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An integrated GIS and Remote sensing Approach to Assess Compound Vulnerabilities in Deltaic Geoheritage to Soil Salinization and Coastal Erosion Dynamics in Saloum Delta Senegal

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Method Article

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Abstract

Low-gradient deltaic Landscapes are globally function as a vulnerable to synergistic soil and coastal hazards. These deltaic geoheritage, although they host hosts a significant concentration of geosites that exemplify millennia of interactions between human societies and their environment, remains under-protection due to a lack of compound approach to asses risks.

This research employs an integrated methodological framework to assess deltaic geoheritage compound vulnerability through a case study in Saloum Delta. This approach combines a Soil Salinization Risk Index (SSRI) adapted to deltaic system derived from multi-criteria analysis and a diachronic analysis of shoreline dynamics using satellite imagery and the Digital Shoreline Analysis System (DSAS) tool. Findings reveal an elevated level of vulnerability, with coastal retreat reaching approximately 1,050 meters between 2000 and 2025.The SSRI classified over 85% of the geosites within the “Very High” risk category, reflecting the convergence of unfavorable natural factors: permeable Quaternary sediments coupled with an almost flat topography that limits drainage, alluvial and hydromorphic soils with low permeability, and a high Aridity Index that promotes evaporation and salt accumulation. These results demonstrated how coastal erosion facilitates saline intrusion, which in turn destabilizes natural protective structure, creating a retroactive degradation cycle. This work provides also a replicable methodology for quantifying the sensivity of deltaic geoheritage to interconnected hazards and a decision-support tool for the conservation and sustainable management of this unique heritage.

1. Introduction

Globally, low-gradient deltaic landscapes serve as invaluable sedimentary and cultural archives, encompassing what is increasingly recognized as deltaic geoheritage. Positioned at the dynamic interface between terrestrial and marine domains, these areas host geosites that document millennia of co-evolution between human societies and their environment. Despite their geomorphological and archaeological significance, deltaic systems are among the most vulnerable environments on Earth, facing a synergistic onslaught of climate-induced and anthropogenic hazards. A critical challenge in the preservation of these landscapes is the systematic lack of integrated assessment methodologies capable of quantifying compound risks. While soil salinization and coastal erosion are frequently analyzed as discrete phenomena, their interconnected nature—where coastal retreat facilitates saline intrusion, thereby destabilizing the pedological foundations of heritage sites—remains poorly addressed in conservation frameworks. This methodological gap hinders the development of proactive management strategies, leaving irreplaceable geological and cultural assets exposed to irreversible degradation.

Illustrating these global challenges, geoheritage research in Senegal is currently undergoing significant expansion, with several remarkable areas already identified (Youm et al., 2018; Youm, 2019; Youm et al., 2022). Among these, the Saloum Delta, situated along Senegal's Atlantic coast, represents an estuarine

ecosystem of exceptional ecological and cultural significance. It benefits from multiple international designations: UNESCO World Heritage Site (2011) (Bocoum & Moriset, 2010), Biosphere Reserve (1981), and Ramsar Wetland of International Importance (1984). This territory hosts major geosites (Fig. 1), including tumuli, shell middens (kjøkkenmøddinger)(Elouard et al., 1974), and megalithic circles such as Diorom Boumak, Wanar, Sine Ngayène, Falia, and Missira—archeological and geomorphological Landscapes that document millennia of human occupation and adaptation to dynamic environmental conditions (Camara et al., 2017). The assessment and conservation of such geoheritage are critical, as outlined in frameworks for geodiversity evaluation (Reynard, 2007). The Saloum Delta's remarkable geodiversity further underscores its potential for geopark designation (Gueye et al., 2023). The area encompasses diverse biotopes-tidal channels (*bolons*), freshwater springs, mangrove mudflats, islands with baobab groves, sandy beaches, and archaeological shell mounds-alongside extensive mangrove ecosystems covering approximately 50% of its surface (JICA, 2005). Ecologically, it supports rich estuarine fauna, reptiles, endangered marine mammals (e.g., manatees, dolphins) (Diop, 1996), and abundant avifauna (Fig. 2). Culturally, the region retains funerary shell mounds and sacred sites, although traditional practices are in decline. Economically, activities such as ecotourism, fishing, shellfish harvesting, agriculture, and handicrafts remain central to local livelihoods, with community-based management and national policies-reinforced by international conventions-contributing to conservation and sustainable development.

Despite its outstanding heritage value, the Saloum Delta faces severe threats from two accelerating processes: soil salinization and coastal erosion. Salinization is primarily driven by saltwater intrusion in what is classified as an inverse estuary, shallow groundwater tables, and limited natural drainage (Descroix et al., 2020), while coastal erosion results from tidal dynamics, storm events, and hydro-sedimentary imbalances, all exacerbated by climate change (Sakho et al., 2024). These phenomena are set against a backdrop of regional climatic shifts, with modern drought conditions in the western Sahel now considered unprecedented in the past 1600 years (Carré et al., 2018). These processes collectively endanger both the ecological integrity and the irreplaceable cultural assets of the delta.

To address this critical vulnerability and this methodological gap, this study develops and demonstrates an integrated geospatial framework for assessing the compound susceptibility of deltaic geosites to interacting soil and coastal hazards. The Saloum Delta in Senegal serves as a critical application site for this approach due to its density of vulnerable geosites and its exposure to pronounced salinization and erosion dynamics. The specific objectives of this research are to i) develop a multi-criteria Soil Salinization Risk Index (SSRI): Tailored specifically for low-gradient deltaic environments, this index integrates lithological, topographical, and climatic variables to quantify subsurface vulnerability. ii) quantify contemporary shoreline dynamics: Utilizing a diachronic analysis of satellite imagery and the Digital Shoreline Analysis System (DSAS), this objective aims to establish precise rates of coastal retreat and land loss between 2000 and 2025. Iii) model the spatial interplay of hazards: By synthesizing SSRI and DSAS datasets, the study evaluates how these processes converge to create a retroactive degradation cycle, thereby prioritizing geosites for urgent conservation. The broader aim is to provide a

transferable assessment model that can inform both deltaic geoheritage research and the prioritization of conservation efforts for irreplaceable sedimentary records in deltaic systems worldwide.

2. Materials And Methods

2.1. Study Area

The Saloum Delta extends over a dense hydrographic network of Bolongs (tidal channels) and floodplains, hosting forty-eight (48) inventory geosites (37 anthropogenic and 9 hydrological).

2.2. Data Collection

Tableau 1: Data Sources and Utilization for compound Vulnerabilities Assessment (Salinization and Erosion)

Data Type	Source	Use
Soil Electrical Conductivity (EC)	Field surveys, lab analysis	Direct estimation of salinity
Groundwater and Surface Water EC	Wells, Bolongs, field	Saltwater intrusion, irrigation
Water Table Depth	DGPRE	Salt accumulation factor
Soil Texture	geosenegal.gouv.sn	Salt mobility
Digital Elevation Model (DEM)	SRTM / Copernicus DEM	Slope, altimetry
Climatic Data	ANACIM / WorldClim	Aridity Index calculation
Superficial Geology	Geological map	Substrate capacity to accumulate/drain salts
Satellite Imagery	Landsat, Sentinel	shoreline change analysis.
Geoheritage Data	GPS, Google Earth	Inventory of geosites

2.3. Salinization Risk Analysis Methodology

This study adopts the methodology proposed by Masoudi et al. (2006) for constructing the Soil Salinization Risk Index (SSRI), which emphasizes the integration and weighting of key factors such as soil and water electrical conductivity (EC), groundwater depth, soil texture, slope, and geological characteristics for spatial risk assessment.

The classification of the Saloum Delta as a hydrogeological salt trap illustrates the local manifestation of this multifactorial convergence. Similarly, Chaaou et al. (2023) highlights the relevance of an index-based approach for mapping salinity risk using multi-source data.

The SSRI developed in this research incorporates nine weighted parameters: Soil EC (weight = 2); Groundwater and irrigation water EC (weight = 1); Water table depth (weight = 1); Soil texture (weight = 1); Slope (weight = 1); Climate/Aridity Index (weight = 1); Geological efficiency (weight = 1). Data were interpolated (Inverse Distance Weighting - IDW), reclassified into five risk levels (from Very Low to Very High), and then aggregated within the GIS using the following formula: SSRI = ∑ (Factor_i × Weight_i)

2.4. Coastal Erosion Risk Analysis Methodology

The diachronic analysis of shoreline evolution was performed over a 25-year period, utilizing a time series of satellite imagery (Landsat and Sentinel-2) covering the years 2000, 2005, 2010, 2015, 2020, and 2025. Following pre-processing steps (radiometric and atmospheric correction), the automatic extraction of the shoreline was carried out by calculating the Normalized Difference Water Index (NDWI), which effectively differentiates the land-water boundary. The shoreline was then consistently digitized for each date. The **Digital Shoreline Analysis System (DSAS)** tool, integrated within ArcGIS, was used to quantify the rates of change and model coastal evolution. Transects, spaced 50 meters apart, were drawn perpendicular to a baseline to measure the change in the shoreline's position over time.

The main statistical parameters calculated included the End Point Rate (EPR), Net Shoreline Movement (NSM), and the Linear Confidence Interval (LCI), allowing for the generation of shoreline evolution maps and the identification of significant erosion and accretion zones.

3. Results

3.1. Soil Salinization Risk Index (SSRI)

The Soil Salinization Risk Index (SSRI) is an aggregate index derived from the combination and weighting of seven environmental and geomorphological parameters (Soil EC, Groundwater EC, water table depth, soil texture, slope, aridity index, and geological efficiency). The spatial classification of the SSRI allowed for the definition of five risk classes, ranging from Very Low to Very High.

The analysis of the cartographic results reveals an extremely high vulnerability of the geosites in the Saloum Delta (*Figure 3*). Nearly the entire study area (approximately 85% of the total surface area) is classified within the 'Very High' risk category (dark red shades).

This high vulnerability is explained by the convergence of unfavorable natural factors:

- the presence of highly permeable Quaternary sediments that facilitate the massive intrusion of seawater into the water table (salt wedge);

- near-zero topography (slopes < 1%), which impedes soil drainage and favors water stagnation, consequently leading to salt accumulation through evaporation;

- a predominance of alluvial and hydromorphic soils characterized by low permeability and high-water retention, optimizing the salt accumulation effect.;

- a high Aridity Index, typical of the Sahelian zone, intensifies evapotranspiration and accelerates the capillary rise of salts;

Structurally, the Delta functions as a "hydrogeological salt trap," where saltwater is constantly captured and concentrated. This phenomenon directly threatens the integrity of fragile ecosystems, such as the mangrove, and compromises the future of agro-silvo-pastoral activities for the local population."

3.2. Coastal Shoreline Evolution Dynamics

The diachronic analysis, conducted using the DSAS tool across six dates between 2000 and 2025, reveals an alarming and generalized trend of net shoreline retreat along the Saloum Delta coastline (*Figure 4*). The study quantifies a cumulative withdrawal of approximately 1,050 meters over 25 years, representing a spectacular average annual rate of 42 meters per year (m/year) (*Figure 5*).

The analysis of temporal variability shows that erosion rates are not constant. The 2015-2020 period recorded the highest rates of retreat, averaging 60 m/year, likely linked to an intensification of extreme climatic events (storms, swells).

Spatial Distribution of Risk :

- **Areas of Very High Retreat:** The most affected sectors are the unconsolidated sand spits and the areas at the mouth of the bolongs (tidal creeks), with localized retreats exceeding **80 m/year**. This phenomenon directly impacts coastal localities and their infrastructure.

- **Consequences for Heritage:** This retreat directly threatens the survival of **littoral geosites**, especially the **shell middens**, many of which are currently being submerged and dismantled by the combined action of marine erosion and salinization.

In conclusion, the Saloum Delta is facing a hyper-rapid coastal erosion process, positioning it as one of the most vulnerable zones on the West African coastline, necessitating urgent protection and redevelopment measures.

4. Discussion

A Synthetic Framework for Deltaic Compound Vulnerability

This research provides an integrated, quantitative, and geo-referenced assessment of landscape susceptibility, successfully deconvolving the compound vulnerability inherent to low-gradient deltaic landscapes. By synthesizing a multi-criteria Soil Salinization Risk Index (SSRI) with a diachronic

shoreline change analysis, this study shifts the perspective from generic hazard mapping toward a targeted safeguarding of "landscape memory" and deltaic geoheritage.

4.1. Soil Salinization Risk

The SSRI results reveal that nearly 85% of the study area exhibits a "Very High" risk. This prevalence is a direct consequence of the Saloum Delta's intrinsic geomorphological architecture. The convergence of permeable Quaternary sediments and a near-flat topography (slope < 1%) transforms the deltaic plain into a permanent hydrogeological salt trap. Under the current high Aridity Index, intense evaporation promotes the vertical migration of salts through capillary rise (Ausseil-Badie et al., 1991; Descroix et al., 2020).

These findings, enabled by GIS-based spatial modeling, align with methodologies proposed by Masoudi et al. (2006) and Chaaou et al. (2023), which highlight the necessity of integrating multiple environmental factors (pedological, hydrological, and climatic) in semi-arid risk assessment. However, they further underscore the severity of the West African context, where modern drought conditions are unprecedented in the last 1,600 years (Carré et al., 2018), acting as a climatic catalyst that amplifies the soil salinization risk in these sensitive lowlands.

2. Shoreline Dynamics and the Feedback Loop

In parallel, the remote sensing and the shoreline analysis reveals exceptional erosion rates. The cumulative retreat of 1,050 meters over 25 years, representing a spectacular average of 42 m/year, with a peak of 60 m/year during the 2015–2020 period, classifies this coastline among the most dynamic and vulnerable in West Africa (Sakho et al., 2024). These rates, significantly higher than regional averages, are exacerbated by the poor consolidation of Bolong (tidal creek) banks and increased sea-level pressure. They confirm and quantify historical observations of coastal evolution and geomorphological dynamics (Diop, 1990; Barusseau et al., 1995) by offering an updated and detailed perspective on the amplification of the saline/marine invasion process.

The critical contribution of this study lies in identifying the synergistic feedback between these hazards. Coastal erosion and the widening of tidal channels facilitate the landward intrusion of the salt wedge. This marine invasion destabilizes the rhizospheres of mangrove ecosystems, which serve as natural protective barriers (Marius, 1984; Alongi, 2008). When mangroves degrade due to hyper-salinity, the shoreline becomes even more susceptible to wave energy, creating a retroactive degradation cycle that accelerates the loss of the deltaic geoheritage records. This retroactive loop offers a generalizable lens for understanding landscape degradation in deltas from the Bengal to the Mississippi, where similar geomorphic archives are at risk.

3. A Transferable Model for Geoconservation

The integrated framework developed here—coupling GIS and remote sensing—provides a replicable methodology for assessing compound vulnerability in comparable low-gradient coastal settings. While

local calibration may be required, the core identified drivers—near-flat topography, unconsolidated Quaternary sediments, and sediment supply deficits—are universal amplifiers of the salinization-erosion feedback in deltaic plains.

Consequently, the spatial susceptibility maps produced are more than site-specific management tools; they represent a prioritization schema for fundamental geomorphological and geoarchaeological research. By identifying high-risk zones for the 37 anthropogenic shell middens (archaeological tells) that characterize the Saloum Delta (Camara et al., 2017), this approach bridges applied hazard assessment with fundamental research needs in landscape evolution.

5. Conclusion, Recommendations and Perspectives

This research demonstrates the effectiveness of an integrated geospatial framework for deconvolving and quantifying the compound vulnerability inherent to low-gradient deltaic geoheritage. By coupling a multi-criteria Soil Salinization Risk Index (SSRI) with a diachronic shoreline change analysis, this study established that the Saloum Delta is subject to a synergistic degradation cycle: a rapid coastal retreat of approximately 1,050 meters (2000–2025) coupled with the intrinsic susceptibility of over 85% of the deltaic plain to high-level salinization. This convergence is governed by a critical interplay of topographic, sedimentary, and climatic factors that threaten the integrity of irreplaceable deltaic geoheritage.

More broadly, this work establishes a transferable assessment model that shifts the perspective from generic hazard mapping toward the targeted safeguarding of "landscape memory." By focusing on the susceptibility of key geomorphic and sedimentary archives—such as the 37 anthropogenic shell middens identified—the methodology provides a replicable basis for prioritizing scientifically critical areas in deltaic systems globally. The accelerating loss of such archives represents an irreversible depletion of our collective understanding of past landscapes and human adaptations.

To ensure the long-term resilience of these ecosystems, the following strategic actions are recommended:

Targeted Geoconservation: Integrating high-resolution vulnerability maps into coastal zone management plans to prioritize interventions for at-risk archaeological tells and shell middens.

Regulatory Strengthening: Limiting activities that exacerbate erosion and salinization, such as unregulated mangrove harvesting and shell exploitation, to preserve natural protective structures.

Sustainable Development: Promoting geotourism infrastructure and community-based management to resolve resource-use conflicts while fostering ecological preservation.

Future research should focus on the establishment of a Permanent Geospatial Observatory for continuous monitoring of shoreline dynamics and saline expansion. While refinements incorporating real-time hydrological data (e.g., groundwater EC) and predictive climate change scenarios will enhance model precision, the core conceptual and methodological approach developed here offers a robust

pathway for linking process-based geomorphology with strategic landscape conservation in deltaic systems worldwide.

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As the corresponding author, I declare on behalf of all co-authors that there are no conflicts of interest related to the publication of this manuscript. All authors have contributed to the work, approved the final version, and have no financial, personal, or professional relationships that could be construed to influence the content of the article.

Contribution of Authors

Cheikh Ibrahima YOUM: Conceptualization, • Data curation, • Formal analysis, • Funding acquisition, • Investigation, • Methodology, • Supervision, • Writing - review editing.

Mourtada FALL: Project administration, • Resources, • Software, • Supervision, • Validation, • Visualization, • Writing - original draft, • Writing - review editing.

Cheikh Moustapha Waly DIOUF: Conceptualization, • Data curation, • Formal analysis, • Funding acquisition, • Investigation, • Methodology.

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Data Availability

All Data used in this study is available on the specific site.if any one need any Data, he can contact the corresponding author.

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URL : http://journals.openedition.org/geomorphologie/16878
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Figures

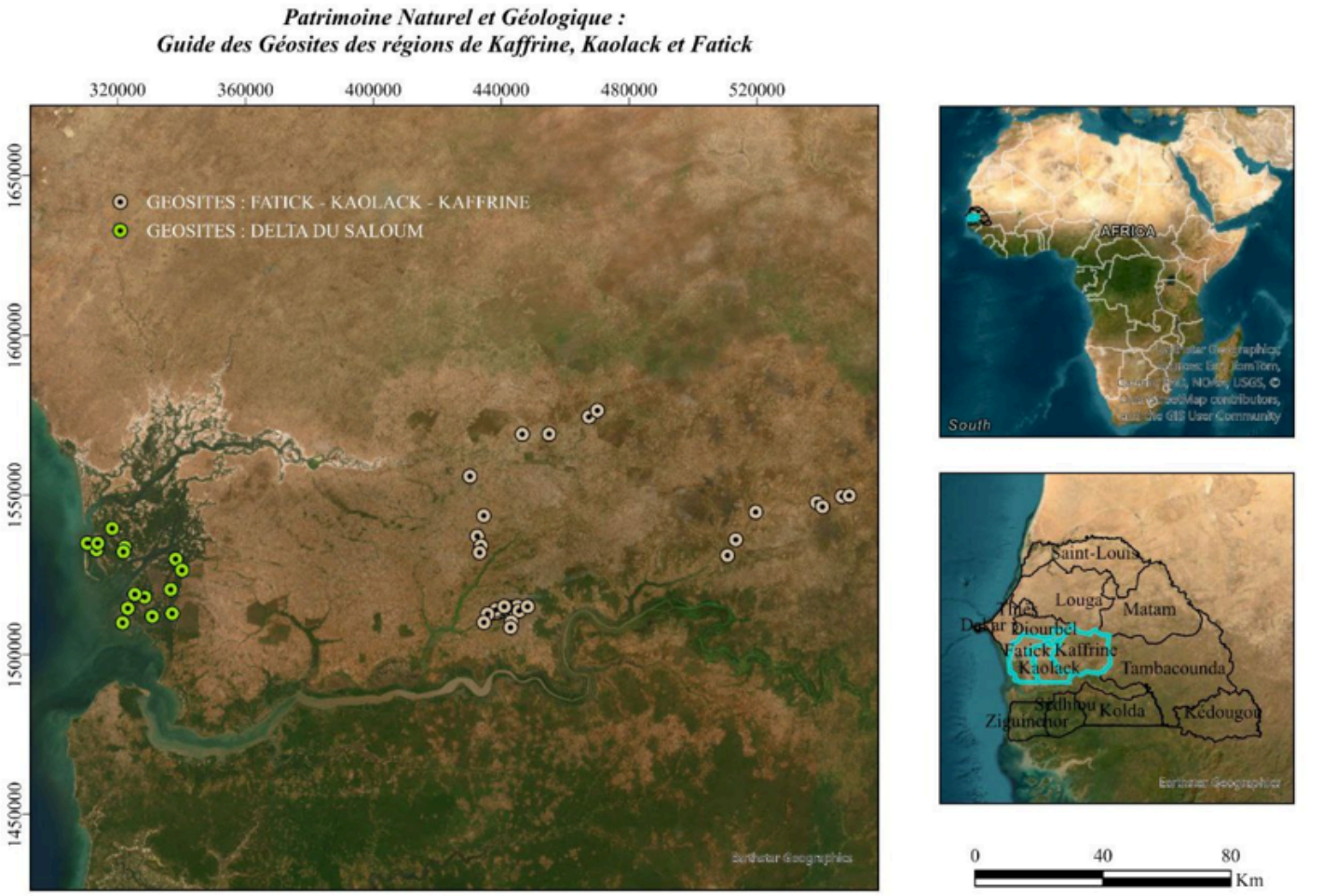


Figure 1

Location Map of the Saloum Delta showcasing the spatial distribution of key deltaic geoheritage sites

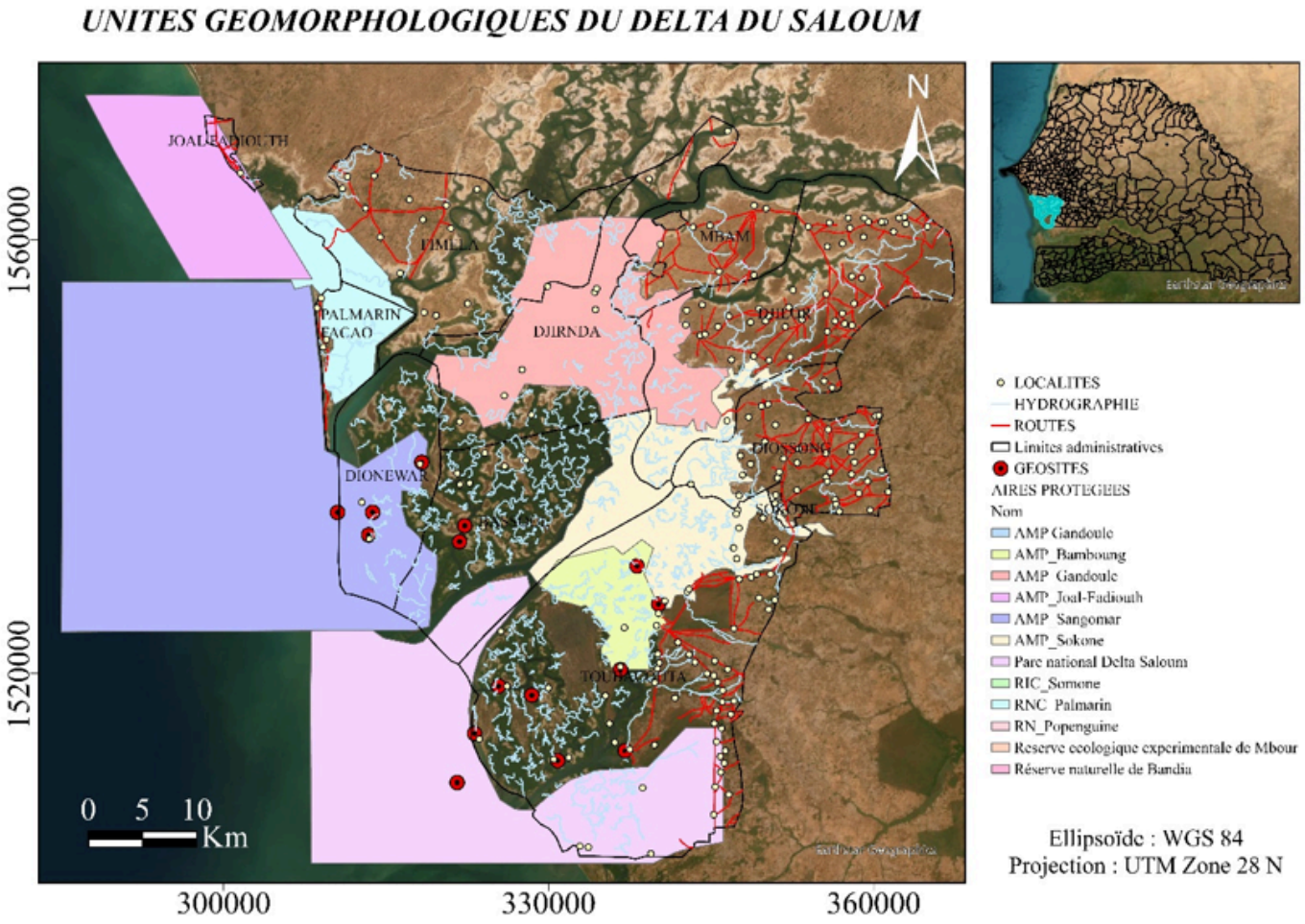


Figure 2

Geomorphological Units of the Saloum Delta

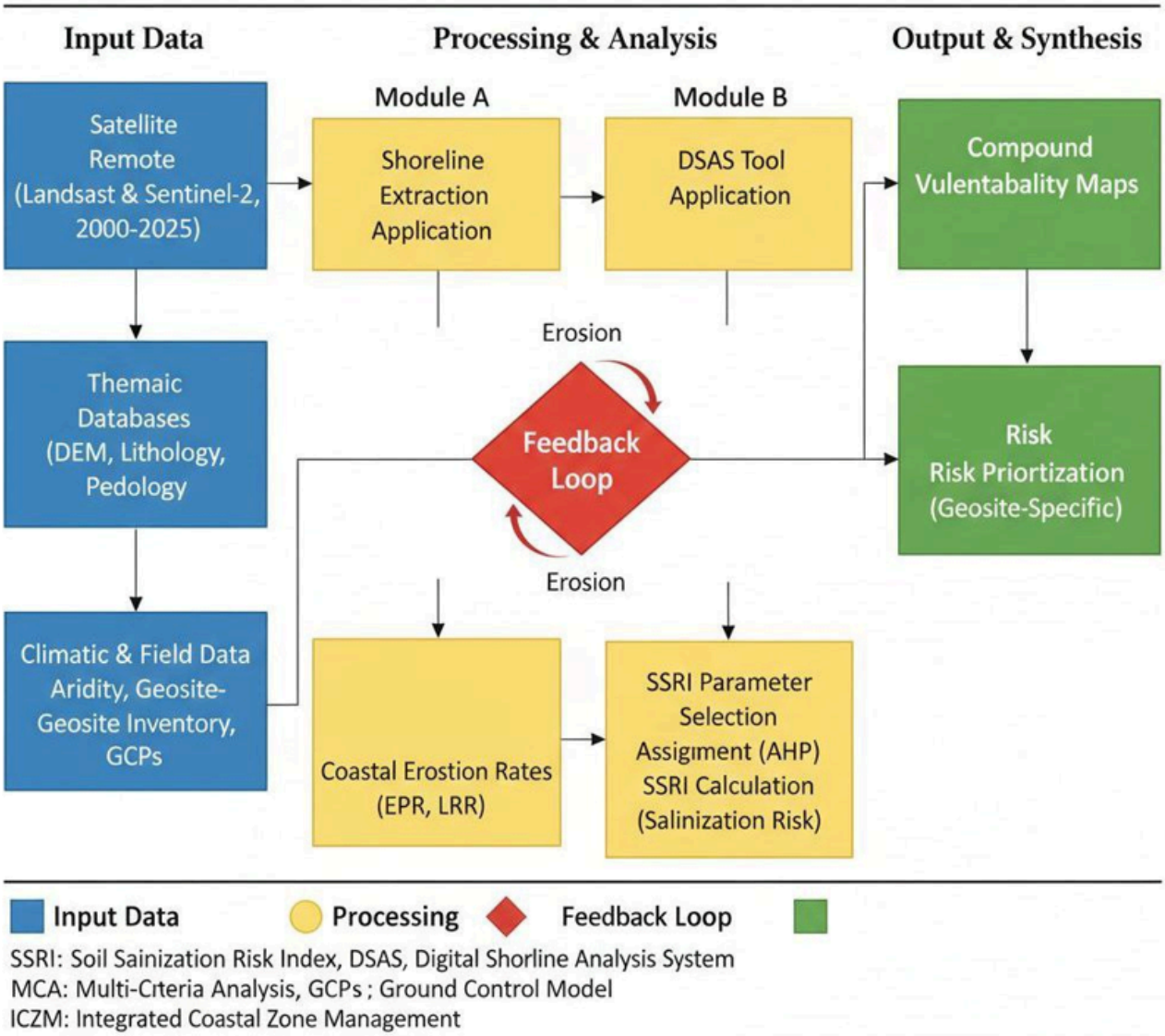


Figure 3

Integrated methodological Framework for deltaic geoheritage compound vulnerabilities assessment

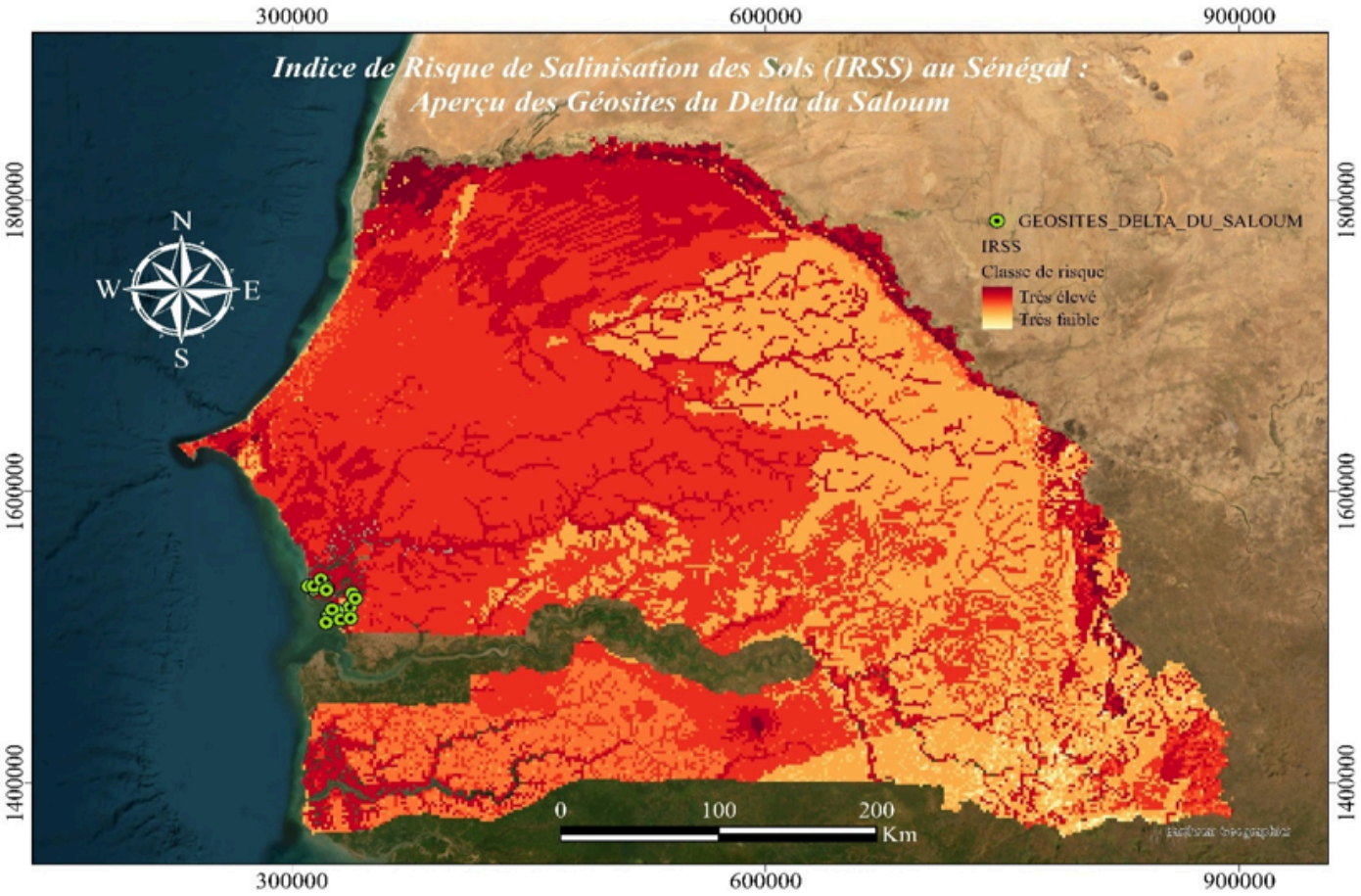


Figure 4

Spatial distribution of the Soil Salinization Risk Index (SSRI) across the deltaic plain illustrating the high intrinsic susceptibility of low-gradient landforms

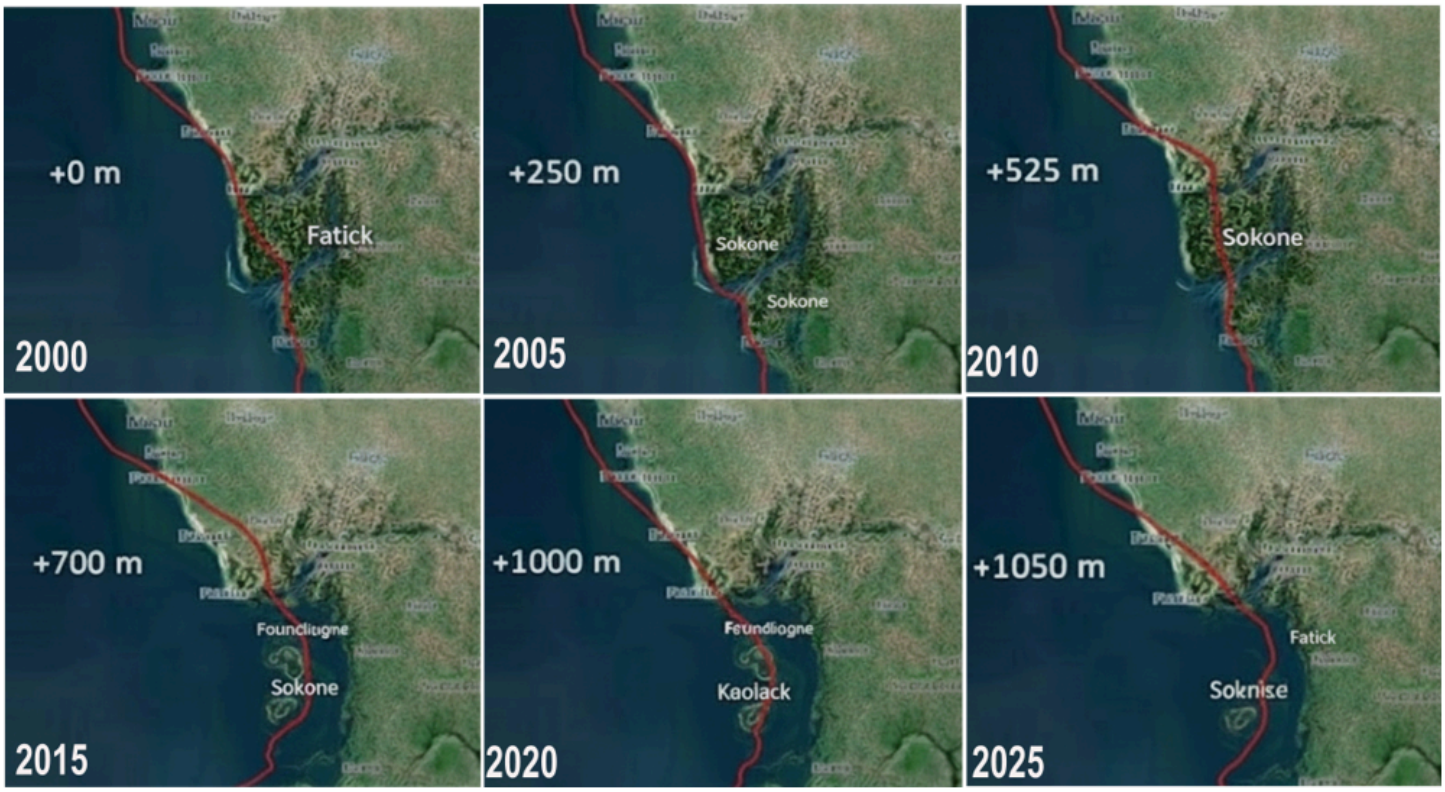


Figure 5

Shoreline Dynamics Map and Coastal Erosion Rates (2000–2025) derived from DASS analysis, highlight critical retreat zone

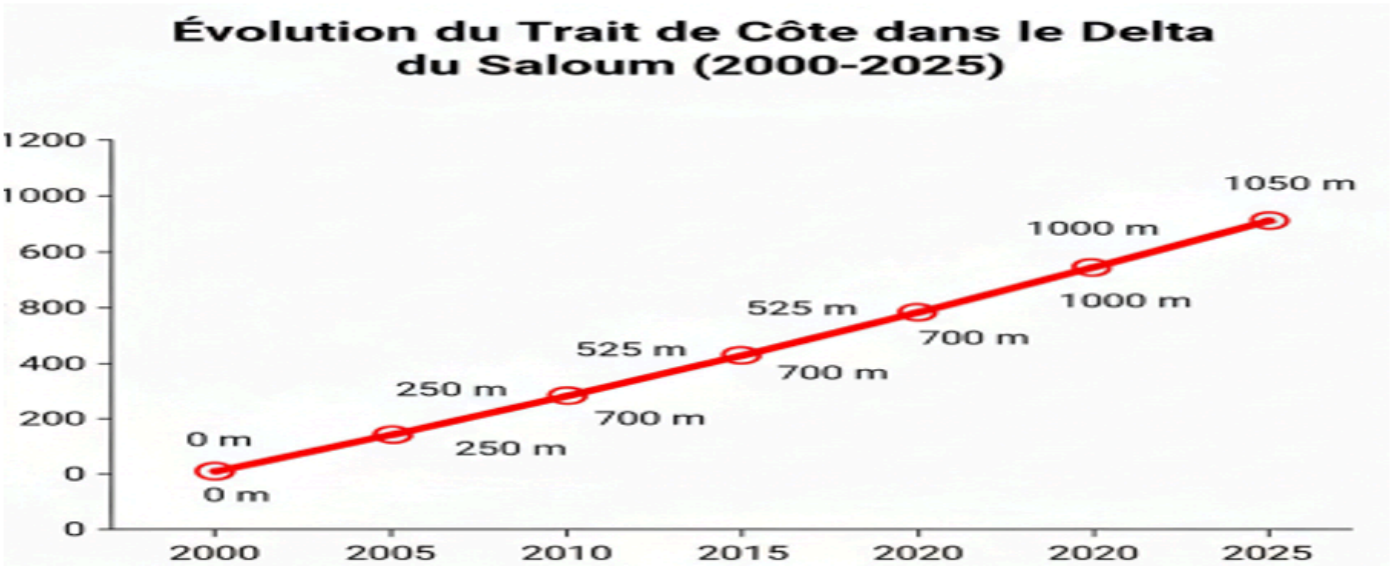


Figure 6

Diachronic evolution of shoreline Retreat Rates (2000–2025) demonstrating the acceleration of erosive processes over the last two decades

Supplementary Files

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- SupplementalMaterial.docx