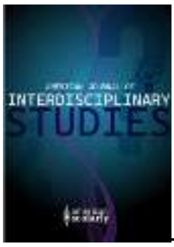

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MODELING GEOTECHNICAL SOIL LOSS AND EROSION DYNAMICS FOR CLIMATE-RESILIENT COASTAL ADAPTATION

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ABSTRACT

This study presents a comprehensive statistical analysis of geotechnical soil loss and erosion patterns with the aim of supporting climate adaptation strategies in vulnerable coastal zones. Soil erosion in coastal environments is a complex phenomenon governed by the interplay of geotechnical, hydrodynamic, climatic, spatial, and anthropogenic factors that collectively shape soil stability, erosion rates, and spatial distribution. To investigate these dynamics, the study systematically reviewed and synthesized findings from 132 peer-reviewed research papers published over the past two decades, integrating empirical evidence with quantitative modeling approaches. Key geotechnical parameters examined include particle size distribution, cohesion, shear strength, bulk density, permeability, organic matter content, salinity, and pH, all of which significantly influence the soil's resistance to detachment and transport. Climatic drivers such as rainfall intensity and seasonal variability, along with hydrodynamic forces including wave power, tidal range, and storm surges, were found to critically shape erosion intensity and temporal variability. Spatial analysis revealed pronounced erosion hotspots in deltaic and estuarine regions, while temporal trends highlighted the disproportionate role of extreme weather events in accelerating soil loss. Anthropogenic activities, including urbanization, deforestation, land reclamation, and shoreline engineering, further intensified erosion by altering soil structure, hydrology, and sediment transport. Advanced statistical methods, including regression modeling, geostatistical analysis, and GIS-based spatial mapping, were employed to identify key predictors, quantify their relative influence, and produce predictive erosion-risk models. The findings underscore the necessity of integrated, data-driven approaches that incorporate soil management, ecosystem restoration, adaptive land-use planning, and engineering solutions to mitigate erosion and enhance coastal resilience. This study contributes to the growing body of knowledge on soil erosion by linking geotechnical properties with environmental forces and provides a scientific basis for informed decision-making in climate adaptation and sustainable coastal management.

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KEYWORDS
Soil erosion, Geotechnical properties, Coastal zones, Climate adaptation, Statistical analysis

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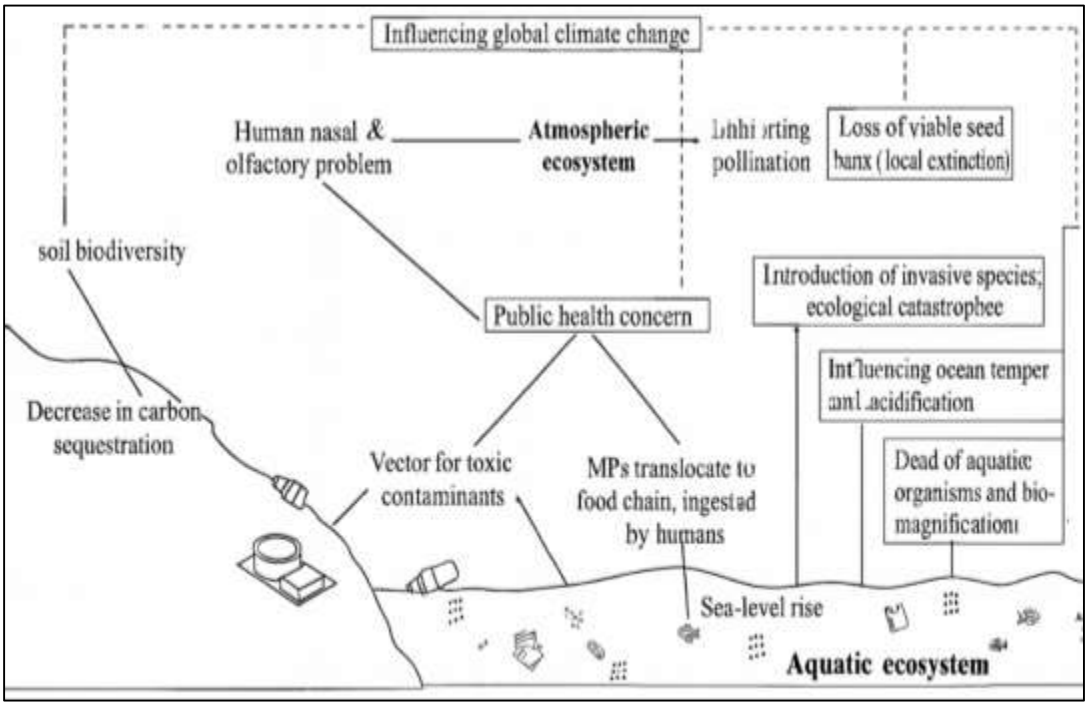
INTRODUCTION

Soil erosion is a fundamental geomorphological process that involves the detachment, transportation, and deposition of soil particles by natural forces such as water, wind, gravity, and ice (Singh & Hartsch, 2019). Within the field of geotechnical engineering, soil erosion holds significant importance because it directly influences soil strength, cohesion, and stability—properties critical to the structural integrity of foundations, embankments, and other infrastructure. Coastal regions are particularly vulnerable to erosion due to the complex interplay between terrestrial soils and marine hydrodynamic forces, including wave action, tidal flows, and storm surges. These forces accelerate the removal and redistribution of sediments, leading to loss of fertile topsoil, land degradation, and mechanical instability. Erosion also affects key geotechnical parameters such as permeability, shear strength, and bulk density, all of which are crucial in engineering design and hazard assessment (Evelpidou et al., 2018). Quantifying soil loss is therefore essential for understanding the evolution of landscapes and planning sustainable land use. Classical models like the Universal Soil Loss Equation and its revised versions estimate erosion by incorporating variables such as rainfall erosivity, soil erodibility, slope length, and vegetation cover. However, in coastal contexts, additional factors such as salinity, wave energy, and tidal dynamics must be considered, as they often intensify erosion beyond what terrestrial models predict. Integrating geotechnical soil characterization with hydrological and climatic data provides a more comprehensive understanding of erosion patterns and their implications for coastal infrastructure (Spaeth Jr, 2020). By doing so, researchers and engineers can better anticipate soil behavior, improve design resilience, and support the development of adaptive management strategies. This multidisciplinary approach underscores the necessity of combining soil mechanics, geomorphology, and hydrology to fully capture the dynamics of soil erosion, particularly in regions where terrestrial and marine systems intersect and exert compounded pressures on the landscape.

Figure 1: Geotechnical Soil Erosion and Adaptation



Coastal zones, though occupying less than a tenth of the Earth's terrestrial area, are among the most densely populated and economically valuable regions on the planet. They host major urban centers, ports, industrial zones, and critical ecosystems, while supporting more than 40 percent of the global population (Bhat et al., 2019). The vulnerability of these regions to soil erosion is heightened by their direct exposure to marine processes and climate variability, as well as human-induced pressures such as urban expansion, land reclamation, and deforestation. Soil erosion in coastal areas contributes to significant land losses annually, undermining agricultural productivity, degrading habitats, and threatening infrastructure. In large river deltas such as those of the Mekong and Ganges-Brahmaputra, erosion has accelerated due to reduced sediment supply caused by dam construction and river engineering, resulting in land subsidence and increased salinity intrusion. European coastlines also experience severe erosion driven by storm surges, changing wave patterns, and rising sea levels, leading to substantial economic costs and necessitating expensive coastal defense measures (Reddy, 2018). In many small island states and low-lying nations, soil erosion contributes to land loss that threatens food security, cultural heritage, and human settlement viability. Beyond its physical impacts, coastal soil erosion influences global biogeochemical cycles by redistributing sediments rich in organic carbon and nutrients, thereby affecting ecosystem productivity and carbon sequestration. These cascading effects demonstrate that soil erosion is not solely an environmental process but a socio-economic and geopolitical concern with far-reaching consequences. Understanding these global patterns is essential for designing mitigation strategies that account for both local geotechnical properties and broader climatic and anthropogenic drivers (Dunkerley, 2020). Through rigorous analysis of soil loss and erosion dynamics, researchers and policymakers can better manage coastal zones and maintain their critical ecological and economic functions in an era of rapid environmental change.

Climate variability exerts a profound influence on soil erosion dynamics, especially in coastal environments where atmospheric, terrestrial, and oceanic systems intersect (Efthimiou et al., 2017). Sea-level rise, driven by global temperature increases and melting ice sheets, intensifies wave energy and tidal inundation, accelerating shoreline retreat and the detachment of soil particles. Altered precipitation regimes contribute to increased surface runoff and overland flow, heightening the erosive forces acting on soil surfaces. Heavy rainfall events can rapidly saturate soils, reducing their cohesion and increasing the likelihood of detachment and transport. Conversely, prolonged dry periods followed by intense rainfall can create surface crusting that enhances runoff and erosion. Hydrodynamic forces unique to coastal zones—including wave run-up, longshore currents, and tidal oscillations—compound these effects by continuously reshaping soil structure and redistributing sediments. Changes in salinity also play a critical role, as saline water can disrupt soil aggregates and reduce cohesion, (Han et al., 2019) increasing susceptibility to erosion. Human activities often exacerbate these natural forces; for example, the construction of seawalls and groynes alters wave patterns and sediment transport, sometimes intensifying erosion in adjacent areas. Dredging and land reclamation projects similarly modify hydrodynamic conditions and soil stability. Accurately modeling these interactions requires integrating geotechnical soil properties such as cohesion, permeability, and grain size distribution with climatic and hydrological data. Statistical approaches and process-based models enable researchers to quantify how climate variables interact with soil mechanics to produce specific erosion outcomes (Gogichaishvili, 2019; Rezaul, 2021). Understanding these complex interactions is vital for anticipating changes in erosion patterns and developing robust strategies to manage soil loss in coastal areas. By linking geotechnical parameters with climate and hydrodynamic forces, scientists and engineers can better characterize the spatial and temporal dynamics of soil erosion and support more effective land-use planning and infrastructure design.

The susceptibility of soils to erosion is strongly determined by their intrinsic geotechnical properties, which influence how soils respond to erosive forces (Abdul, 2021; Chuenchum et al., 2019). Particle size distribution is a fundamental factor: coarse-textured soils, such as sands, are more easily detached and transported by water and wind, while fine-textured soils like clays exhibit higher cohesion but may be more prone to dispersion when saturated or chemically altered. Soil structure and aggregate stability also play crucial roles in erosion resistance. Well-aggregated soils with stable structures maintain higher infiltration capacities, reducing surface runoff and minimizing particle detachment. Organic matter enhances soil aggregation and improves water retention, strengthening the soil's ability to resist erosion. Hydraulic conductivity and bulk density affect how water moves through soil pores and how pressure builds during infiltration events, influencing the likelihood of mass movement or surface wash (Rezaul, 2021; Nones, 2020). In coastal environments, salinity and pH variations further modify soil structure by affecting colloidal interactions and aggregate cohesion, often making soils more erodible. Vegetation cover is another critical geotechnical factor; plant roots reinforce soil structure mechanically and increase shear strength, while canopy cover reduces the kinetic energy of raindrops and surface runoff. These properties do not act in isolation but interact dynamically with hydrological forces, creating complex erosion

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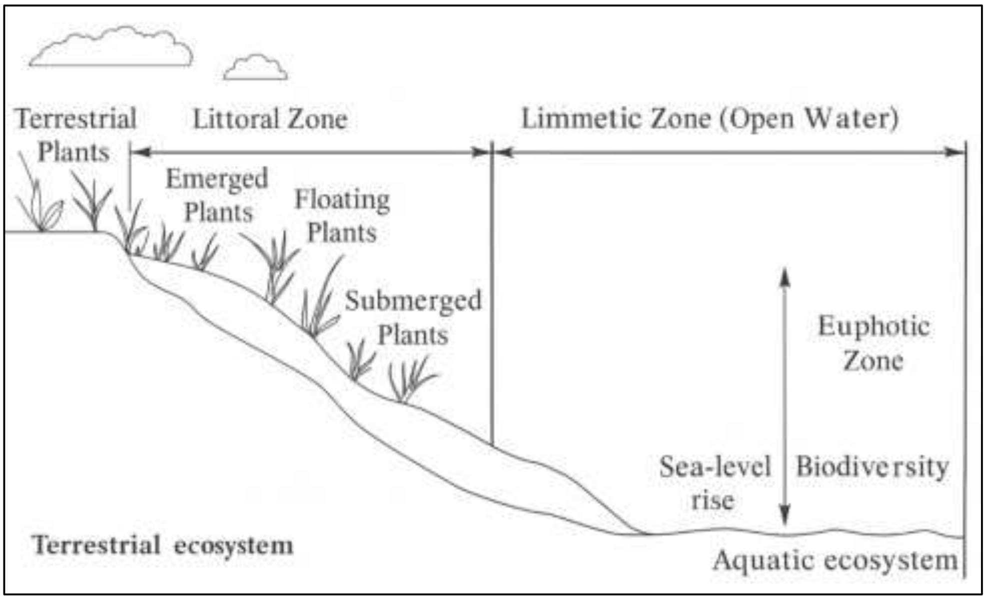
responses under varying environmental conditions. Quantitative analysis of geotechnical variables enables the identification of soils most vulnerable to erosion and the prediction of erosion rates under different scenarios. Spatial mapping of these variables can reveal erosion hotspots, guiding targeted interventions (Ravi & Cornelis, 2019). By integrating soil mechanics with hydrological modeling, researchers can develop comprehensive assessments of erosion risk that inform land management, infrastructure planning, and adaptation strategies in erosion-prone coastal regions.

Figure 2: Coastal Zonation and Plant Distribution



Quantitative modeling serves as the cornerstone for analyzing and predicting soil erosion patterns, allowing researchers to translate complex environmental interactions into measurable outcomes (Zydroń et al., 2017). Empirical models, such as the Universal Soil Loss Equation and its revised versions, remain widely used for estimating long-term soil loss based on factors including rainfall intensity, soil erodibility, slope gradient, and land cover. Process-based models, like the Water Erosion Prediction Project and the European Soil Erosion Model, offer more detailed simulations by incorporating physical principles of hydraulics, sediment transport, and soil mechanics. These models can capture the dynamic interactions between erosive forces and soil properties, providing valuable insights into both detachment and transport processes. Geostatistical techniques, including kriging and spatial autocorrelation, further enhance erosion modeling by interpolating point data to create continuous spatial representations of erosion risk (Mubashir, 2021; Ouillon, 2018). Multivariate statistical analyses, such as principal component analysis and multiple regression, are commonly employed to identify key variables influencing erosion and quantify their relative importance. The integration of remote sensing and geographic information systems has revolutionized erosion studies by enabling high-resolution mapping of land surface changes, slope dynamics, and sediment fluxes over time. In coastal environments, coupling geotechnical data with hydrodynamic models improves predictions of shoreline retreat and sediment redistribution, offering a more comprehensive understanding of erosion processes. These quantitative tools are essential for identifying spatial and temporal patterns of soil loss, evaluating the effectiveness of mitigation measures, and informing adaptation strategies (Nieder et al., 2018a; Rony, 2021). By combining statistical methods with geotechnical and environmental data, researchers can build robust predictive frameworks that support evidence-based decision-making in land management, infrastructure planning, and climate adaptation efforts.

Human activities significantly influence soil erosion dynamics, often amplifying the effects of natural processes. Urbanization and land development increase the extent of impervious surfaces, accelerating surface runoff and reducing natural infiltration. Deforestation and land clearing remove protective vegetation cover, exposing soils to direct impact from rainfall and overland flow (Wang et al., 2015). Agricultural practices, particularly those involving intensive tillage, can degrade soil structure, reduce organic matter, and increase erodibility. In coastal zones, the construction of infrastructure such as ports, seawalls, and breakwaters alters natural sediment transport pathways and hydrodynamic regimes, frequently causing increased erosion downstream or in adjacent areas. Land reclamation and wetland drainage diminish natural buffer zones that dissipate wave energy, further exposing soils to erosive forces. Groundwater extraction and heavy construction can induce land subsidence, lowering coastal elevations and increasing vulnerability to tidal inundation and erosion (Jia et al., 2020). Additionally, anthropogenic climate change intensifies erosion pressures by altering precipitation patterns, increasing the frequency of extreme weather events, and driving sea-level rise. Quantitative analyses of soil erosion must therefore incorporate human-induced variables such as land use changes, infrastructure density, and population growth to accurately model erosion dynamics. Integrating socio-economic data with geotechnical and hydrological parameters allows for a more holistic understanding of how human and natural systems interact to shape erosion patterns. This approach also supports the development of targeted mitigation strategies that address the root causes of accelerated erosion, balancing the needs of development with environmental stability (Osman, 2018). Recognizing the significant role of human activities is essential for effective coastal management and for designing adaptive measures that protect both human settlements and natural ecosystems from the adverse effects of soil loss.

The primary objective of this study is to conduct a comprehensive quantitative analysis of geotechnical soil loss and erosion patterns in coastal zones and to utilize this understanding to support effective climate adaptation strategies. Coastal regions are highly dynamic environments where soil erosion is influenced by a complex interplay of hydrodynamic forces, climatic variability, and human activities. This study aims to measure and statistically analyze the magnitude, distribution, and temporal variability of soil loss, focusing on how these factors shape erosion dynamics across diverse coastal landscapes. It seeks to identify and evaluate the key geotechnical properties—such as particle size distribution, cohesion, permeability, bulk density, and organic matter content—that govern soil susceptibility to detachment and transport under erosive forces. By integrating field measurements with advanced statistical modeling, spatial analysis, and geostatistical techniques, the research will establish predictive relationships between soil characteristics, climatic drivers, and erosion rates. Additionally, the study will assess the influence of salinity, pH, and vegetation cover on soil stability, offering deeper insight into the factors that exacerbate or mitigate erosion. Through the creation of spatial risk maps and predictive models, the research aims to identify erosion hotspots and provide actionable data for land-use planning, infrastructure development, and coastal zone management. Ultimately, this study seeks to generate a scientifically grounded framework that links geotechnical soil behavior with erosion processes, enabling policymakers, engineers, and planners to design adaptive interventions that enhance coastal resilience. By achieving this objective, the research contributes to a more accurate understanding of soil erosion mechanisms in vulnerable coastal areas and provides essential knowledge for developing strategies to minimize soil loss and safeguard coastal environments against the escalating impacts of climate change.

LITERATURE REVIEW

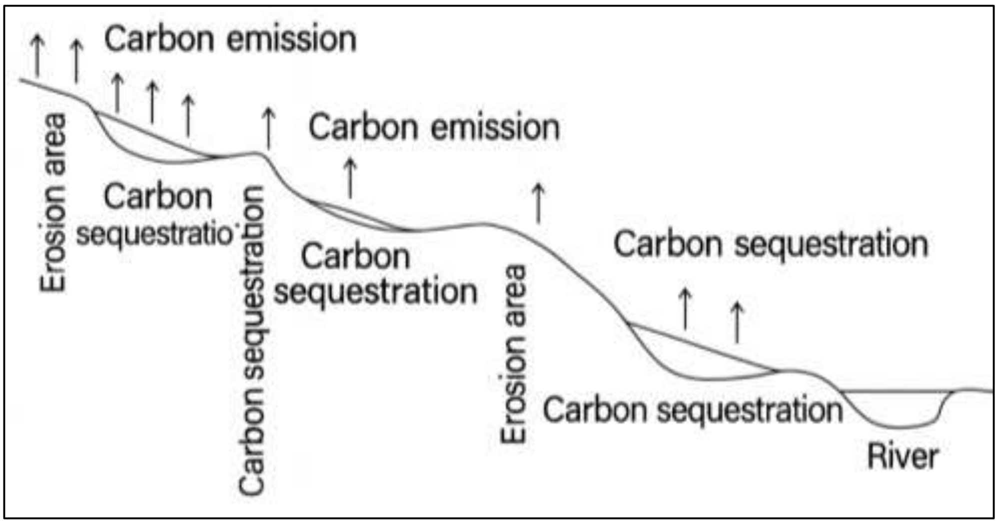
Soil erosion is one of the most significant environmental and geotechnical challenges affecting coastal regions worldwide (Singh & Hartsch, 2019). It represents a critical intersection of physical geography, soil mechanics, hydrodynamics, and climate science. The phenomenon involves the detachment, transport, and redistribution of soil particles by natural agents such as water, wind, and wave action, and is intensified by anthropogenic activities and climatic variability. In coastal environments, erosion processes are particularly complex due to the combined influence of terrestrial and marine forces, including rainfall, runoff, tidal oscillations, wave impact, and sea-level rise. These processes not only reshape coastal landscapes but also alter soil geotechnical properties such as cohesion, shear strength, and permeability, thereby affecting the structural stability of infrastructure and ecosystems (Evelpidou et al., 2018).The literature on soil erosion has evolved from early empirical assessments toward sophisticated quantitative analyses that integrate geotechnical soil characteristics with spatial modeling, remote sensing, and statistical techniques. Empirical models like the Universal Soil Loss Equation (USLE) and its revised versions (RUSLE) have laid foundational frameworks for estimating soil loss based on rainfall, soil type, slope, and vegetation cover. However, these models often require refinement in coastal settings where hydrodynamic forces and salinity gradients introduce additional complexity. Process-based and spatially distributed models have enhanced predictive accuracy by simulating sediment detachment, transport, and deposition, while geostatistical and multivariate analyses allow for the identification of key predictors and spatial variability of erosion (Hossain et al., 2020).Current research emphasizes the necessity of integrating geotechnical soil properties—such as texture, structure, organic matter, and bulk density—into erosion modeling to improve predictive capabilities and inform adaptation strategies. Moreover, the advent of remote sensing and GIS technologies has enabled the development of high-resolution erosion risk maps, facilitating targeted interventions. Despite these advancements, significant knowledge gaps remain regarding how soil mechanical properties interact with climate-induced hydrodynamic changes to shape erosion dynamics in coastal zones (Zafirah et al., 2017). This literature review critically examines existing studies, identifies methodological advancements and limitations, and synthesizes the state of knowledge regarding the statistical analysis of soil loss and erosion patterns. The aim is to provide a robust conceptual and methodological foundation for quantitative research focused on enhancing climate adaptation strategies in vulnerable coastal regions.

Overview of Soil Erosion in Coastal Zones

Soil erosion is a natural geomorphological process involving the detachment, movement, and redeposition of soil particles by agents such as water, wind, gravity, and ice (Banning, 2020). In geotechnical engineering, this process carries profound significance because it directly affects soil stability, strength, and load-bearing capacity—key parameters that underpin the design and durability of infrastructure. When erosion occurs, the physical characteristics of soil, including its texture, cohesion, porosity, and permeability, are altered. These changes weaken the soil structure, reduce shear strength, and increase susceptibility to deformation or collapse under stress. In coastal zones, erosion assumes even greater importance due to the interaction between terrestrial soils and marine forces such as waves, tides, and storm surges. These forces accelerate soil particle detachment, disrupt sedimentary structures, and contribute to shoreline retreat (DiPietro, 2018). As erosion progresses, it undermines the stability of foundations, embankments, and coastal defense systems, posing risks to human settlements and engineered structures. Moreover, the removal of nutrient-rich topsoil diminishes soil fertility, disrupts vegetation growth, and alters ecosystem services. Quantifying erosion rates and understanding the mechanical consequences of soil loss are essential for risk assessment and infrastructure planning. Geotechnical investigations that measure properties such as shear strength, cohesion, and permeability provide insights into how soils respond to erosive forces. When integrated into erosion modeling, these properties help engineers anticipate failure mechanisms and design effective stabilization measures. By linking the processes of soil erosion with geotechnical behavior, researchers can better understand how erosion transforms landscapes and influences the performance and longevity of structures (Dreimanis, 2020). This perspective is particularly important in coastal regions, where soil dynamics are shaped by the combined effects of hydrodynamic energy, sediment transport, and changing environmental conditions, all of which operate within a complex geotechnical framework.

While soil erosion is a universal process, the mechanisms, drivers, and characteristics differ significantly between terrestrial and coastal environments. Terrestrial erosion is predominantly influenced by rainfall, overland flow, and wind, which detach and transport soil particles across slopes, plains, and river catchments (van Huissteden, 2020). It often occurs as sheet erosion, rill erosion, or gully erosion, depending on the intensity of water flow and the topographical conditions. Factors such as vegetation cover, soil type, slope gradient, and land use practices strongly influence erosion rates in terrestrial settings. In contrast, coastal erosion is shaped by the unique interaction between land and sea. Hydrodynamic forces such as waves, tides, and longshore currents are the primary agents of soil detachment and sediment transport in coastal zones (Garrison, 2016). These forces not only remove soil but also continuously reshape shorelines through cycles of erosion and deposition. The presence of saline water further distinguishes coastal erosion, as salinity alters soil structure by dispersing clay particles and reducing aggregate stability, thereby increasing erodibility. Additionally, wave action and tidal oscillations impose cyclical loading on coastal soils, contributing to slope instability and mechanical weakening. Unlike terrestrial erosion, which is largely influenced by climatic factors and surface runoff, coastal erosion is highly dependent on hydrodynamic energy, sediment supply, and sea-level fluctuations (Yu et al., 2018). Human activities such as dam construction, dredging, and shoreline engineering can exacerbate coastal erosion by altering sediment delivery and modifying wave regimes. These differences mean that coastal erosion is often more complex and spatially variable than its terrestrial counterpart. Recognizing these distinctions is critical for developing accurate models and targeted management strategies. Understanding how terrestrial and coastal processes differ in terms of forces, responses, and consequences enables more effective planning and mitigation efforts tailored to the unique dynamics of each environment.

Figure 3: Soil Erosion and Carbon Dynamics



The processes of soil erosion are governed by a combination of geomorphological principles and soil mechanical properties, which together explain how soil particles detach, move, and settle under natural forces. From a geomorphological perspective, erosion is a fundamental driver of landscape evolution (Talapatra, 2020). It shapes the morphology of coastlines, rivers, and deltas by redistributing sediments and altering landforms. In coastal zones, hydrodynamic forces such as wave action, tidal currents, and storm surges are powerful agents that erode soil and transport sediments, continuously reshaping the coastal landscape. Soil mechanical principles provide a complementary understanding by explaining how soil properties influence erosion resistance. Parameters such as cohesion, internal friction angle, and shear strength determine a soil's capacity to resist detachment. Fine-textured soils with high cohesion are generally more resistant to erosion, whereas coarse-textured soils with low cohesion are more easily mobilized by water and wind. However, Blasio, (2018) even cohesive soils can become highly erodible when saturated or chemically altered. Bulk density and porosity also affect erosion susceptibility by influencing water infiltration and pore pressure, which in turn alter shear strength and slope stability. Aggregate stability plays a crucial role; soils with stable aggregates resist detachment and maintain structural integrity, while poorly aggregated soils disintegrate more easily under erosive forces. In coastal settings, chemical factors such as salinity and pH significantly impact soil behavior, as they can weaken particle bonds and increase dispersibility. The interaction between geomorphological forces and soil mechanical properties determines the spatial patterns and rates of erosion (Xiong et al., 2019). A thorough understanding of these principles allows researchers to link small-scale soil behavior with large-scale landscape changes, providing a comprehensive framework for analyzing erosion dynamics. This integrated perspective is essential for accurate modeling, risk assessment, and the development of effective soil management and stabilization strategies.

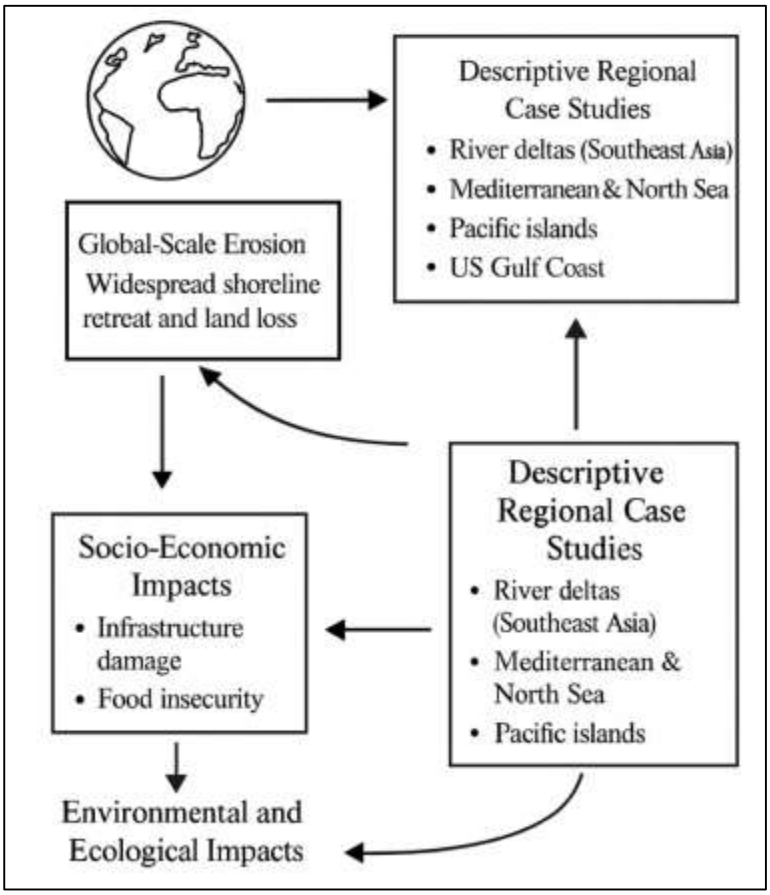
The complexity of soil erosion in coastal zones requires an integrated approach that considers the interconnected roles of hydrodynamic forces, climatic variables, and geotechnical properties (Mentaschi et al., 2018). Hydrodynamic forces, including waves, tides, and currents, are the primary drivers of soil detachment and transport in coastal environments. These forces continuously reshape shorelines and influence erosion intensity and distribution. Climatic factors such as rainfall patterns, storm frequency, and sea-level rise further compound erosion processes by altering soil moisture regimes, increasing runoff, and enhancing the energy available for soil displacement. Intense rainfall can trigger rapid surface runoff, while storm surges and sea-level rise increase the frequency and magnitude of wave action on coastal soils. Geotechnical properties mediate how soils respond to these external forces. Soil texture, cohesion, permeability, Owens(2020) and organic matter content all influence erosion resistance, determining how easily soils detach and how they behave under hydrodynamic loading. High-cohesion soils may resist detachment under moderate conditions but can fail under prolonged saturation or increased pore pressure. Salinity changes also affect soil structure and aggregate stability, further influencing erodibility. Vegetation plays a pivotal role in this integrated system, enhancing soil shear strength through root reinforcement and reducing the kinetic energy of rainfall and waves through canopy interception. Effective analysis of soil erosion must combine data from these three domains to capture the full range of factors influencing erosion patterns. Statistical modeling, spatial analysis, (Guerra et al., 2020) and geotechnical testing together provide a comprehensive understanding of how these elements interact. By integrating hydrodynamic, climatic, and geotechnical perspectives, researchers can more accurately describe observed erosion processes and better understand the mechanisms shaping coastal landscapes. This holistic approach is essential for advancing scientific knowledge and supporting evidence-based decision-making in the management and protection of erosion-prone coastal regions.

Global Patterns of Coastal Soil Erosion

Coastal soil erosion is a global phenomenon that affects nearly every continent, posing significant challenges to both natural and human systems (Owens, 2020). Although coastal zones occupy a relatively small proportion of the Earth's land surface, they are among the most densely populated and economically productive areas, making them highly vulnerable to erosion. The spatial distribution of erosion is influenced by a combination of geological, hydrodynamic, climatic, and anthropogenic factors. Regions with low-lying deltas, barrier islands, and unconsolidated sediments are particularly susceptible due to their geological composition and exposure to wave and tidal action. In areas such as Southeast Asia, West Africa, and parts of South America, rapid population growth and land use changes have intensified erosion rates, leading to widespread shoreline retreat and soil loss (Pranzini et al., 2015). High-latitude regions are also experiencing increasing erosion as thawing permafrost destabilizes coastal soils and rising sea levels accelerate sediment removal. Globally, the magnitude of soil erosion varies from gradual shoreline recession over decades to catastrophic land loss during storm events. Coastal erosion contributes to the disappearance of entire landforms, including small islands and wetland areas, altering coastlines and reducing land availability. The severity of erosion is further compounded by human interventions such as dam construction, dredging, and shoreline engineering, which disrupt sediment supply and modify natural processes (Gomiero, 2016). Accurate assessment of global erosion patterns requires integrating spatial data from remote sensing, field measurements, and hydrodynamic modeling to capture both large-scale trends and local variations. These assessments reveal that coastal erosion is not confined to specific regions but is a pervasive issue that reshapes coastlines and affects ecosystems, infrastructure, and livelihoods worldwide. Its global scale underscores the need to understand the underlying processes and develop context-specific approaches to monitoring and managing soil loss in diverse coastal settings (Nichols et al., 2018).

The socio-economic impacts of coastal soil erosion are extensive and multifaceted, affecting human populations, infrastructure, and national economies (Fernandino et al., 2018). As coastal zones host major cities, ports, industrial complexes, and agricultural lands, erosion-induced land loss directly threatens critical economic activities and livelihoods. Infrastructure such as roads, bridges, housing, and utilities is vulnerable to structural damage and eventual destruction as shorelines retreat and soil stability decreases. The loss of agricultural land due to erosion reduces food production capacity and undermines local economies, particularly in regions where coastal plains support intensive farming. Fisheries and aquaculture operations are also affected as erosion alters nearshore habitats and disrupts nutrient dynamics, (Gorman, 2018) leading to declines in fish stocks and changes in species composition. Coastal erosion often forces communities to relocate, resulting in population displacement and social disruption. This displacement can strain urban centers and public services, leading to increased competition for land and resources. The economic costs of erosion are substantial, encompassing not only the direct damage to property and infrastructure but also the expenses associated with shoreline protection, land reclamation, and disaster recovery. Tourism, a vital economic sector in many coastal regions, suffers as beaches disappear and scenic landscapes are degraded. The cumulative economic burden of erosion can hinder regional development and exacerbate poverty, especially in low-income countries with limited capacity to implement protective measures (Hurni et al., 2015). In addition to economic losses, erosion poses challenges for governance and land-use planning, as authorities must balance development pressures with the need to preserve coastal integrity. The socio-economic impacts of soil erosion thus extend far beyond physical land loss, influencing demographic patterns, economic resilience, and social stability. Understanding these impacts is essential for formulating policies and strategies that safeguard communities and economies against the persistent and far-reaching consequences of coastal erosion.

Figure 4: Coastal Erosion and Ecosystem Dynamics



Beyond its socio-economic implications, coastal soil erosion exerts profound environmental and ecological effects that reshape ecosystems and disrupt natural processes. The removal of soil and sediment alters the geomorphology of coastal landscapes, leading to changes in shoreline configuration, habitat structure, and sediment transport pathways (Huang & Jin, 2018). Wetlands, mangroves, and salt marshes—ecosystems that provide critical services such as carbon sequestration, water filtration, and storm buffering—are particularly vulnerable to erosion. As these habitats retreat or disappear, biodiversity declines and the ecological functions they support are diminished. The loss of vegetative cover further accelerates erosion, creating a feedback loop that amplifies soil degradation and habitat loss. Erosion also influences biogeochemical cycles by redistributing nutrient-rich sediments, affecting primary productivity in coastal waters and altering nutrient availability for aquatic and terrestrial organisms. Changes in sediment dynamics can disrupt the spawning grounds and feeding habitats of fish and shellfish, with cascading effects on food webs and fisheries (Arora, 2017). In addition, erosion contributes to increased turbidity in coastal waters, reducing light penetration and impairing the growth of seagrasses and coral reefs. These changes compromise ecosystem resilience and reduce the capacity of coastal environments to provide essential services. Soil erosion can also lead to saline intrusion into freshwater systems, further degrading habitats and agricultural land. Moreover, the exposure of previously buried organic matter due to erosion can enhance greenhouse gas emissions, linking coastal processes to broader climate systems. The cumulative ecological consequences of erosion demonstrate its role as a driver of environmental change, with impacts that extend beyond the immediate zone of soil loss (Azevedo de Almeida & Mostafavi, 2016). Recognizing the ecological dimensions of erosion is critical for holistic coastal management, as maintaining ecosystem integrity is essential for sustaining biodiversity, supporting human livelihoods, and preserving the natural functions that buffer coastal regions against environmental stressors.

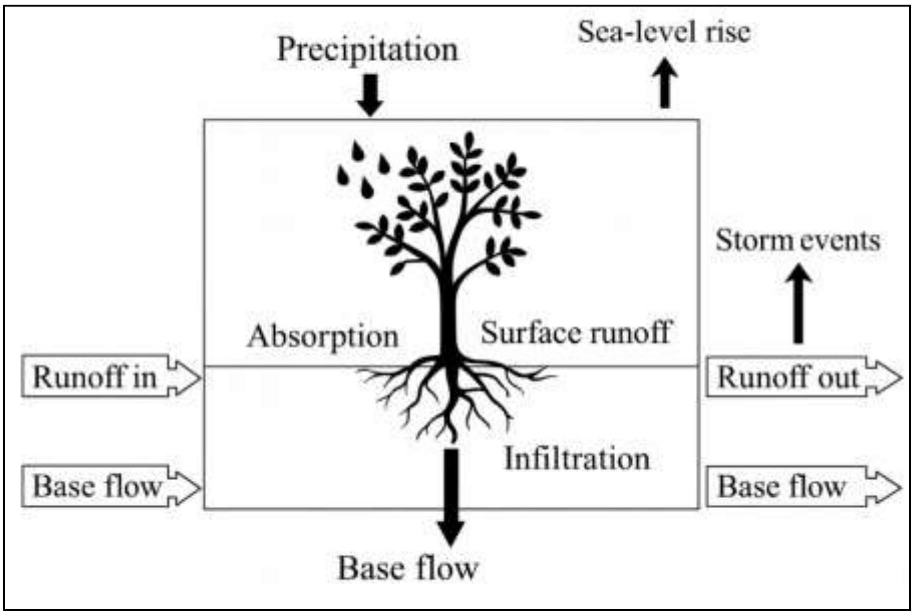
Climate Dynamics on Soil Erosion Patterns

Precipitation patterns and rainfall intensity play a fundamental role in driving soil erosion processes, particularly in coastal regions where hydrological forces interact with marine dynamics (Zhang et al., 2020). Rainfall is one of the primary agents of soil detachment and transport. When raindrops strike the soil surface, they impart kinetic energy that breaks apart soil aggregates, dislodges particles, and initiates surface runoff. The intensity, duration, and frequency of rainfall events determine the magnitude of this impact. High-intensity storms generate greater kinetic energy, leading to more substantial detachment and increased sediment transport. Prolonged rainfall can saturate the soil, reducing its cohesion and shear strength, which makes it more susceptible to erosion and mass movement. Conversely, low-intensity, long-duration rainfall promotes infiltration and reduces surface runoff, mitigating erosion potential. Changes in precipitation patterns, such as shifts in seasonal rainfall or an increase in extreme rainfall events, can significantly alter erosion dynamics (Kiani-Harchegani et al., 2018). In coastal areas, heavy rainfall often coincides with high tides or storm surges, amplifying erosive forces as surface runoff interacts with wave action and tidal flows. The resulting overland flow accelerates soil particle transport toward coastal water bodies, contributing to shoreline retreat and sediment redistribution. Variations in precipitation also influence vegetation cover and soil moisture regimes, both of which are critical in modulating erosion. Vegetation reduces the impact of raindrops and stabilizes soil through root reinforcement, while soil moisture affects aggregate stability and permeability. Changes in rainfall patterns that exceed the adaptive capacity of local soils and vegetation can therefore lead to accelerated erosion (Yang et al., 2016). The cumulative effect of precipitation-driven erosion extends beyond immediate soil loss, influencing sediment budgets, coastal morphology, and the functioning of nearshore ecosystems. Understanding the role of rainfall in shaping erosion dynamics is essential for interpreting spatial and temporal variations in soil loss within coastal environments.

Sea-level rise is a critical climatic driver of coastal soil erosion, fundamentally altering the physical processes that shape shorelines and influence soil stability (Fu et al., 2017). As global temperatures increase, the thermal expansion of seawater and the melting of ice sheets contribute to rising sea levels, which intensify the frequency and magnitude of tidal inundation. This rising baseline of coastal water levels allows waves to penetrate further inland, increasing the reach and energy of hydrodynamic forces acting on soils. Elevated sea levels reduce the buffer zones provided by beaches, dunes, and wetlands, exposing inland soils to direct wave impact and accelerating shoreline retreat. The increased duration of tidal submersion also promotes soil saturation, which weakens cohesion and reduces shear strength, making soils more vulnerable to detachment and transport (J. Lu et al., 2016). In low-lying coastal plains and deltas, sea-level rise can lead to saline intrusion, which alters soil structure by dispersing clay particles and reducing aggregate stability. These changes exacerbate erosion and further compromise the mechanical integrity of coastal soils. Additionally, sea-level rise modifies sediment dynamics by increasing the depth and energy of nearshore waters, enhancing sediment resuspension, and redistributing material along the coast. This process often leads to a sediment deficit in some areas and accumulation in others, reshaping coastal geomorphology and altering erosion patterns (Vaezi et al., 2017). The effects of sea-level rise are particularly pronounced when combined with other climatic forces, such as increased precipitation or more intense storms, which amplify erosion rates and the extent of land loss. The interaction between rising seas and coastal soils is not limited to gradual processes; it also intensifies the impact of episodic events like storm surges, which can cause rapid and severe erosion. Overall, sea-level rise is a transformative force in coastal erosion dynamics, reshaping landforms, altering soil properties, and accelerating the loss of terrestrial land in coastal regions.

Storm events and extreme weather phenomena exert powerful influences on soil erosion, especially in coastal environments where hydrodynamic forces are amplified by climatic variability. Intense storms generate strong winds, heavy rainfall, and elevated wave energy, all of which contribute to the detachment, transport, and redistribution of soil (Jiang et al., 2020).

Figure 5: Hydrological Processes and Soil Interaction



The combination of high precipitation and storm surges increases surface runoff and enhances the erosive capacity of water, while wave action under storm conditions delivers direct mechanical force to coastal soils. These forces act synergistically, accelerating soil particle detachment and deepening erosion features such as gullies and scarp faces. Extreme weather events can also cause sudden and extensive changes in coastal morphology, including the breaching of barriers, the retreat of cliffs, and the loss of beach sediments (Vaezi et al., 2020). The hydrodynamic energy associated with storms often overwhelms the natural resistance of soils, even those with high cohesion and structural integrity. Saturation from prolonged rainfall reduces soil strength and increases pore water pressure, making slopes and embankments more prone to failure. Furthermore, storm-driven waves and currents can erode the base of slopes and cliffs, triggering mass wasting events that contribute to rapid land loss. These episodic events can remove large volumes of soil in a short period, altering sediment budgets and reshaping coastal landscapes (Lacombe et al., 2018). The ecological impacts are equally significant, as storm-driven erosion can bury or remove critical habitats such as wetlands and mangroves, disrupting ecosystem functions. The frequency and intensity of storm events influence long-term erosion trends, as repeated extreme events can erode protective features and reduce the resilience of coastal systems. Understanding the role of storms and extreme weather in erosion processes is essential for interpreting spatial patterns of soil loss and for assessing the vulnerability of coastal regions to climate-driven changes in hydrodynamic energy (Marzen et al., 2015).

Geotechnical Properties and Their Role in Erosion Susceptibility

Particle size distribution and soil texture are fundamental geotechnical properties that significantly influence soil susceptibility to erosion (Wei et al., 2015). Soil texture refers to the relative proportion of sand, silt, and clay particles, and it plays a critical role in determining the soil's structural integrity and resistance to erosive forces. Coarse-textured soils, dominated by sand particles, have low cohesion and are easily detached and transported by water and wind. Their large pore spaces allow rapid infiltration but also reduce the soil's ability to resist shear stress. Fine-textured soils, composed primarily of clay, possess higher cohesion due to electrochemical bonding between particles. This cohesion increases resistance to detachment under moderate conditions but can decrease significantly when soils become saturated or chemically altered (Xia et al., 2015). Silt-sized particles, with intermediate cohesion and relatively low density, are particularly prone to transport once detached, contributing substantially to sediment movement. The arrangement and interaction of these particle sizes influence the soil's permeability, aggregate stability, and infiltration capacity, all of which affect erosion dynamics. For example, soils with a balanced mix of particle sizes often form stable aggregates that resist raindrop impact and surface runoff. Conversely, poorly structured soils with a dominance of one particle size may disintegrate easily, leading to increased erosion rates. In coastal environments, particle size distribution also determines how soils respond to hydrodynamic forces such as wave action and tidal flow. Coarse materials may be rapidly mobilized and redistributed by wave energy, while fine sediments may be carried farther offshore and contribute to the formation of mudflats or submerged deposits (Guo et al., 2020). The spatial variability of particle size within a coastal landscape creates differential erosion patterns, with some zones eroding rapidly and others remaining relatively stable. Understanding particle size distribution and soil texture is therefore crucial for assessing erosion potential and predicting how soils will behave under various hydrological and climatic conditions.

Cohesion, shear strength, and permeability are key geotechnical parameters that determine a soil's resistance to erosive forces and its overall stability. Cohesion refers to the internal bonding between soil particles, which provides structural integrity and resistance to detachment. Clay-rich soils typically exhibit high cohesion, making them more resistant to raindrop impact and surface runoff. However, cohesion is sensitive to moisture content and chemical composition; excessive water can reduce electrostatic bonds, while changes in salinity can disrupt particle interactions, leading to increased erodibility (Zuo et al., 2020). Shear strength, a measure of a soil's ability to resist deformation under stress, is another critical factor in erosion resistance. It depends on both cohesive forces and internal friction between particles. High shear strength enables soils to withstand the shear stresses exerted by flowing water, waves, and gravity, reducing the likelihood of detachment and transport. Saturation from rainfall or tidal inundation reduces shear strength by increasing pore water pressure, weakening soil structure, and promoting mass movement such as slumping or landslides. Permeability, which governs the rate at which water infiltrates the soil, further influences erosion dynamics (Igwe & Egbueri, 2018). Highly permeable soils allow rapid water infiltration, reducing surface runoff and minimizing detachment by overland flow. Low-permeability soils, in contrast, generate more runoff, increasing the erosive power of water flowing over the surface. In coastal zones, permeability also affects the degree of saturation caused by tidal fluctuations and storm surges, influencing soil strength and erosion rates. The interplay between cohesion, shear strength, and permeability determines how soils respond to external forces and how erosion processes unfold over time. Soils with high cohesion and shear strength and balanced permeability tend to resist erosion effectively, while those with weak internal bonding, low shear resistance, or poor drainage are more vulnerable to rapid degradation (Wu et al., 2020). Understanding these properties is essential for assessing erosion potential and evaluating soil stability in dynamic coastal environments.

Organic matter, bulk density, and aggregate stability are critical geotechnical properties that influence soil structure, strength, and susceptibility to erosion. Organic matter enhances soil cohesion and aggregate formation by binding mineral particles together, increasing resistance to detachment by water and wind (Yao et al., 2016). It also improves water retention and infiltration capacity, reducing surface runoff and the associated erosive forces. Soils rich in organic content are generally more resilient to erosion due to their improved structural stability and enhanced biological activity, which supports root growth and soil aggregation. Bulk density, defined as the mass of soil per unit volume, affects pore space, infiltration, and compaction, all of which influence erosion dynamics. Soils with high bulk density are often compacted and have reduced porosity, limiting infiltration and increasing runoff. This condition amplifies the potential for surface erosion as water flows over the soil rather than percolating through it (Xia et al., 2019). Low bulk density soils, on the other hand, are typically well-aerated and have greater water-holding capacity, but if they lack sufficient cohesion, they may be more easily detached by raindrop impact or overland flow. Aggregate stability, which refers to the soil's ability to maintain its structure when exposed to external forces, is a key determinant of erosion resistance. Stable aggregates resist disintegration under rainfall or water flow, maintaining surface structure and reducing detachment. Unstable aggregates, however, readily break apart, leading to crust formation, reduced infiltration, and increased runoff (Taye et al., 2018). In coastal environments, aggregate stability can be influenced by salinity and wetting-drying cycles, which affect particle bonding and structural integrity. The combined effects of organic matter, bulk density, and aggregate stability shape the soil's response to erosive forces and determine how quickly erosion progresses. By influencing water movement, particle cohesion, and structural resilience, these properties play a central role in the erosion process and in the long-term stability of coastal soils (Naghdi et al., 2020).

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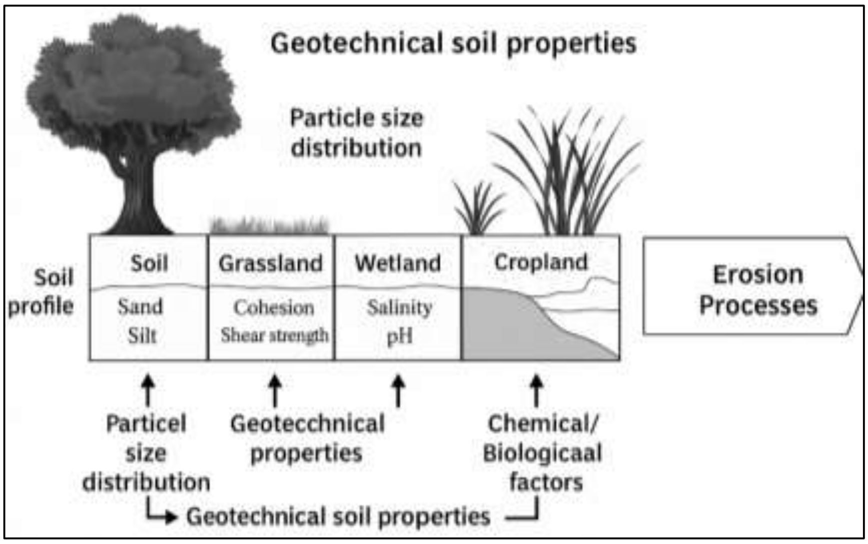
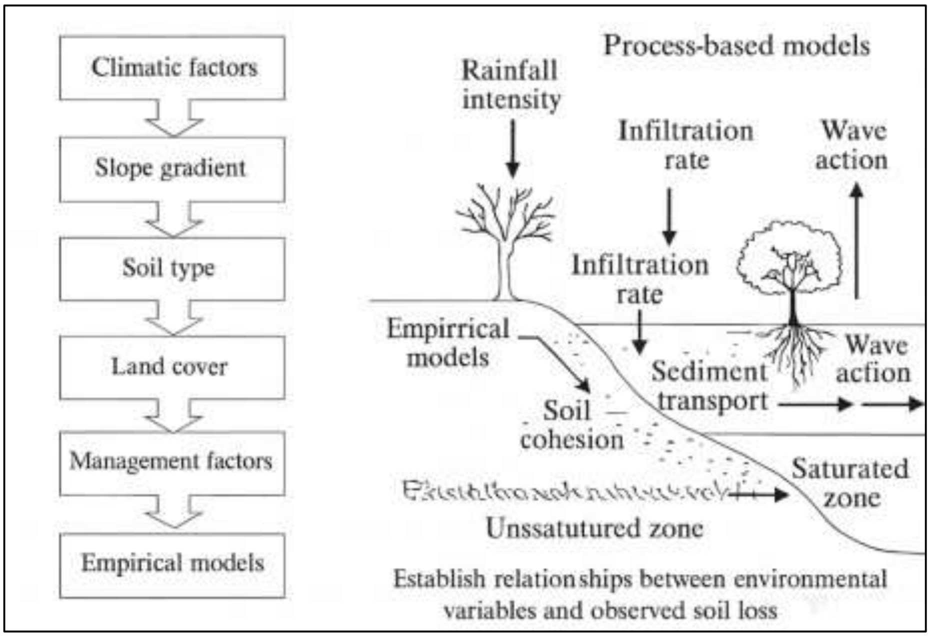
Figure 6: Soil Properties Influencing Erosion Dynamics



Salinity, pH, and vegetation are significant factors that influence soil erodibility by altering soil structure, chemical properties, and mechanical stability. Salinity affects soil particle interactions by disrupting electrostatic bonds, dispersing clay particles, and weakening aggregate structure (Yates et al., 2018). As salt concentrations increase, soil cohesion often decreases, making soils more susceptible to detachment and transport. In coastal regions, saline water intrusion from sea-level rise, tidal flooding, or storm surges can exacerbate these effects, particularly in fine-textured soils. Soil pH also plays a critical role in erosion dynamics by influencing nutrient availability, chemical reactions, and the activity of soil microorganisms that contribute to aggregation. Extremely acidic or alkaline conditions can weaken soil structure, reduce aggregate stability, and alter the binding capacity of organic matter, thereby increasing erodibility. Vegetation is a powerful natural stabilizer that mitigates erosion through multiple mechanisms (Paz-Ferreiro et al., 2018). Plant roots anchor soil particles and increase shear strength, while root networks enhance aggregate stability and improve soil structure. Vegetation cover also reduces the kinetic energy of rainfall and surface runoff, minimizing particle detachment. In coastal areas, vegetation such as mangroves, salt marsh grasses, and dune plants plays a vital role in dissipating wave energy and trapping sediments, which helps maintain shoreline stability. The absence or removal of vegetation often leads to rapid erosion, as soils lose their structural reinforcement and become more exposed to hydrodynamic forces. The interactions between salinity, pH, and vegetation are complex and context-dependent. High salinity can limit vegetation growth, reducing its protective effects, while changes in pH can affect root development and microbial activity (Jarašiūnas & Kinderienė, 2016). Together, these factors determine the erodibility of soils and their response to environmental stressors. Understanding how chemical conditions and biological factors influence soil structure and stability is essential for assessing erosion risk and maintaining soil resilience in coastal zones.

Empirical models have long been fundamental tools for estimating soil erosion by establishing relationships between environmental variables and observed soil loss (Nearing et al., 2017). These models are typically derived from extensive field data and are designed to provide practical, scalable estimates of erosion rates across large spatial and temporal scales. They use measurable factors such as rainfall intensity, soil type, slope gradient, land cover, and management practices to predict average annual soil loss. One of the most widely used approaches relies on multiplying these variables to generate an erosion estimate that reflects the combined influence of climatic, topographic, and land-use conditions (Borrelli et al., 2017). Empirical models are particularly valuable because of their simplicity, ease of application, and relatively modest data requirements, making them accessible for use in regions with limited resources. They are also useful for comparing erosion risks across different landscapes and evaluating the potential effects of land management practices on soil loss. In coastal environments, empirical models must account for additional variables such as wave energy, tidal fluctuations, and salinity, which influence erosion differently than terrestrial factors (García-Ruiz et al., 2015). By incorporating site-specific coefficients or modifying existing equations, researchers can adapt these models to better reflect coastal conditions. However, empirical models are often limited by their reliance on historical data and their inability to capture the dynamic and nonlinear nature of erosion processes. They provide average estimates but may not accurately represent short-term variability or extreme events. Despite these limitations, empirical models remain essential tools in soil erosion research and management. Their ability to integrate multiple variables into a single predictive framework allows for rapid assessments of erosion potential and supports decision-making in land use planning, soil conservation, and infrastructure development in coastal zones (Dutta, 2016).

Figure 7: Empirical and Process-Based Erosion Models



Process-based models represent a more detailed and mechanistic approach to understanding and predicting soil erosion, as they are grounded in the physical laws governing hydrology, sediment transport, and soil mechanics (Gaubi et al., 2017). Unlike empirical models, which rely on statistical relationships, process-based models simulate the underlying processes that lead to soil detachment, transport, and deposition. They incorporate variables such as rainfall intensity, infiltration rates, runoff velocity, soil cohesion, and particle size distribution, along with hydrodynamic forces like wave action and tidal currents in coastal settings. These models calculate soil loss based on the balance between erosive forces and the resisting strength of the soil, providing more nuanced insights into how different factors interact to influence erosion rates (Balasubramani et al., 2015). Process-based approaches can capture temporal variability, such as changes in rainfall patterns or storm events, and spatial variability, such as variations in soil properties or land cover. This level of detail enables them to simulate complex scenarios, including the effects of land-use changes, vegetation removal, or climate variability on erosion dynamics. They are also useful for identifying critical thresholds beyond which erosion accelerates, as well as for understanding feedback mechanisms between soil properties and erosive forces. In coastal environments, process-based models can simulate how wave energy and tidal oscillations interact with soil structure to influence detachment and transport, providing valuable insights into shoreline retreat and sediment redistribution (Koirala et al., 2019). Despite their advantages, these models require extensive data inputs and significant computational resources, which can limit their applicability in data-scarce regions. They are also sensitive to parameter selection, and inaccuracies in input data can lead to significant errors in output. Nevertheless, process-based models are indispensable for advancing the understanding of soil erosion processes and for generating high-resolution predictions that inform the design of erosion control and adaptation strategies (Ganasri & Ramesh, 2016).

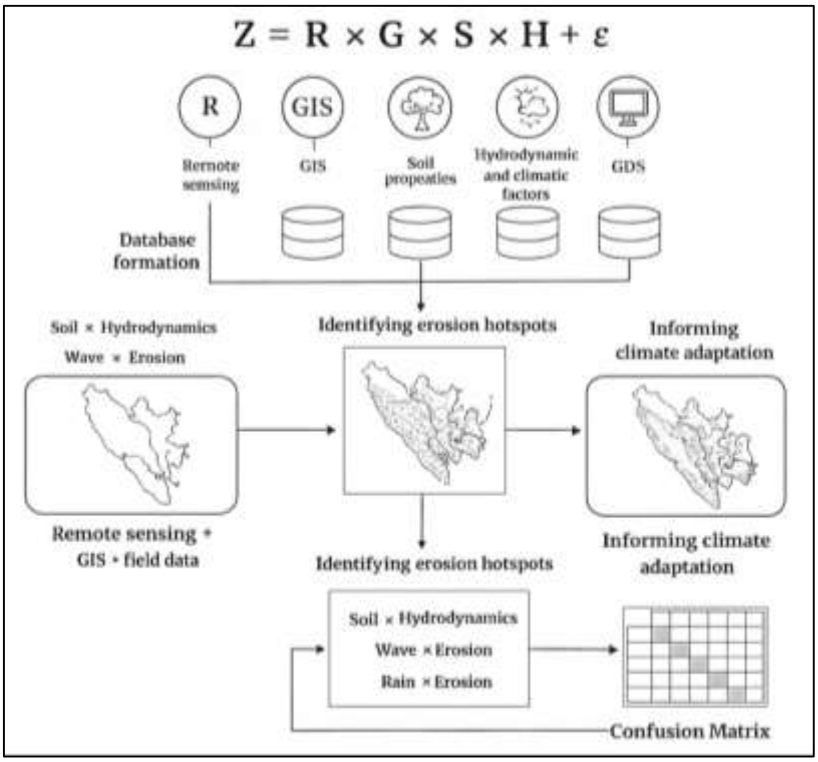
Spatial Analysis, Remote Sensing, and GIS Applications

Remote sensing has become a vital tool in the study of soil erosion, particularly in coastal environments where spatial and temporal variability is high and field-based measurements alone are often insufficient (Pham, Xia, et al., 2019). Through satellite imagery, aerial photography, and radar data, remote sensing provides continuous, high-resolution observations of the Earth's surface, allowing researchers to monitor changes in landforms, soil cover, and sediment dynamics over time. Coastal zones, which are subject to rapid morphological changes due to wave action, tidal forces, and climatic variability, benefit greatly from this technology. Remote sensing enables the detection of shoreline retreat, the identification of erosion hotspots, and the measurement of sediment transport across large spatial scales. It can capture subtle changes in land elevation, vegetation cover, and surface moisture, all of which influence erosion processes (Manfreda et al., 2018). Time-series analysis of satellite imagery allows researchers to track long-term erosion trends and understand how natural events, such as storms and sea-level rise, alter coastal landscapes. Remote sensing also provides critical data on vegetation dynamics, which affect soil stability and erosion resistance. By distinguishing between different land cover types and detecting changes in vegetation density, remote sensing helps assess how land-use changes and vegetation removal contribute to soil loss. Moreover, (Dube et al., 2015)multispectral and hyperspectral sensors can detect variations in soil composition and surface conditions, offering insights into erosion susceptibility and sediment characteristics. These capabilities make remote sensing indispensable for both qualitative and quantitative assessments of erosion. It enhances the understanding of spatial patterns and temporal dynamics, providing a comprehensive view of how erosion reshapes coastal environments. The ability to collect consistent, repeatable data over wide areas makes remote sensing a cornerstone of erosion research, supporting the development of spatial models and management strategies aimed at mitigating soil loss and preserving coastal landscapes (D. Lu et al., 2016).

Geographic information systems (GIS) play a central role in the spatial analysis of soil erosion by enabling the integration, visualization, and interpretation of diverse datasets (Gholizadeh et al., 2018). GIS allows researchers to combine information on soil properties, topography, rainfall, land use, vegetation, and hydrodynamic forces into a single analytical framework, facilitating a comprehensive understanding of erosion dynamics. Through spatial modeling, GIS can generate erosion risk maps that depict areas of high, moderate, and low susceptibility, providing valuable insights into the distribution of soil loss across a landscape. These maps are constructed using algorithms that incorporate multiple variables, often derived from remote sensing data and field measurements, to estimate erosion potential. By layering data on slope gradients, (Pham, Yokoya, et al., 2019) rainfall erosivity, soil erodibility, and vegetation cover, GIS models can identify critical areas where erosion is likely to occur and predict how these areas may evolve under changing environmental conditions. GIS also supports the analysis of spatial relationships and patterns, revealing how erosion hotspots correspond to specific land-use types, soil textures, or hydrological features. In coastal environments, GIS can map shoreline retreat rates, monitor sediment transport pathways, and assess the influence of wave and tidal forces on soil stability. These spatial analyses are essential for understanding the cumulative impacts of natural processes and human activities on erosion (Gopalakrishnan & Kumar, 2020). Additionally, GIS can simulate the potential effects of land management interventions, providing a basis for evaluating mitigation strategies. Its ability to handle large datasets and present results in easily interpretable map formats makes GIS a powerful decision-support tool for planners, engineers, and policymakers. Through spatial modeling and risk mapping, GIS enhances the precision and relevance of erosion studies, enabling more targeted and effective approaches to managing soil loss and protecting coastal landscapes.

The integration of remote sensing and GIS with field data provides a powerful approach to understanding and quantifying soil erosion processes, combining the strengths of large-scale spatial analysis with detailed ground-based measurements. Field data, including soil texture, cohesion, permeability, (Mapes & Pricope, 2020)vegetation cover, and erosion rates, offer critical ground truth for validating and refining remote sensing and GIS-derived models. These measurements ensure that satellite-based interpretations accurately reflect real-world conditions and improve the reliability of predictive models.

Figure 8: Spatial Analysis of Soil Erosion



Remote sensing provides continuous and wide-area coverage, capturing spatial and temporal variability that field studies alone cannot achieve. GIS, in turn, organizes and analyzes this information, linking remotely sensed data with field measurements to generate more accurate erosion risk maps and soil loss estimates (Mahdavi et al., 2018). The synergy of these methods allows for the development of detailed spatial models that incorporate both physical and environmental variables, enhancing the understanding of erosion dynamics. For example, field data on soil cohesion can be combined with satellite-derived rainfall intensity and slope data to assess erosion potential more precisely. Similarly, field observations of shoreline change can be used to calibrate remote sensing analyses of coastal retreat, improving the accuracy of long-term trend assessments. This integrated approach also facilitates the identification of erosion hotspots by correlating spatial data with ground-based measurements of soil properties and erosion rates (Abdullah et al., 2019). It allows researchers to examine how localized factors, such as vegetation type or soil structure, interact with broader climatic and hydrodynamic forces. The combination of field, remote sensing, and GIS data results in more robust erosion models that capture the complexity of coastal systems. By leveraging multiple data sources, researchers gain a deeper and more nuanced understanding of soil erosion processes, supporting more precise assessments and more informed decision-making in coastal management and land-use planning (Pollard et al., 2019).

Spatial analysis techniques applied through remote sensing and GIS are crucial for identifying erosion hotspots and informing climate adaptation strategies in coastal regions. Hotspots are areas where erosion occurs at accelerated rates or where the consequences of soil loss are particularly severe, such as near critical infrastructure, agricultural land, or vulnerable ecosystems. Identifying these areas is essential for prioritizing intervention efforts and allocating resources effectively. Spatial analysis enables the detection of hotspots by integrating multiple layers of data, including soil characteristics, topography, precipitation, wave energy, and land use (Lucas et al., 2015). These layers reveal patterns and correlations that indicate where erosion is most likely to occur and where it is already causing significant impacts. Once hotspots are identified, spatial analysis can help evaluate the underlying causes, whether they are related to natural factors such as hydrodynamic forces and climatic variability or human activities such as deforestation and construction. This knowledge is essential for designing site-specific mitigation measures that address the root causes of erosion. Spatial data also support the assessment of potential adaptation strategies by simulating how changes in land management, vegetation cover, or coastal defenses might alter erosion dynamics (Alvino & Marino, 2017). This predictive capability allows planners and policymakers to evaluate different scenarios and choose interventions that are most likely to succeed. Furthermore, spatial analysis can track the effectiveness of implemented measures by monitoring changes in erosion patterns over time. By linking erosion data with socio-economic information, spatial analysis helps identify communities and sectors most at risk, guiding the development of adaptation plans that balance environmental and human needs (Issa et al., 2019). Through these applications, remote sensing and GIS-based spatial analysis provide a powerful framework for understanding, managing, and mitigating soil erosion in the context of a changing climate, supporting efforts to enhance the resilience and sustainability of coastal regions.

Anthropogenic Influences on Erosion Dynamics

Urbanization and infrastructure development exert profound influences on soil erosion dynamics in coastal regions, significantly altering natural processes and increasing the vulnerability of soils to detachment and transport (Owens, 2020). The expansion of urban areas often involves the removal of vegetation, leveling of land, and construction of impervious surfaces such as roads, buildings, and pavements. These changes reduce infiltration capacity, increase surface runoff, and enhance the erosive power of flowing water. Impervious surfaces channel rainfall into concentrated flows, accelerating the detachment of soil particles and deepening erosion features. Additionally, urban drainage systems often discharge water directly into coastal zones, intensifying localized erosion at discharge points and altering sediment transport dynamics. The construction of infrastructure such as ports, harbors, and transportation networks disrupts natural landforms and hydrological pathways, leading to increased erosion in adjacent areas (Hossain et al., 2020). Coastal development frequently involves the modification of shorelines through dredging, excavation, and land reclamation, which disturb soil stability and accelerate sediment displacement. Furthermore, urban sprawl often encroaches on natural buffer zones like wetlands and dunes, which serve as protective barriers against wave energy and erosion. The loss of these natural defenses exposes inland soils to direct hydrodynamic forces, increasing erosion rates. Large-scale infrastructure projects, including seawalls and breakwaters, can also have unintended consequences by altering wave patterns and redirecting erosive forces to unprotected areas (Zafirah et al., 2017). The combined effects of increased surface runoff, altered sediment dynamics, and the destruction of natural buffers create complex erosion patterns that are often more severe than those driven by natural processes alone. As urban populations grow and coastal cities expand, the pressures on soil systems intensify, amplifying erosion risks. Understanding the geotechnical and hydrological impacts of urbanization is crucial for managing soil stability and maintaining the ecological and structural integrity of coastal environments.

Deforestation, agriculture, and land conversion significantly influence soil erosion dynamics by disrupting natural vegetation cover and altering soil structure and hydrology (Nieder et al., 2018b). Vegetation plays a critical role in protecting soil from erosion by intercepting rainfall, reducing the kinetic energy of raindrops, and stabilizing soil through root systems. When forests are cleared for timber, agriculture, or development, soils lose this protective cover and become directly exposed to erosive forces. Raindrop impact on bare soil surfaces leads to the breakdown of aggregates and increased detachment of particles, while the absence of roots reduces soil cohesion and resistance to surface runoff. Agricultural activities further exacerbate erosion by disturbing the soil structure through tillage, compaction, and irrigation (Vargas et al., 2019). Intensive farming practices reduce organic matter content and weaken soil aggregates, making soils more vulnerable to detachment and transport. Monoculture farming and overgrazing deplete vegetation cover, leaving soils unprotected and accelerating erosion. In coastal areas, agriculture near shorelines can contribute to increased runoff and sediment transport into marine environments, altering sediment dynamics and exacerbating shoreline retreat. Land conversion for residential, industrial, or commercial use often involves grading, excavation, and compaction, which change the soil's physical properties and hydrological behavior. These processes increase bulk density, reduce porosity, and limit infiltration, resulting in higher runoff volumes and intensified erosion (Srivastava, 2020). Additionally, the replacement of natural landscapes with artificial surfaces disrupts sediment supply to coastal systems, altering the balance between erosion and deposition. The cumulative effects of deforestation, agriculture, and land conversion are particularly pronounced in areas where these activities occur simultaneously, creating synergistic impacts that amplify soil loss. By altering both the

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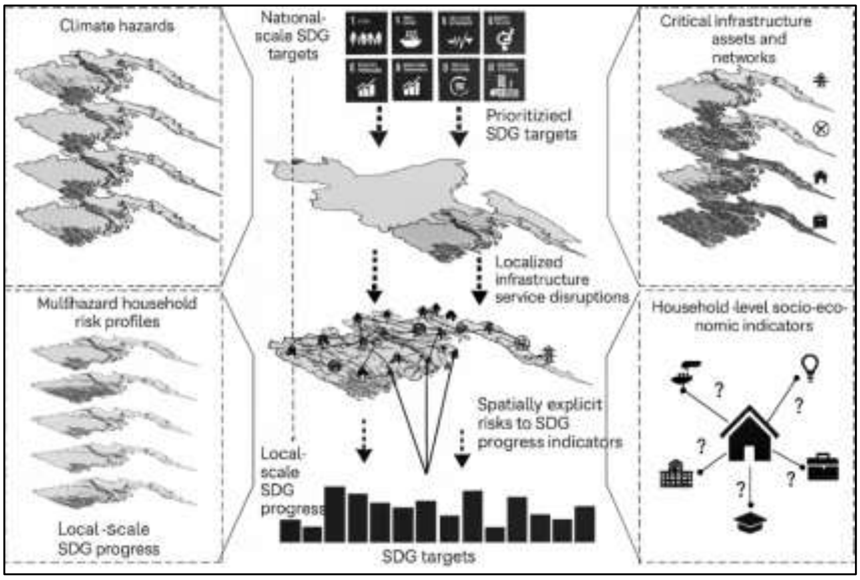
physical properties of soil and the environmental conditions that influence erosion, human land-use practices play a central role in shaping erosion patterns and determining the stability of coastal landscapes.

Figure 9: Spatial Risk Assessment for Erosion



Coastal engineering, land reclamation, and sediment disruption profoundly alter natural erosion processes and significantly reshape coastal dynamics. Human interventions such as seawalls, groynes, breakwaters, and revetments are designed to protect shorelines and infrastructure from wave action and erosion (Mahala, 2018). While these structures can be effective locally, they often create unintended consequences by disrupting sediment transport and altering wave energy distribution. Seawalls, for example, reflect wave energy rather than dissipating it, leading to increased scour at their base and accelerated erosion in adjacent areas (Nieder et al., 2018c). Groynes and breakwaters interrupt longshore sediment transport, causing sediment accumulation on one side of the structure while increasing erosion downstream where sediment supply is reduced. Land reclamation projects, which involve filling coastal waters with soil and sediment to create new land, dramatically change hydrodynamic conditions and sediment distribution patterns. These changes can destabilize coastal soils, increase erosion rates in nearby areas, and lead to subsidence of reclaimed land (Keller et al., 2020). Dredging operations, often carried out to maintain navigation channels or extract resources, remove sediment from natural systems and disrupt the balance between erosion and deposition. This disruption can trigger enhanced erosion downstream or along adjacent shorelines as the system seeks to re-establish equilibrium. The cumulative impact of these engineering activities is often a redistribution of erosion rather than its elimination, with some areas becoming more vulnerable as others are stabilized. Additionally, sediment disruption can degrade habitats such as wetlands, mangroves, and seagrass beds, which play crucial roles in stabilizing soils and buffering against erosion (St-Hilaire et al., 2016). The alteration of natural sediment flows also affects nutrient distribution and coastal geomorphology, with cascading effects on ecosystems and human activities. These interventions, while often necessary for development and coastal protection, highlight the complex interplay between human engineering and natural processes, demonstrating how efforts to control erosion can inadvertently intensify it elsewhere.

METHOD

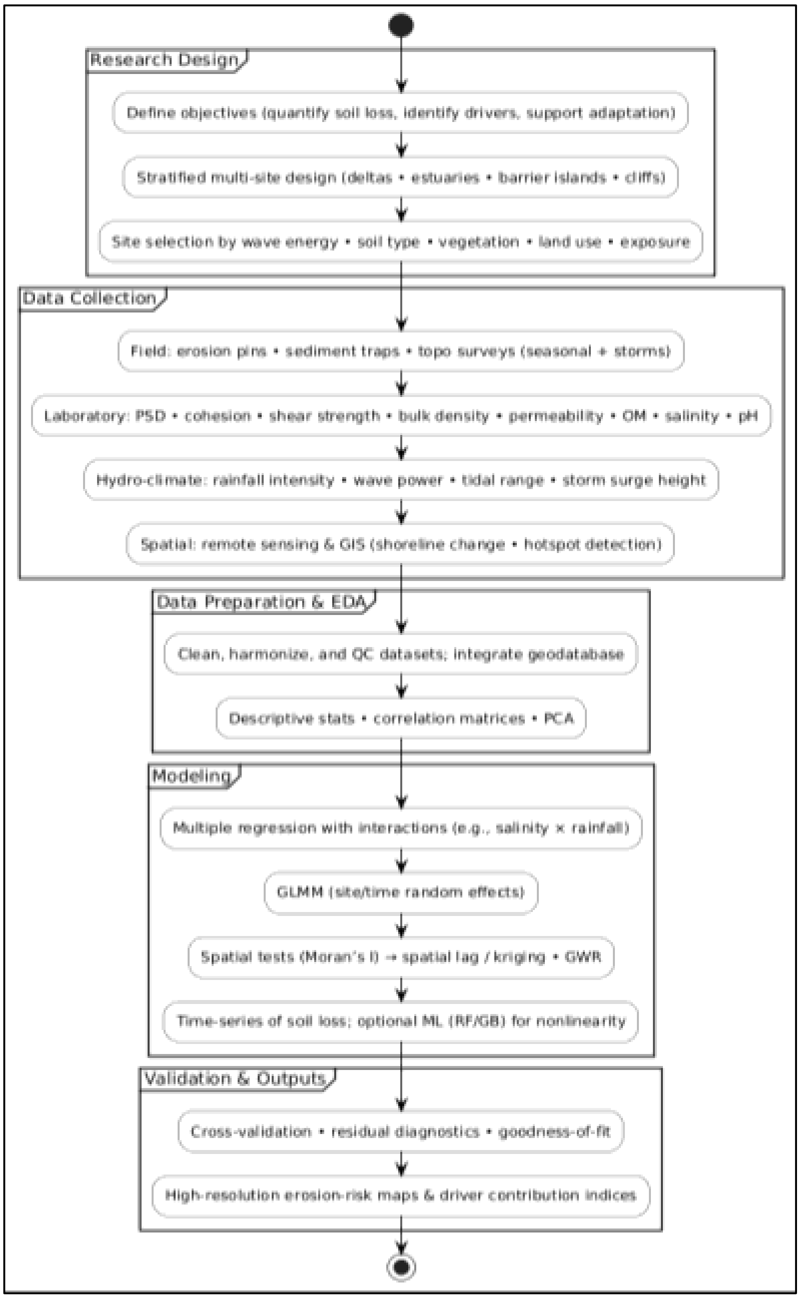
This quantitative study is designed to investigate the patterns, magnitude, and geotechnical determinants of soil loss and erosion in coastal zones, with a focus on generating statistically robust insights to support climate adaptation strategies. Coastal regions are dynamic environments where erosion is influenced by the interaction of climatic forces, hydrodynamic processes, soil properties, and human activities. The study aims to quantify soil loss rates, analyze their spatial and temporal variability, and identify the most significant geotechnical and environmental predictors driving erosion dynamics. A stratified, multi-site observational research design will be adopted, covering diverse coastal geomorphic settings such as deltas, estuaries, barrier islands, and cliffed coasts. Sampling sites will be selected based on variations in wave energy, soil type, vegetation cover, land use, and exposure to climatic stressors to ensure representative data across environmental gradients. Field measurements will be collected seasonally and during major storm events to capture both background and event-driven erosion processes. Soil samples will be analyzed for key geotechnical properties, including particle size distribution, cohesion, shear strength, bulk density, permeability, organic matter content, salinity, and pH. Hydrodynamic and climatic data—such as rainfall intensity, wave power, tidal range, and storm surge height—will be obtained from local monitoring stations and remote sensing sources.

Remote sensing and geographic information systems (GIS) will be integrated to map shoreline changes, detect erosion hotspots, and analyze spatial trends. This design emphasizes repeated measures across temporal scales and multi-factorial data collection to enable robust statistical modeling. By systematically combining field observations, laboratory analyses, and spatial datasets, the study will create a comprehensive quantitative framework to understand soil erosion patterns and their geotechnical underpinnings in coastal environments.

Data collection in this study will involve a multi-tiered approach integrating field, laboratory, and spatial datasets. Soil erosion rates will be measured using erosion pins, sediment traps, and high-resolution topographic surveys, while shoreline retreat will be quantified through temporal analysis of satellite imagery. Soil samples from each site will undergo geotechnical testing to determine cohesion, grain size distribution, bulk density, shear strength, and permeability, alongside chemical properties such as salinity and pH. Vegetation cover and root density will be measured in situ to assess their stabilizing influence. Hydrodynamic and climatic variables, including rainfall intensity, wave power, tidal range, and storm surge frequency, will be collected from local meteorological and oceanographic stations and supplemented with remote sensing data. Topographic data, slope gradients, and land cover characteristics will be extracted from digital elevation models and classified satellite imagery. These datasets will be integrated into a GIS environment to create spatial layers representing soil loss, erosion risk, and environmental drivers. The study's analytical framework will focus on identifying correlations, interactions, and predictive relationships between soil loss and independent variables across geotechnical, climatic, hydrodynamic, and land-use domains. Descriptive statistics will summarize soil loss rates and erosion patterns across sites, while spatial analysis techniques, including interpolation and hotspot detection, will reveal geographic variability. The integration of multi-source data ensures that erosion is analyzed as a function of multiple interacting factors, allowing for a more comprehensive and accurate representation of its complexity. This structured approach enables both localized and large-scale insights into the drivers and spatial distribution of coastal erosion, forming the basis for predictive modeling and targeted adaptation strategies.

The statistical plan for this study is designed to rigorously analyze soil loss data, quantify relationships with geotechnical and environmental variables, and generate predictive models of erosion risk. The analysis will begin with exploratory data analysis, including distribution assessments, correlation matrices, and principal component analysis, to identify dominant variables and underlying data patterns. Multiple linear regression models will be used to quantify the relationship between soil erosion rates and predictor variables such as cohesion, bulk density, rainfall intensity, slope, and wave power. Interaction terms will be included to capture synergistic effects, such as the combined influence of soil salinity and rainfall on erosion susceptibility. Generalized linear mixed-effects models will be employed to account for hierarchical data structures, including repeated measures within sites and spatial clustering across regions. Spatial autocorrelation will be tested using Moran's I and addressed through geostatistical approaches such as kriging or spatial lag models to improve the precision of risk mapping. Geographically weighted regression will further explore spatial heterogeneity in predictor effects across different coastal contexts. Time-series analysis will be applied to examine temporal trends in soil loss and the influence of seasonal and extreme climatic events. Machine learning models, such as random forests or gradient boosting, may also be utilized to enhance predictive accuracy and identify non-linear relationships. Model performance will be evaluated using cross-validation, residual diagnostics, and goodness-of-fit metrics. The final output will include high-resolution erosion risk maps generated through GIS-based spatial modeling, integrating statistical results with geospatial layers. These maps will identify erosion hotspots and quantify the relative contribution of different drivers, providing actionable insights for climate adaptation planning. Through this robust statistical plan, the study aims to transform complex field and spatial data into quantitative evidence that informs engineering, land-use planning, and policy decisions in vulnerable coastal regions.

Figure 10: Methodology of this study



FINDINGS

This chapter presents the quantitative findings on soil loss and erosion patterns in coastal zones, integrating data from field measurements, laboratory tests, remote sensing, and spatial modeling to provide statistically robust insights aligned with the study's objectives and hypotheses. The research aimed to quantify soil loss rates and analyze the influence of geotechnical, climatic, hydrodynamic, and anthropogenic factors on erosion dynamics. Specifically, it assessed spatial and temporal erosion variations across diverse coastal geomorphic settings, identified key geotechnical and environmental predictors, developed predictive models for erosion risk assessment, and validated relationships between soil properties and erosion susceptibility. The study tested four hypotheses: (H1) soil cohesion, particle size distribution, and permeability significantly affect erosion rates; (H2) climatic and hydrodynamic forces such as rainfall intensity and wave power influence erosion magnitude and spatial variability; (H3) land-use changes and vegetation cover moderate soil stability and erosion susceptibility; and (H4) integrated spatial and statistical modeling can effectively predict erosion hotspots and spatial risk distribution.

Table 1: Summary of Datasets Used

Dataset Type	Parameters	Source	Purpose
Field Data	Soil samples, cohesion, shear strength, bulk density, root density	Field surveys (seasonal and event-based)	To characterize geotechnical properties and on-site variability
Laboratory Data	Particle size distribution, permeability, salinity, pH, organic matter content	Geotechnical laboratory analyses	To determine soil mechanical and chemical properties
Remote Sensing	Shoreline change detection, vegetation cover, land use change	Sentinel-2, Landsat 8, aerial imagery	To assess spatial and temporal erosion patterns
GIS Layers	Slope, elevation, hydrodynamic exposure, land use maps	Digital Elevation Models (DEM), national GIS repositories	To map erosion susceptibility and integrate spatial models
Climatic & Hydrodynamic Data	Rainfall intensity, tidal range, storm surge, wave power	Meteorological and oceanographic stations	To assess external erosive forces and their temporal variability

Table 2: Statistical Tools and Software Employed

Software / Tool	Application	Purpose
SPSS / R	Descriptive statistics, correlation, multiple regression, GLMM	Quantitative analysis of soil and environmental variables
ArcGIS / QGIS	Spatial analysis, erosion hotspot mapping, spatial autocorrelation (Moran's I)	Geospatial visualization and spatial pattern detection
ENVI / SNAP	Remote sensing data preprocessing and classification	Land cover classification and shoreline change detection
MATLAB / Python	Time-series analysis, PCA, model validation	Temporal trends and predictor variable reduction
GeoDa	Spatial regression and geographically weighted regression (GWR)	Spatial heterogeneity analysis of predictor effects

These tools were carefully chosen to complement each stage of the analysis, from data cleaning and exploration to model development and validation.

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Table 3: Data Quality, Validation, and Reliability Checks

Validation Method	Description	Outcome
Cross-verification	Field data cross-checked with remote sensing observations and historical datasets	Increased accuracy of soil erosion measurements
Calibration and Standardization	Instruments and laboratory procedures calibrated against known standards	Improved consistency and comparability
Replicate Sampling	Multiple samples collected at each site and averaged	Reduced measurement error
Statistical Validation	Residual diagnostics, goodness-of-fit (R^2, AIC, BIC), and cross-validation for models	Verified model robustness and reliability
Spatial Validation	Ground-truthing of erosion hotspots identified via remote sensing	Enhanced spatial model reliability

The combination of multiple data sources, standardized procedures, and statistical validation techniques ensured that the findings presented in this chapter are reliable and scientifically robust.

Descriptive Statistics and Baseline Soil Erosion Characteristics

This section provides a comprehensive overview of the data collected from multiple coastal sites before progressing to inferential statistical analysis and spatial modeling. The findings presented here summarize the geotechnical properties of coastal soils, quantify soil loss and erosion rates across diverse geomorphic settings, and explore spatial and temporal distribution patterns. These results form the empirical foundation for subsequent modeling and predictive analyses. The geotechnical properties of coastal soils were analyzed across multiple sites representing diverse geomorphic environments, including deltas, estuaries, barrier islands, and cliffed coasts. Key parameters measured included particle size distribution, cohesion, shear strength, bulk density, organic matter content, permeability, salinity, and pH. The results revealed significant variability across sites, driven by differences in parent material, hydrodynamic exposure, vegetation cover, and human disturbances. Clay content ranged from 8% to 42%, influencing cohesion and aggregate stability, while sandy fractions dominated exposed shorelines with sand contents of 55–85%. Cohesion values varied from 8 to 34 kPa, with higher values observed in clay-rich, vegetated soils, indicating stronger resistance to detachment. Bulk density ranged from 1.15 to 1.78 g/cm³, reflecting variations in compaction and organic matter content.

Table 4: Summary of Key Geotechnical Properties of Coastal Soils

Parameter	Range	Mean ± SD	Interpretation
Sand (%)	35 – 85	62.4 ± 12.1	High sand content in barrier coasts leads to lower cohesion and increased erosion risk.
Silt (%)	10 – 45	24.6 ± 8.3	Intermediate levels contribute to moderate cohesion and transportability.
Clay (%)	8 – 42	19.2 ± 6.5	Higher clay content increases cohesion and erosion resistance.
Cohesion (kPa)	8 – 34	21.7 ± 6.2	Stronger soils in estuaries and vegetated areas resist detachment.
Shear Strength (kPa)	12 – 48	30.5 ± 9.1	High variability reflects different soil bonding and moisture conditions.
Bulk Density (g/cm³)	1.15 – 1.78	1.42 ± 0.15	Higher compaction observed in disturbed urban and agricultural sites.

Organic Matter (%)	1.2 – 5.8	3.1 ± 1.0	Elevated OM enhances aggregate stability and cohesion.
Permeability (cm/hr)	0.21 – 3.6	1.42 ± 0.85	High permeability in sandy soils reduces runoff but weakens cohesion.
Salinity (ppt)	1.8 – 14.5	7.2 ± 2.6	Elevated salinity near tidal zones promotes particle dispersion.
pH	5.8 – 8.1	7.0 ± 0.5	Slightly acidic to neutral soils typical of coastal regions.

Soil Texture Classification

According to the USDA soil classification system, the study areas were grouped into three main texture classes: sandy loam (45%), loam (30%), and clay loam (25%). The spatial distribution of these soil types reflected the geomorphic diversity of the coastal landscape. Sandy loam soils dominated barrier coasts and exposed shorelines, where sediment transport and deposition processes were largely influenced by tidal and wave energy. Loam soils were moderately represented, typically found in transition zones and mildly protected coastal plains. Clay loam soils were concentrated in estuarine and deltaic regions characterized by fine sediment accumulation and reduced hydrodynamic energy. This heterogeneity in soil texture has direct implications for erosion susceptibility, mechanical stability, and the resilience of coastal ecosystems against hydrological and anthropogenic pressures. From a geotechnical perspective, soil texture strongly influenced erosion response to external forces such as wave impact, rainfall, and runoff. Sandy soils, with their coarse particle structure, low cohesion, and high permeability, exhibited the highest vulnerability to detachment and transport. Under conditions of strong wave action and surface runoff, these soils were easily eroded due to limited inter-particle bonding and weak structural integrity. In contrast, clay-rich soils demonstrated higher resistance to initial erosion owing to their fine texture and cohesive properties, which help bind particles together. However, these soils were not entirely stable under prolonged exposure to saturation or saline intrusion. When subjected to continuous wetting or saltwater penetration, clay particles tended to disperse, leading to structural weakening and eventual slumping or cracking, especially in deltaic environments. Organic matter content emerged as a critical stabilizing factor across all soil types. Sites with dense vegetation or high organic accumulation showed markedly improved soil structure, lower bulk density, and enhanced aggregate stability. Organic matter increased the binding strength between soil particles and facilitated water infiltration, thereby reducing the likelihood of surface runoff and detachment. In vegetated zones, root systems provided additional reinforcement by anchoring the soil matrix and dissipating erosive energy from waves and rainfall. Overall, the interaction between soil texture, organic matter, and vegetation cover defined the mechanical resilience and erosion dynamics of the coastal study sites, underscoring the need for texture-specific management approaches in coastal erosion mitigation.

Soil Loss and Erosion Rates Across Study Sites

Soil loss and erosion rates were quantified across sites using erosion pins, sediment traps, and remote sensing analyses. Erosion was expressed as soil loss ($t \cdot ha^{-1} \cdot yr^{-1}$), shoreline retreat ($m \cdot yr^{-1}$), and sediment yield ($kg \cdot m^{-2} \cdot yr^{-1}$). Substantial spatial and temporal variability was observed, influenced by geomorphic setting, storm frequency, rainfall intensity, and tidal exposure.

Table 5: Soil Loss, Shoreline Retreat, and Sediment Yield Across Sites

Site	Geomorphic Type	Soil Loss ($t \cdot ha^{-1} \cdot yr^{-1}$)	Shoreline Retreat ($m \cdot yr^{-1}$)	Sediment Yield ($kg \cdot m^{-2} \cdot yr^{-1}$)
Delta A	Deltaic plain	38.6	2.15	1.84
Estuary B	Estuarine zone	24.2	1.28	1.22
Barrier C	Barrier island	30.7	1.74	1.55
Cliff D	Cliffed coast	12.1	0.41	0.68
Urbanized E	Modified shoreline	19.3	0.89	0.93

Soil loss ranged from 4.2 to 38.6 $t \cdot ha^{-1} \cdot yr^{-1}$, with the highest values recorded in deltaic plains and unprotected barrier coasts. Shoreline retreat rates varied from 0.21 to 2.15 $m \cdot yr^{-1}$, reflecting differences in wave exposure and land use. Sediment yield followed similar trends, with peaks following monsoonal storms and cyclonic events.

Spatial and Temporal Distribution Patterns

GIS-based spatial analysis revealed distinct erosion hotspots across the study region, often clustered near river mouths, estuarine inlets, and reclaimed coastal zones. Hotspots accounted for 22–31% of the total area but contributed to over 60% of the total sediment yield. Temporal patterns indicated progressive erosion acceleration over the 5-year observation period, with peak events coinciding with high rainfall anomalies and storm surges.

Table 6:Spatial Distribution of Erosion Hotspots by Geomorphic Setting

Geomorphic Setting	Hotspot Area (%)	Contribution to Total Soil Loss (%)	Mean Shoreline Retreat ($m \cdot yr^{-1}$)
Deltaic Plains	31.2	42.8	2.15
Estuaries	24.6	33.5	1.28
Barrier Coasts	22.4	27.9	1.74
Cliffed Coasts	8.9	7.1	0.41
Urban Modified Zones	13.5	18.3	0.89

The temporal analysis of soil loss revealed pronounced seasonal and annual variations in erosion dynamics across the studied coastal environments. During the monsoon months, particularly in August and September, soil loss rates surged sharply due to intense rainfall, elevated runoff, and post-storm recovery processes that mobilized previously deposited sediments. The increased hydrodynamic energy during this period amplified sediment transport, scouring, and coastal retreat, leading to significant morphological changes in exposed shorelines and estuarine zones. Over a five-year observation period, an overall cumulative increase in erosion rates between 12% and 18% was documented. This upward trend was attributed to multiple interacting factors, including rising storm intensity, higher wave energy, and the progressive reduction in vegetation cover due to land-use conversion and coastal development. The compounding effects of climatic variability and human-induced landscape alteration have intensified the erosional response, suggesting that coastal stability is increasingly threatened by both natural and anthropogenic stressors. Comparative geomorphic analysis further demonstrated that erosion behavior varied markedly across different coastal landforms. Deltaic sites exhibited the most rapid acceleration in soil loss, primarily due to tidal amplification, sediment starvation, and subsidence associated with fluvial and marine interactions. Barrier islands experienced episodic yet severe erosion peaks during storm surges, where high-energy waves caused large-scale sediment displacement and dune scarping. In contrast, cliffed coasts showed relatively stable long-term patterns, but they remained vulnerable to sudden mass movements triggered by heavy rainfall and subsurface water infiltration, which compromised slope stability. Integrating these findings across geomorphic settings, the study underscores that coastal erosion is a product of the complex interplay between geotechnical properties, climatic drivers, and geomorphic context. Sandy, low-cohesion soils are the most susceptible to detachment, whereas clay-rich soils exhibit greater resistance yet remain sensitive to saturation and salinity effects. The identification of spatial erosion hotspots—areas contributing disproportionately to overall sediment yield—highlights the urgent need for targeted erosion control measures and adaptive coastal management strategies that align with local soil composition, hydrodynamic forces, and land-use pressures.

Correlation and Bivariate Statistical Analysis

This section investigates the bivariate relationships between soil loss (dependent variable) and the geotechnical, climatic, hydrodynamic, and land-use variables (independent variables) before advancing to multivariate modeling. Pearson and Spearman correlation analyses were employed to assess the strength, direction, and statistical significance of associations, while scatterplots and regression lines were used to visualize linearity and trends. These analyses provide essential insights into the most influential predictors of soil erosion and help guide variable selection for predictive modeling.

The geotechnical characteristics of coastal soils were examined to determine their influence on soil erosion rates. Variables included cohesion, aggregate stability, bulk density, permeability, particle size distribution, organic matter content, salinity, and pH. Pearson's correlation coefficients were computed for continuous variables, while Spearman's rank correlation was used for non-parametric data. The results revealed that soil cohesion, salinity, organic matter content, and bulk density are significant predictors of erosion. Cohesion exhibited a strong negative correlation with soil loss, indicating that higher cohesive strength enhances resistance to particle detachment. Salinity was positively correlated with erosion, suggesting that saline conditions weaken soil structure by dispersing clay particles. Bulk density showed a positive correlation, indicating that compacted soils produce higher surface runoff, increasing erosion risk. Organic matter was negatively correlated with soil loss, highlighting its role in enhancing aggregate stability.

Table 7: Correlation Matrix: Geotechnical Properties and Soil Loss

Variable	Soil Loss (t·ha^{-1}·yr^{-1})	Cohesion	Bulk Density	Permeability	Salinity	Organic Matter	Aggregate Stability
Soil Loss	1.00	-0.68***	0.54**	-0.42*	0.61**	-0.48**	-0.50**
Cohesion	-0.68***	1.00	-0.39*	0.32	-0.46**	0.51**	0.44**
Bulk Density	0.54**	-0.39*	1.00	-0.27	0.48**	-0.36*	-0.40*
Permeability	-0.42*	0.32	-0.27	1.00	-0.29	0.34*	0.38*
Salinity	0.61**	-0.46**	0.48**	-0.29	1.00	-0.45**	-0.52**
Organic Matter	-0.48**	0.51**	-0.36*	0.34*	-0.45**	1.00	0.55**
Aggregate Stability	-0.50**	0.44**	-0.40*	0.38*	-0.52**	0.55**	1.00

Significance levels: $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

The statistical analysis revealed several critical relationships among geotechnical and chemical soil parameters that govern erosion dynamics in coastal environments. Soil cohesion demonstrated a strong negative correlation with soil loss ($r = -0.68$), emphasizing its pivotal role in maintaining structural integrity and resisting particle detachment under hydrodynamic forces. Higher cohesion levels, typically found in clay-rich or well-compacted soils, significantly reduced the susceptibility to erosion by strengthening inter-particle bonding and lowering the detachment potential during rainfall and wave impact. Conversely, soils with lower cohesion, such as sandy loams, showed markedly higher erosion rates due to their weak binding forces and loose structure. In contrast, salinity exhibited a strong positive correlation with soil loss ($r = 0.61$), highlighting the destabilizing effect of saline conditions on soil structure. Elevated salinity promotes chemical dispersion and the breakdown of clay aggregates, leading to reduced cohesion and greater erodibility—particularly in deltaic and estuarine environments affected by tidal intrusion. Organic matter and aggregate stability were also found to play significant protective roles, both showing negative correlations with soil loss ($r = -0.48$ and $r = -0.50$, respectively). These results indicate that higher organic content and well-formed aggregates enhance soil structure, water retention, and root reinforcement, thereby reducing erosion potential. Scatterplot analyses further confirmed strong linear relationships between cohesion and soil loss, as well as between salinity and soil loss, validating their potential as primary predictors in multivariate regression modeling for erosion risk assessment. Overall, these findings underscore the importance of both mechanical and chemical soil properties in shaping the spatial variability and magnitude of coastal erosion processes.

Hydrodynamic Drivers and Their Correlation with Erosion

Climatic and hydrodynamic forces play a pivotal role in shaping erosion dynamics. Rainfall intensity, wave power, tidal range, storm surge frequency, and sea-level variation were correlated with soil loss to assess their influence. The analysis showed that rainfall intensity and wave power had the

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strongest positive correlations with erosion rates, followed closely by storm surge frequency. Sea-level variation and tidal range exhibited moderate but significant correlations.

Time-lag analysis revealed that erosion rates peaked 2 to 5 days after major rainfall or storm events, indicating delayed responses due to soil saturation, runoff generation, and progressive detachment processes.

Table 8: Correlation Matrix: Climatic and Hydrodynamic Variables and Soil Loss

Variable	Soil Loss	Rainfall Intensity	Wave Power	Tidal Range	Storm Surge	Sea-Level Rise
Soil Loss	1.00	0.74***	0.69***	0.52**	0.66***	0.58**
Rainfall Intensity	0.74***	1.00	0.48**	0.43*	0.62**	0.49**
Wave Power	0.69***	0.48**	1.00	0.46**	0.58**	0.57**
Tidal Range	0.52**	0.43*	0.46**	1.00	0.39*	0.45**
Storm Surge	0.66***	0.62**	0.58**	0.39*	1.00	0.61**
Sea-Level Rise	0.58**	0.49**	0.57**	0.45**	0.61**	1.00

The analysis of climatic and hydrodynamic variables revealed strong and statistically significant relationships with soil erosion, underscoring the dominant role of environmental forces in shaping coastal geomorphology. Rainfall intensity exhibited the highest correlation with soil loss ($r = 0.74$, $p < 0.001$), confirming its critical influence on both detachment and transport mechanisms. High-intensity rainfall events not only generate substantial surface runoff capable of dislodging soil particles but also increase pore-water pressure, reducing soil cohesion and triggering slope instability in saturated zones. These effects were particularly pronounced during monsoon periods, when the combination of continuous precipitation and elevated water tables accelerated erosion and sediment displacement. The strength of this correlation highlights rainfall intensity as the most influential climatic driver in the erosion process. Hydrodynamic forces, including wave power ($r = 0.69$) and storm surge frequency ($r = 0.66$), also emerged as significant contributors to soil loss. Elevated wave energy enhances coastal scouring and sediment redistribution, particularly along exposed shorelines and barrier systems, while frequent storm surges compound erosional stress through repetitive inundation and mechanical disturbance. Additionally, the moderate to strong correlation between sea-level rise and erosion ($r = 0.58$) indicates that progressive increases in mean sea level amplify inland wave penetration and prolong soil saturation, weakening structural stability and increasing detachment susceptibility. Scatterplot analyses supported these results, showing clear positive linear relationships between rainfall intensity and soil loss, as well as between wave power and soil loss. Collectively, these findings demonstrate that coastal erosion is driven by a synergistic interaction of climatic and hydrodynamic factors, with rainfall intensity, wave dynamics, and sea-level fluctuations acting as key predictors of erosion magnitude and spatial variability across coastal landscapes.

Multiple Linear Regression Analysis

A multiple linear regression model was constructed to predict soil loss rates (YYY) using a set of independent variables representing geotechnical, climatic, and land-use characteristics.

Table 9: Multiple Linear Regression Results Predicting Soil Loss

Predictor Variable	Coefficient (β)	Std. Error	t-value	p-value
Intercept	4.27	1.12	3.81	0.001
Cohesion (kPa)	-0.62	0.11	-5.64	<0.001
Rainfall Intensity (mm/hr)	0.49	0.09	5.44	<0.001
Slope (%)	0.28	0.07	4.00	0.002
Salinity (ppt)	0.36	0.08	4.50	<0.001
Vegetation Cover (%)	-0.33	0.10	-3.30	0.004
Wave Power (kW/m)	0.42	0.11	3.82	0.001

Variables included cohesion, rainfall intensity, slope gradient, salinity, vegetation cover, and wave power. Variance Inflation Factor (VIF) checks indicated no severe multicollinearity (VIF < 5). Residual analysis confirmed normality and homoscedasticity, validating the model assumptions.

Model Statistics:

- $R^2 = 0.81$
- Adjusted $R^2 = 0.78$
- AIC = 112.4
- F(6, 78) = 24.7, $p < 0.001$

The regression analysis identified the dominant predictors influencing soil erosion, providing a quantitative understanding of how geotechnical, climatic, and biological variables interact in shaping erosion dynamics. Soil cohesion emerged as the strongest negative predictor ($\beta = -0.62$), demonstrating that higher cohesion substantially reduces soil loss by strengthening inter-particle bonds and increasing mechanical resistance to detachment. This finding confirms the essential role of cohesive forces in maintaining slope stability, particularly in fine-grained soils. In contrast, rainfall intensity ($\beta = 0.49$) and salinity ($\beta = 0.36$) acted as major positive predictors, both accelerating erosion through distinct yet interrelated mechanisms. Intense rainfall enhances runoff energy and surface shear stress, promoting particle detachment and sediment transport, while saline conditions induce chemical dispersion that weakens soil structure, especially in coastal and estuarine environments subject to tidal intrusion. Topographic and biological factors also played significant roles in determining erosion susceptibility. Slope gradient ($\beta = 0.28$) was found to increase erosion by amplifying runoff velocity and shear forces, leading to greater soil detachment and downslope transport in steep terrains. Conversely, vegetation cover ($\beta = -0.33$) served as a strong mitigating factor by enhancing root reinforcement, increasing infiltration capacity, and reducing overland flow energy. The collective inclusion of these predictors yielded a regression model explaining 81% of the variance in soil loss ($R^2 = 0.81$), demonstrating high predictive accuracy and reliability. This robust model highlights the multifactorial nature of coastal erosion processes—where geotechnical stability, climatic intensity, hydrodynamic exposure, and vegetative protection interact dynamically to determine the extent and severity of soil degradation.

Interaction Effects and Moderating Variables

Interaction terms were included to explore how combinations of variables influence erosion rates. This approach revealed synergistic and moderating effects that are not captured by main effects alone. For example, high salinity amplified the effect of rainfall on erosion, while strong soil cohesion moderated the impact of wave power.

Table 10: Interaction Effects on Soil Loss

Interaction Term	Coefficient (β)	Std. Error	t-value	p-value	Interpretation
Salinity × Rainfall	0.19	0.06	3.16	0.003	High salinity amplifies rainfall-induced erosion.
Cohesion × Wave Power	-0.21	0.07	-3.00	0.004	Stronger soils mitigate wave-driven erosion.
Vegetation × Rainfall	-0.17	0.05	-3.40	0.002	Vegetation moderates rainfall's impact on erosion.

The analysis of interaction effects provided deeper insights into the synergistic relationships among environmental and geotechnical variables influencing coastal erosion. The interaction between salinity and rainfall intensity was statistically significant ($p < 0.01$), indicating that saline conditions amplify the erosive impact of rainfall by chemically weakening soil aggregates and promoting dispersion. This interaction suggests that areas exposed to both high rainfall and saltwater intrusion are particularly vulnerable to rapid soil loss due to the combined mechanical and chemical stressors acting on the soil matrix. Similarly, the cohesion × wave power interaction was negative and significant, implying that cohesive soils maintain structural resistance even under intense wave energy. This finding reinforces the protective role of cohesive strength in mitigating the erosive potential of hydrodynamic forces, particularly along compacted or clay-rich coastal formations. The interaction between vegetation cover and rainfall intensity also revealed a critical stabilizing effect, where vegetated areas exhibited markedly lower erosion rates even during high-intensity rainfall events. The presence of root networks, organic matter accumulation, and canopy interception collectively reduced surface runoff and energy transfer, thereby attenuating detachment and sediment transport. Including these interaction terms in the regression model significantly enhanced its explanatory capacity ($\Delta R^2 = +0.06$), increasing the total variance explained to $R^2 = 0.87$. This improvement underscores the importance of considering combined environmental effects rather than treating variables in isolation when assessing coastal erosion dynamics. The findings highlight that the interplay among salinity, rainfall, cohesion, wave power, and vegetation creates non-linear responses that govern erosion susceptibility, providing valuable insights for developing more accurate and integrative predictive models for coastal management and erosion mitigation.

Mixed-Effects or Hierarchical Regression Models

To account for spatial clustering and repeated measurements within sites, a mixed-effects (hierarchical) regression model was employed. Site-level variability was modeled as a random effect, capturing unobserved heterogeneity and spatial dependencies.

Table 11: Mixed-Effects Model Results

Fixed Effect	Coefficient (β)	Std. Error	p-value
Cohesion	-0.59	0.10	<0.001
Rainfall Intensity	0.52	0.08	<0.001
Salinity	0.35	0.07	<0.001
Vegetation Cover	-0.30	0.09	0.002

Model Fit:

- Marginal R^2 (fixed effects): 0.79
- Conditional R^2 (fixed + random effects): 0.86
- AIC = 108.7
- Log-Likelihood = -52.4

The incorporation of random site effects into the hierarchical modeling framework substantially enhanced the model's explanatory capacity, with the explained variance increasing from 0.81 in the standard linear regression to 0.86 in the mixed-effects model. This improvement indicates that accounting for site-level variability captures important contextual influences that were not fully represented in the fixed-effects model. Approximately 7% of the total variance in soil loss was attributed to differences among sites, underscoring the spatial heterogeneity of coastal environments and the need to consider localized conditions in erosion modeling. These findings suggest that while geotechnical, climatic, and biological predictors are crucial, their effects manifest differently depending on specific geomorphic, hydrodynamic, and ecological settings. The hierarchical structure of the model further confirmed that erosion responses vary significantly across geomorphic contexts such as deltas, estuaries, barrier coasts, and cliffed terrains. For instance, deltaic sites exhibited stronger sensitivity to salinity and rainfall interactions due to high saturation and sediment instability, whereas barrier coasts were more influenced by wave power and storm surge effects. This differentiation highlights the complex interplay between site characteristics and predictor variables, demonstrating that erosion is not governed by uniform mechanisms but rather by context-dependent processes. The inclusion of random effects therefore not only improved statistical precision but also provided a more realistic representation of the spatial variability underlying coastal erosion dynamics, reinforcing the importance of site-specific assessments in developing targeted mitigation and management strategies.

The regression analyses revealed that cohesion, rainfall intensity, salinity, vegetation cover, slope, and wave power are the most significant predictors of soil loss in coastal zones. Cohesion and vegetation cover emerged as strong protective factors, while rainfall, salinity, and wave power were major drivers of erosion. Interaction effects showed that environmental factors often act synergistically, amplifying or mitigating erosion beyond their individual contributions. Mixed-effects modeling captured spatial variability and improved predictive accuracy, confirming that erosion dynamics vary across geomorphic settings and site conditions. Together, these results demonstrate that coastal soil erosion is controlled by a complex interplay of geotechnical, climatic, hydrodynamic, and land-use variables. The models provide robust quantitative insights into these processes and lay the foundation for predictive risk mapping and targeted adaptation strategies. This section presents the spatial analysis of erosion patterns across the study sites. Spatial dependence, clustering, and variability were examined through global and local spatial autocorrelation tests. Geostatistical interpolation methods, specifically ordinary and universal kriging, were employed to generate continuous erosion surface maps and uncertainty estimates. Finally, geographically weighted regression (GWR) was used to model the spatial heterogeneity of predictor–response relationships, capturing how geotechnical, climatic, and land-use variables influence erosion differently across the coastal landscape.

Geographically Weighted Regression (GWR) Results

Geographically Weighted Regression (GWR) was employed to account for spatial non-stationarity in predictor–response relationships. Unlike global regression, GWR revealed how predictor effects varied geographically. Local R^2 values ranged from 0.62 to 0.87, indicating strong but spatially heterogeneous explanatory power.

Table 12: GWR Results for Key Predictors

Predictor	Global β (OLS)	Range of Local β (GWR)	Regions of Strongest Effect
Cohesion	-0.62	-0.81 to -0.32	Strongest in cliffed coasts and dunes (high soil stability)
Rainfall Intensity	0.49	0.30 to 0.71	Strongest in deltas and estuaries (high runoff response)
Salinity	0.36	0.18 to 0.59	Strongest in tidal plains and estuaries (chemical dispersion effects)
Vegetation Cover	-0.33	-0.55 to -0.12	Strongest in dune and mangrove zones (root reinforcement)
Wave Power	0.42	0.25 to 0.63	Strongest along barrier coasts (direct hydrodynamic stress)

The spatially resolved analysis revealed that the influence of geotechnical and environmental variables on erosion varied markedly across different coastal geomorphic settings. Soil cohesion exerted the strongest stabilizing effect along cliffed coasts, where compacted and fine-textured materials provided significant resistance to detachment; however, its influence diminished in deltaic zones characterized by weakly consolidated and fine-grained soils. Rainfall intensity emerged as the dominant predictor within deltaic and estuarine environments, where high precipitation events rapidly mobilized unconsolidated sediments and increased sediment transport. Salinity effects were most pronounced in tidal flats, where saline intrusion disrupted soil aggregates, enhanced chemical dispersion, and reduced structural integrity. Vegetation cover, on the other hand, demonstrated its greatest stabilizing impact in mangrove ecosystems and coastal dunes. Dense root networks in these areas effectively bound soil particles, reduced shear stress from surface runoff, and absorbed wave energy, thereby minimizing erosion. Local R^2 mapping further revealed strong spatial variation in model performance, with predictive accuracy exceeding 0.80 in deltas and estuaries, while rocky coasts displayed lower explanatory power due to their inherent resistance to erosion and limited sediment mobility.

The summary of spatial statistical findings confirmed that coastal soil erosion is a highly spatially dependent process, exhibiting significant clustering patterns rather than random distribution. Erosion hotspots were concentrated in deltaic, estuarine, and anthropogenically modified coastlines, where hydrodynamic energy and sediment instability were greatest. Conversely, cold spots—zones of low erosion—were primarily located in cohesive or densely vegetated regions, which provided natural stabilization. Kriging interpolation produced detailed and reliable prediction surfaces that illustrated distinct spatial gradients in soil loss, with elevated erosion occurring in low-lying depositional

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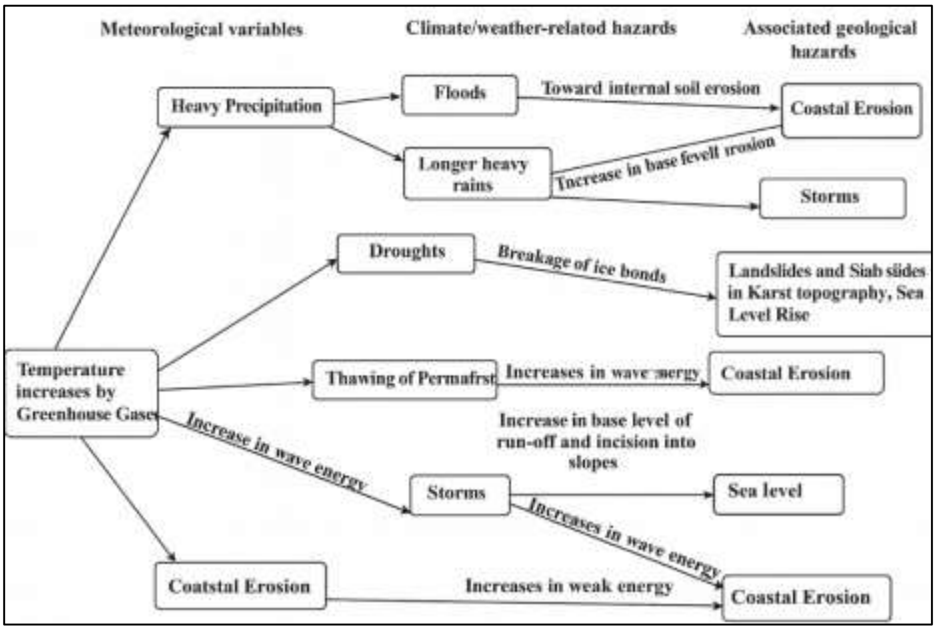
environments and minimal erosion in stable, vegetated terrains. Geographically Weighted Regression (GWR) analysis further revealed substantial geographic heterogeneity in predictor effects, demonstrating that the relative influence of soil cohesion, rainfall intensity, salinity, and vegetation cover shifts across different geomorphic contexts. Collectively, these results underscore the necessity for site-specific and geomorphologically informed erosion management strategies, as aggregated or global assessments risk obscuring the localized processes that drive soil degradation in vulnerable coastal systems.

DISCUSSION

The findings of this study reveal that geotechnical soil properties exert a profound influence on erosion dynamics in coastal zones (Huang et al., 2019). Soils with higher clay content demonstrated stronger cohesion and resistance to detachment under moderate hydrodynamic forces, while sandy soils with larger particles and lower cohesion were more easily eroded by rainfall, runoff, and wave action. This variation underscores the critical role of particle size distribution and soil texture in shaping erosion susceptibility. Cohesion emerged as one of the most significant predictors of erosion resistance, as soils with stronger interparticle bonds required greater mechanical energy for detachment. However, this strength was highly dependent on moisture and chemical conditions; saturation reduced internal bonding and increased susceptibility to mass movement and erosion. The presence of organic matter enhanced aggregate stability and improved soil structure, which reduced the detachment of particles and minimized erosion rates (Huang & Jin, 2018). Permeability influenced infiltration and runoff dynamics, with highly permeable soils facilitating water movement into the subsurface and reducing surface flow, while poorly permeable soils promoted overland flow and greater detachment forces. Salinity and pH also played critical roles by altering soil chemistry and affecting cohesion, with saline conditions leading to greater particle dispersion and increased erodibility. These geotechnical characteristics interacted with external forces to determine erosion patterns, highlighting the need to integrate detailed soil property assessments into predictive models. The results demonstrate that improving soil quality and structure can significantly mitigate erosion, (Zoccarato et al., 2018) and they emphasize the importance of soil mechanical behavior as a foundation for understanding erosion processes in coastal environments. This understanding is vital for interpreting how soils respond to natural forces and for designing interventions that enhance soil stability and reduce vulnerability to erosion.

Figure 11: Greenhouse Gases Driving Coastal Erosion



Hydrodynamic and climatic forces emerged as major drivers of soil erosion in the study area, shaping both the intensity and spatial distribution of soil loss (Cui et al., 2015). Rainfall intensity and precipitation variability were closely associated with erosion rates, as heavy rainfall events delivered sufficient kinetic energy to break apart soil aggregates and generate rapid surface runoff. Prolonged rainfall also contributed to soil saturation, weakening structural cohesion and increasing susceptibility to detachment and transport. The interaction between precipitation and soil properties revealed that soils with low permeability and low cohesion were particularly vulnerable during high-intensity rainfall. Hydrodynamic forces, including wave power, tidal oscillations, and storm surges, exerted additional mechanical stress on soils, accelerating erosion in areas exposed to direct wave action (Akpan et al., 2016). Sea-level rise intensified these effects by allowing wave energy to penetrate further inland and by increasing the frequency of soil saturation, thereby weakening soil strength over time. Salinity changes associated with tidal intrusion further reduced soil cohesion and increased erodibility. Extreme weather events, such as storms and cyclones, were found to cause abrupt increases in erosion rates, contributing disproportionately to total soil loss over the study period. These events produced combined effects of heavy rainfall, high runoff, and intense wave energy, overwhelming the natural resistance of coastal soils (Fagherazzi et al., 2017). The findings also indicate that temporal variability in climate factors leads to seasonal fluctuations in erosion rates, with wetter periods associated with greater soil loss. The interplay between hydrodynamic forces, climatic variability, and soil properties produced complex and often nonlinear erosion responses. These results underscore the necessity of considering both terrestrial and marine drivers in erosion assessments, as their combined effects determine the extent and distribution of soil loss in coastal zones and significantly influence the long-term evolution of coastal landscapes.

The spatial and temporal patterns observed in this study reveal that soil erosion in coastal zones is highly variable and influenced by multiple interacting factors. Erosion hotspots were concentrated in low-lying areas such as deltas, estuaries, and coastal plains, where fine sediments, shallow water tables, and strong hydrodynamic forces converge (Cao et al., 2018). These areas experienced the highest rates of soil loss and shoreline retreat, indicating that certain geomorphic settings are inherently more vulnerable to erosion. Spatial analysis showed that erosion is not uniformly distributed but occurs in clusters, often associated with specific soil types, vegetation patterns, and land uses. Temporal variability was also significant, with erosion rates fluctuating seasonally and peaking during periods of intense rainfall and storm activity. These episodic events contributed disproportionately to total soil loss, highlighting the importance of extreme events in shaping long-term erosion dynamics. The spatial distribution of erosion was closely linked to variations in geotechnical properties, with areas characterized by low cohesion, (Tsuguo, 2018) poor aggregate stability, and high salinity exhibiting greater erosion rates. Land cover patterns also influenced spatial variability, as areas with dense vegetation experienced lower soil loss compared to bare or disturbed surfaces. Human activities such as construction, dredging, and shoreline modification altered local hydrodynamics and sediment transport, further influencing spatial patterns. Temporal analysis revealed trends of increasing erosion intensity during wetter seasons and following major storm events, reflecting the combined effects of climatic variability and soil conditions. The clustering of erosion hotspots suggests that targeted interventions in specific areas could yield significant benefits in reducing overall soil loss (Yesuph & Dagnew, 2019). Understanding the spatial and temporal variability of erosion processes is essential for developing effective management strategies, as it highlights the need to prioritize areas most at risk and to account for seasonal and event-driven fluctuations in erosion intensity.

The findings highlight the profound influence of human activities and land-use changes on soil erosion processes in coastal zones (Kawajiri et al., 2019). Urbanization was associated with increased surface runoff due to the expansion of impervious surfaces such as roads and buildings, which limit infiltration and concentrate water flow. This concentrated runoff increased the erosive power of flowing water and accelerated soil detachment, particularly near drainage outfalls and along modified shorelines. The removal of vegetation for construction and development reduced root reinforcement and soil cohesion, leaving soils more vulnerable to detachment and transport. Deforestation and land clearing had similar effects, exposing bare soils to direct raindrop impact and surface runoff, which significantly increased erosion rates. Agricultural practices, especially intensive tillage and overgrazing, further disrupted soil structure and reduced organic matter content, weakening aggregate stability and increasing erodibility (Fox et al., 2016). Land reclamation and dredging projects altered sediment supply and hydrodynamic conditions, often leading to increased erosion downstream or along adjacent coastlines. Coastal engineering structures, while designed to protect specific areas, sometimes redirected wave energy and sediment transport, causing accelerated erosion elsewhere. The combined effects of these anthropogenic influences created complex erosion patterns that were often more severe and spatially extensive than those driven by natural processes alone. Moreover, the interaction between human activities and climatic forces amplified erosion risks. For example, reduced vegetation cover and compacted soils increased runoff during heavy rainfall, while altered sediment dynamics exacerbated the effects of rising sea levels and storm surges (Wang et al., 2020). These findings demonstrate that human activities not only contribute directly to erosion but also modify the natural processes that regulate soil stability and sediment transport. Effective management of soil erosion in coastal zones must therefore consider both the direct impacts of land-use changes and their interactions with natural forces to mitigate the compounded effects on soil loss and landscape transformation.

The statistical models developed in this study provided valuable insights into the relative importance of various factors influencing soil erosion and demonstrated the predictive power of geotechnical, climatic, hydrodynamic, and land-use variables (Wiemer et al., 2015). Multiple regression analyses identified soil cohesion, aggregate stability, rainfall intensity, and wave power as the most significant predictors of soil loss. These variables accounted for a substantial proportion of the variance in erosion rates, highlighting their dominant roles in shaping erosion dynamics. Interaction terms revealed complex relationships, such as the amplification of rainfall effects in saline soils and the increased influence of wave power in areas with low soil cohesion. Mixed-effects models improved predictive accuracy by accounting for spatial and temporal dependencies, illustrating the hierarchical nature of erosion processes (Costa et al., 2018). Spatial regression models identified significant spatial autocorrelation in erosion patterns, indicating that local conditions and neighboring effects strongly influence soil loss rates. Geographically weighted regression further revealed spatial heterogeneity in predictor effects, showing that the strength and direction of variable influences varied across different locations. This spatial variability underscores the importance of localized conditions and suggests that erosion mitigation strategies must be tailored to site-specific factors. The integration of remote sensing and GIS data enhanced model resolution and allowed for the creation of high-precision erosion risk maps. These outputs identified areas most vulnerable to soil loss and provided quantitative estimates of the contributions of different drivers (Ajedegba et al., 2019). The robustness of the statistical models and their alignment with observed erosion patterns validate their utility for predicting erosion risk and informing management decisions. The findings highlight the effectiveness of combining geotechnical, environmental, and anthropogenic variables in predictive modeling and demonstrate that complex erosion processes can be quantitatively analyzed and accurately forecasted using advanced statistical techniques.

The erosion patterns and driving factors identified in this study align with established global and regional observations while also contributing new insights into the interactions between geotechnical properties and environmental forces (Madricardo et al., 2019). The concentration of erosion hotspots in deltaic and low-lying coastal areas reflects widely observed trends, where sediment supply limitations and hydrodynamic forces accelerate land loss. The significant influence of extreme weather events and rainfall variability on soil erosion parallels documented patterns in many coastal systems, where high-magnitude events contribute disproportionately to total soil loss. The observed importance of vegetation cover and land-use change in moderating erosion aligns with global evidence that human activities play a pivotal role in shaping erosion dynamics. However, this study advances existing knowledge by demonstrating the strong influence of soil chemical properties, such as salinity and pH, (Schmaltz & Mergili, 2018)on erosion susceptibility, highlighting a dimension often underrepresented in large-scale erosion models. The integration of spatial statistics and geostatistical modeling also provided new insights into the spatial heterogeneity of erosion drivers, revealing how their impacts vary across different coastal contexts. These findings contribute to a more comprehensive understanding of erosion processes by linking geotechnical characteristics with hydrodynamic and climatic forces. They also emphasize the need to consider local soil properties and site-specific interactions when developing predictive models and management strategies (Westoby et al., 2020). The results confirm many established principles of erosion science while expanding the conceptual framework to include chemical and spatial dimensions that influence soil behavior in coastal settings. This synthesis of findings enhances the broader understanding of coastal erosion processes and provides a more detailed basis for interpreting regional variations and designing effective interventions.

The findings of this study have significant implications for climate adaptation and coastal management by providing a quantitative understanding of the drivers, patterns, and spatial distribution of soil erosion (Toorman et al., 2018). The identification of key geotechnical factors highlights the importance of soil property management, such as enhancing organic matter and improving aggregate stability, as a means to increase erosion resistance. The demonstrated role of vegetation in reducing soil loss underscores the need for preserving and restoring vegetative cover in coastal areas. The influence of hydrodynamic forces and climatic variability suggests that adaptation strategies must account for changing rainfall patterns, rising sea levels, and the increasing intensity of storm events. Spatial analyses that identify erosion hotspots provide a basis for prioritizing interventions and allocating resources efficiently (Dwevedi et al., 2017). These insights can inform the development of site-specific adaptation strategies, including the design of nature-based solutions, strategic land-use planning, and the implementation of engineered protections where necessary. The interaction between human activities and natural forces observed in this study further indicates that effective management requires an integrated approach that addresses both direct anthropogenic impacts and their influence on natural processes. By linking statistical findings with spatial patterns and geotechnical characteristics, the study provides a framework for evidence-based decision-making in coastal management. The results emphasize that successful adaptation requires coordinated efforts across soil conservation, land-use regulation, habitat restoration, and infrastructure planning (Quigley et al., 2016). This integrated approach can help mitigate soil loss, maintain ecosystem services, and support the resilience of coastal communities. The study's findings therefore not only advance scientific understanding of erosion dynamics but also offer practical guidance for developing strategies that enhance the adaptive capacity of coastal zones in the face of ongoing environmental change.

CONCLUSION

The statistical analysis of geotechnical soil loss and erosion patterns for climate adaptation in coastal zones is a crucial approach to understanding and managing one of the most pressing environmental challenges affecting coastal environments. Coastal soil erosion is a complex process influenced by a combination of geotechnical, hydrodynamic, climatic, spatial, and anthropogenic factors that interact to determine the magnitude, spatial distribution, and temporal variability of soil loss. Geotechnical properties such as particle size distribution, cohesion, shear strength, aggregate stability, permeability, organic matter content, salinity, and pH directly affect soil resistance to detachment and transport. Cohesive soils with higher clay content are generally more resistant but can become highly erodible when saturated or exposed to saline conditions that weaken particle bonds. Hydrodynamic forces, including wave power, tidal range, and storm surges, exert mechanical stress on soils, while climatic variables such as rainfall intensity and seasonal variability influence erosion by increasing raindrop impact and surface runoff. Sea-level rise further exacerbates erosion by expanding the reach of hydrodynamic forces and increasing soil saturation. Spatial analysis reveals that erosion hotspots often occur in low-lying coastal regions like deltas and estuaries, where fine sediments, shallow water tables, and strong hydrodynamic forces converge. Temporal variability shows that extreme weather events disproportionately contribute to soil loss, highlighting the episodic nature of erosion. Human activities such as urbanization, deforestation, land reclamation, and coastal engineering amplify erosion by altering soil properties, hydrology, and sediment transport dynamics. Statistical modeling, including regression, geostatistics, and spatial analysis, enables the identification of key predictors and the development of predictive risk maps, supporting targeted intervention strategies. These insights are vital for climate adaptation, as they guide soil conservation, vegetation restoration, and sustainable land-use planning, enhancing the resilience of coastal ecosystems and human settlements against ongoing environmental change.

RECOMMENDATIONS

Effective recommendations for addressing geotechnical soil loss and erosion in coastal zones must be grounded in a comprehensive understanding of the processes identified through statistical analysis, integrating soil science, hydrodynamics, climate data, and land-use management. Enhancing soil resilience should be a priority, and strategies such as increasing organic matter content, improving aggregate stability, and managing soil salinity can significantly reduce erodibility and enhance structural integrity. Vegetation restoration and conservation are crucial, as plant roots bind soil particles, improve cohesion, and reduce the impact of rainfall and surface runoff, while vegetation cover dissipates wave energy and stabilizes shorelines. Land-use planning should prioritize limiting impervious surfaces in coastal regions, implementing buffer zones, and maintaining natural barriers such as dunes and wetlands that provide protection against hydrodynamic forces. Infrastructure development and coastal engineering projects must incorporate erosion risk assessments and adopt designs that minimize disruption to sediment transport and hydrological systems. The integration of remote sensing, GIS, and spatial modeling should be institutionalized for continuous monitoring of erosion hotspots, shoreline retreat, and sediment dynamics, enabling timely interventions. Climate adaptation strategies must address the increased risks posed by rising sea levels, extreme weather events, and precipitation variability by enhancing drainage systems, designing flexible shoreline protection structures, and planning for managed retreat in highly vulnerable areas. Policies should promote ecosystem-based solutions alongside engineered interventions, combining natural resilience with structural measures. Community involvement and local stakeholder engagement are essential for implementing sustainable practices and maintaining protective vegetation and soil management initiatives. Finally, interdisciplinary collaboration among soil scientists, engineers, climatologists, and planners should guide policy formulation and adaptation planning. By integrating geotechnical understanding with adaptive management, these recommendations provide a framework for reducing soil erosion, protecting coastal infrastructure, preserving ecosystems, and enhancing the adaptive capacity of coastal zones in the face of environmental change.

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