driven measures into a coherent resilience framework.

Table 6: Regional Examples of Saltwater Intrusion.

Strategy Type	Examples
Engineering	Breakwaters, seawalls, groundwater drainage, beach nourishment
Nature-based	Mangrove planting, wetland conservation
Planning & Policy	GIS mapping, hazard zoning, settlement restrictions

5. Discussion and Conclusion

Climate change exerts profound and, in many cases, irreversible pressures on the geological frameworks of coastal regions. This study has explored in depth the pathways through which climate drivers reshape coastal ecosystems and destabilize their structural balance, highlighting mechanisms and regional evidence. Core challenges—coastal erosion, sea-level rise, saltwater intrusion, and geohazards—were examined with a focus on their long-term consequences.

The geological and ecological fabric of coasts is undergoing rapid transformation as a result of direct influences such as rising seas and intensifying storm activity [17]. Erosion contributes to shoreline retreat, topsoil depletion, and the destruction of habitats, creating risks for both natural systems and human settlements [7]. Low-lying coasts are disproportionately affected, facing mounting economic, agricultural, and social vulnerabilities [8].

Saltwater intrusion represents another major threat to coastal resilience. Driven by sea-level rise and unsustainable human activity, salinization of aquifers is increasing and undermining agricultural output, potable water supplies, and overall ecological integrity [10]. These impacts are particularly acute in fragile environments such as deltas, lagoons, and low-lying shorelines [9].
Instability in geological structures and heightened geohazard exposure further compound these risks. Storm surges, landslides, liquefaction, and the collapse of infrastructure systems impose long-lasting damage on ecosystems and communities [14]. Rising seas and advancing erosion weaken the structural resilience of critical infrastructure, leading to economic losses of increasing magnitude [18]. Collectively, these processes jeopardize the sustainability of coastal regions and complicate efforts at societal adaptation.

The Role of Adaptation and Management Strategies
Addressing these challenges requires a combination of engineered and ecosystem-based approaches. Hard-engineering solutions, reinforced natural barriers, and GIS-supported risk mapping have proven valuable in safeguarding coastal zones [13]. Equally, ecological measures—such as mangrove restoration and wetland conservation—provide sustainable defenses while maintaining ecological functionality [17]. Emerging technologies, including remote sensing and monitoring systems, also offer critical tools for anticipating risks and supporting the design of early-warning mechanisms [18].

Policies and Future Directions
Beyond technical solutions, the establishment of robust policy frameworks and regulatory mechanisms is essential. Regional planning strategies should incorporate restrictions on construction in vulnerable areas and reinforce environmental protections [15]. International collaboration, coupled with the active engagement of local communities, will be vital in advancing adaptation to climate pressures. Future research, particularly scenario-based modeling and regional-scale analyses, will serve as the scientific foundation for designing effective long-term management responses [9].

General Reflections
In summary, climate change presents wide-ranging risks to coastal regions, demanding integrated management. Processes such as sea-level rise, saline intrusion, soil degradation, and geological instability undermine both ecological stability and economic viability [7]. The evidence presented underscores the necessity of combining engineering interventions with nature-based strategies to create resilient coastal systems. The active participation of communities, alongside coordinated policy action, will be critical for successful adaptation.
Protecting coastal zones is not only an environmental imperative but also a prerequisite for sustaining social and economic stability. Advancing research and applying adaptive strategies will play a central role in mitigating climate impacts and fostering more resilient ecosystems for the future.

Acknowledgment
All acknowledgements (if any) should be included in a separate section before the references and may comprise a list of people who contributed to the work in the manuscript but were not listed in the author list, supporting grants, presentations, and so forth. The names of funding agencies should be written in full.

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