Journal of Hydrological Ecology and Water Security
https://ojs.ukscip.com/index.php/jhews

Article

Coastal Land Dynamics in South-Eastern Bangladesh: Interplay of Climate Forcing and Mangrove Ecosystems

Prabal Barua [1,*] and Nahida Nargis [2]

[1] Department of Environmental Sciences, Jahangirnagar University, Dhaka 1342, Bangladesh

[2] Department of Environmental Sciences and Engineering, Chang'an University, Xi'an 710064, China

[*] Correspondence: prabalims@gmail.com

Received: 20 February 2025; **Revised:** 7 April 2025; **Accepted:** 16 April 2025; **Published:** 25 April 2025

Abstract: Coastal land erosion and accretion (EA) are highly dynamic processes influenced by local climatic variability, often resulting in land loss and population displacement in Bangladesh. This study examines the linkages between climatic variables and coastal land transformations by analyzing 33 years of daily precipitation and temperature data from multiple meteorological stations. Following a moving average smoothing process, three statistical approaches—Spearman's rank, Pearson's, and Kendall's tau correlations—were applied to identify robust associations. Results demonstrate a strong rainfall–temperature relationship (0.78–0.85), exhibiting consistent spatial patterns with minor regional variations. Annual correlation analyses were calibrated against observed erosion and accretion rates, indicating that Kutubdia loses approximately 0.29 km^2 of land annually, while Sandwip, Teknaf, and Sitakund gain 0.59, 7.6, and 7.3 km^2 per year, respectively. Mangrove ecosystems substantially enhance shoreline stability, with trunk densities of 30–40 per m^2 and inland coverage extending about 200 m from creek margins. Mangrove-dominated zones such as Cox's Bazar show net land gains of around 0.6 km^2 annually. Overall, spatial heterogeneity in southeastern coastal dynamics reflects both erosional vulnerability and accretional resilience. The study proposes an integrated, scalable framework that couples climatic and ecological indicators for sustainable coastal land management and climate resilience planning.

Keywords: Coastal Land Erosion and Accretion; Displacement; Rainfall; Temperature; Correlation; Climate Resilience Planning

1. Introduction

Bangladesh, a major deltaic region, is intrinsically vulnerable to many hydro-meteorological hazards owing to its geographic location and largely low-lying terrain [1,2]. About 80% of the nation's geographical surface comprises floodplains created by over 300 rivers, including significant ones such as the Ganges, Brahmaputra, and Meghna, making much of the country susceptible to seasonal monsoon floods [3]. Each year, approximately 20–25% of the nation encounters floods during the monsoon season, with extreme occurrences impacting up to 60% of the territory [4]. The detrimental impacts of climate change, including elevated temperatures, sea-level rise, cyclones, storm surges, saline intrusion, and intense monsoon rainfall, have significantly intensified the nation's economic development issues. These climate alterations are anticipated to exacerbate existing pressures, notably by diminishing water and food security and compromising critical infrastructure [5]. Bangladesh is geographically located between 20° and 26° North latitude and 88° to 92° East longitude. It is bordered to the west, north, and east by India, to the southeast by Myanmar, and to the south by the Bay of Bengal [6]. The nation's terrain is predominantly

https://doi.org/10.54963/jhewa.v1i1.1451

flat, mostly comprising the vast delta created by the merging of the Ganges, Brahmaputra, and Meghna rivers [7]. Tidal floodplains generally exist at elevations below 1 meter above sea level, but river and estuarine floodplains typically vary 1–3 m in height. The Sylhet basin in the northeast attains elevations of up to 6 meters, whereas the extreme northwest contains regions above 30 m above sea level [7]. The northeastern and southeastern regions include mountainous topography, with certain tertiary hills exceeding 1000 m in elevation [8]. The geographic and topographical characteristics substantially enhance the nation's susceptibility to flooding and other climate-related threats [9]. Bangladesh routinely rates poorly on most economic development measures, rendering the nation exceedingly susceptible to climate change [10]. The vulnerability is exacerbated by the nation's geographic and climatic characteristics, together with its elevated population density, which heightens exposure to climate-related hazards [11].

Internal migration is limited by land shortage, exacerbating the difficulties encountered by the people [12]. The interplay of these elements renders Bangladesh one of the most climate-vulnerable nations globally, with considerable ramifications for its future growth [13]. Numerous districts in Bangladesh encounter climate-induced hazards, such as flooding, cyclones, and rising sea levels [14,15]. A recent analysis indicates that Bangladesh is among the nations most impacted by environmental hazards, with significant climate-related losses in human lives and economic damage over the previous two decades [16]. The nation's challenges with poverty, inadequate infrastructure, and restricted adaptability render it increasingly susceptible to these threats. The coastal areas of southern Bangladesh are significantly susceptible to recurrent cyclones, saline intrusion, waterlogging, and sea-level rise resulting from global warming [17,18]. The coastal riverine regions undergo both land erosion and accretion as a result of fluctuating water flows and flooding, in addition to the impacts of weathering. Land EA rates, pertaining to the movement of materials over the Earth's surface, are intrinsic geodynamic processes. These processes are profoundly affected by climatic and meteorological variables. Alongside solid-state mantle convection, propelled by thermally generated density differentials, and the development of gravity-magnetic fields, hydrological processes in the present climate are essential for comprehending land stability [19].

In Bangladesh, a notable consequence of climate change is seen in hydrological alterations, including modified precipitation patterns and river flows [20]. Water resource management continues to be a significant climatic issue for the nation, as emphasized in publications regarding climate change susceptibility [21]. The observed patterns and magnitudes of climate change in Bangladesh correspond with global trends, demonstrating substantial increases in temperature and fluctuations in precipitation. Physical susceptibility is the primary determinant of places susceptible to coastal erosion, with proximity to the coastline, soil texture, and geomorphology being the most significant determinants. Socio-economic vulnerability, conversely, is shaped by elements such as the dependent population, literacy rates, and road buffers [22,23]. Different studies indicate that a multi-faceted strategy is essential to tackle both acute physical dangers and the fundamental socio-economic factors. This strategy ought to encompass community involvement, educational initiatives, and sustainable development methodologies that enable communities to adjust and prosper throughout challenges [24–26].

Coastal systems undergo long-term dynamic processes, including sea-level rise, which transform beaches, inundate marshes, and destroy infrastructure, significantly modifying the physical environment. Rivers and oceans are instrumental in the transportation of sediments, which may be deposited ashore, reprocessed, or removed, hence perpetually altering the coastal topography [27]. Coastal land formation is essential for supporting livelihoods, which are significantly impacted by climatic variables like precipitation and temperature, therefore influencing local climate patterns. Coastal forests with their intricate root systems play a crucial ecological role by capturing sediments and offering natural defense against coastal floods induced by storm surges or cyclones, thus stabilizing shorelines [28]. These trees function as natural sediment reservoirs, mitigating soil erosion and minimizing harm to coastal properties. Their function in coastal stabilization is crucial as a substitute for artificial structures, offering a cost-efficient and sustainable approach to reducing coastal erosion [29]. Considering these dynamics, it is plausible to propose a strong correlation between land formation—resulting from both natural processes and human activities—and climatic variables, especially temperature and precipitation [30]. The interplay of sediment transport, coastal morphology, and climatic conditions highlights the intricate feedback mechanisms that influence coastal ecosystems. Consequently, the quantification of suspended sediment concentration [SSC] is essential for determining the resultant sediment movement in mangroves [31,32].

The correlation between precipitation and temperature is crucial in influencing agricultural productivity, as both elements are vital for crop development and land stewardship [33,34]. Agricultural production is intricately connected to land, water, and climate, which are mutually reliant. Thus, alterations in land—whether due to erosion or accretion—are directly affected by variations in temperature and precipitation patterns. A multitude of studies have investigated the correlation between rainfall and temperature across many temporal and spatial dimensions [30–34]. Notwithstanding these endeavours, a thorough comprehension of the interplay between rising rainfall and temperature, especially through monthly or seasonal data analysis, continues to be elusive [35]. The intricacy of this relationship, particularly regarding climate variability, necessitates more examination to consider the wider effects on land dynamics.

Comprehending the dynamics of land use change and its effects on the environment of the southwestern coastal region of Bangladesh is essential for efficient coastal zone management and conservation planning. This area, extending from 21.5° N to 23.5° N latitude and 89.0° E to 91.5° E longitude, is particularly susceptible to climate-related threats, including sea-level rise, saline intrusion, erosion, and severe weather phenomena. Although prior research has examined several facets of coastal changes, none have quantitatively evaluated the correlation between rainfall and temperature time series or investigated the spatiotemporal patterns of land erosion and accretion.

This study utilizes a correlation-based methodology to assess rainfall concentration, temperature fluctuations, and their effects on coastal landforms. The objectives are (1) to analyze daily rainfall concentration, temperature time series, and their spatial distribution, (2) to ascertain the correlation between rainfall intensity and daily rainfall concentration, and (3) to investigate the function of mangrove forests in sediment stabilization and coastal degradation mitigation.

Recent studies underscore that climate-induced sea-level rise, along with alterations in land use and upstream hydrological changes, is exacerbating erosion on the eastern coast of Bangladesh [36–38]. These cumulative effects are changing places that used to be moderate-risk into areas that are now high-risk for erosion. The growing urban area of the South-Eastern Coast of Bangladesh, unplanned coastal development, and sand mining have made shoreline retreat and sediment imbalance worse [37]. According to forecasts, sea levels might rise by as much as 0.89 m by 2100 in high-emission scenarios [38]. This would not only relocate communities but also increase saline intrusion, lower agricultural productivity, and put regional food security at risk. Geospatial vulnerability evaluations are also very important for finding regional variability in the effects of erosion. They do this by looking at terrain, land use, population density, and socioeconomic sensitivity to help in localized adaptation [39]. Additionally, Bangladesh is expected to see significant effects from climate change, which would worsen coastal erosion in its coastal areas, presenting additional risks to the local economy and environment. Evaluate coastal erosion susceptibility by amalgamating physical and socio-economic factors, and pinpoint susceptible zones along the Chattogram coastline through geospatial methodologies.

There is a gap in the research work about the relationship between climate parameters and mangrove forest availability and regeneration on coastal land dynamics factors of the highly climate-vulnerable Bangladesh. This study investigates the relationship between climatic variables and coastal land alterations by analyzing daily precipitation and temperature data from several meteorological stations during a 33-year period. So, this study aims to incorporate Suspended Sediment Concentration (SSC) measurements to investigate sediment transport pathways and underscores the ecological importance of mangroves as natural barriers to coastal dangers. This study offers a comprehensive framework that connects climate factors with land use changes and ecological stability, delivering essential insights for sustainable coastal management, in contrast to earlier fragmented approaches. The authors have explored the substantiated evidence-based policy recommendations aimed at bolstering resilience, advancing ecosystem-based adaptation measures, and alleviating the detrimental impacts of climate change on coastal communities through the present study findings.

2. Materials and Methods

The research area is situated in the south-eastern coastal region of Bangladesh, extending from approximately 21.5° N to 23.5° N latitude and 89.0° E to 91.5° E longitude. It includes Cox's Bazar, Chattogram, Feni, Lakhmipur, Chandpur, and Noakhali. This region features a complex system of rivers, estuaries, and tidal floodplains, rendering it highly dynamic and susceptible to both natural and human-induced factors (**Figure 1**). The coastal zone is influenced by the interactions of the Ganges-Brahmaputra-Meghna (GBM) river system, which regulates sediment movement, land accretion, and erosion processes in the deltaic environment.

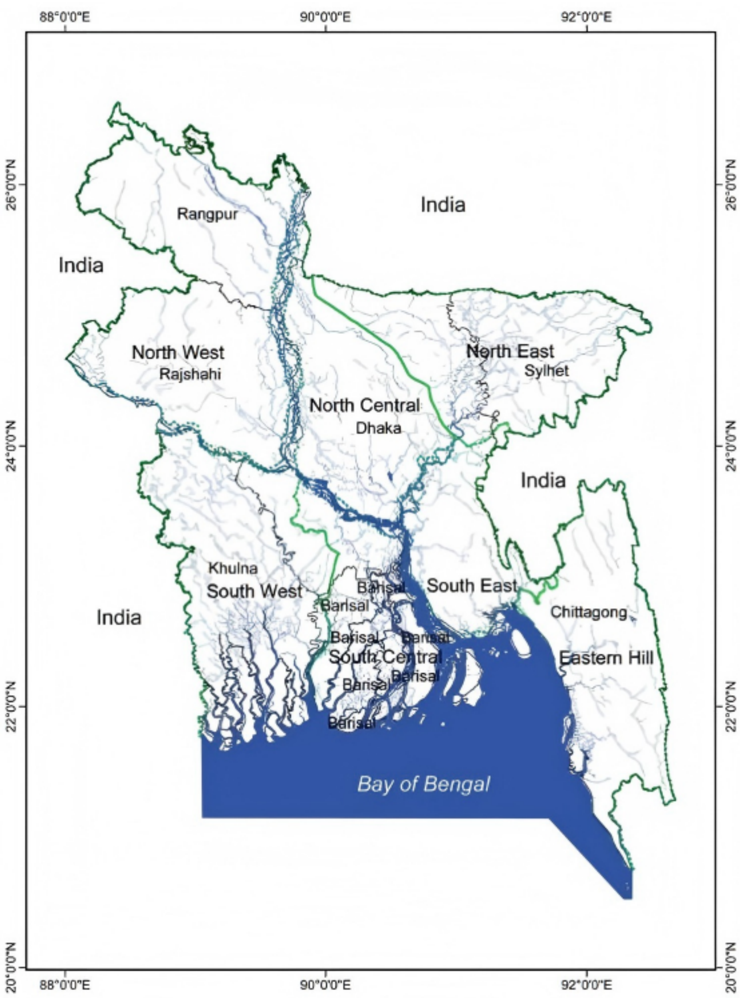

Figure 1. Map showing the study area, highlighting the locations of meteorological recording stations (NWRD, Bangladesh).

The study region is especially susceptible to coastal hazards, including sea-level rise, storm surges, cyclones, saline intrusion, and coastal erosion, due to its geographic location [40]. These issues present considerable obstacles to local livelihoods, particularly for people dependent on agriculture, fisheries, and aquaculture. The rising incidence of extreme weather events, intensified by climate change, jeopardizes infrastructure, food security, and biodiversity in this area.

2.1. Climatic Pattern in South-Eastern Coast

The coastal zone of Bangladesh consists of 19 administrative districts encompassing 147 Upazilas, defined by tidal variations, cyclones, storm surge hazard, and salinity incursion.

Of the Upazilas, 48 from 12 districts are situated along the coast or lower estuary, classified as exposed coast, while the remaining 99 Upazilas, located inland from the exposed coast, are referred to as interior coast. The climate of Bangladesh is dominated by the seasonal reversal of winds, with southwest winds prevailing in summer and northwest winds in winter, resulting in a wet southwest monsoon and a dry northwest monsoon, respectively. The South-Eastern coastal region of Bangladesh is relatively vulnerable to cyclones, tidal floods, coastal erosion, and variable heavy rains, both in intensity and duration, from year to year. A number of studies were undertaken regarding climatic trends and the effects of climate change in the coastal region of Bangladesh [41,42].

Analysis of temperature data from the past century in Bangladesh reveals that the pace of temperature increase exceeds the current rate of 0.5 °C. A separate study indicates that the mean annual temperature of Bangladesh rose by 0.3 °C from 1895 to 1980 and increased by about 0.80 °C from 1900 to 2017. The correlation of the growing trend is observed in both summer and winter temperatures [43–45]. No notable trend was observed in the annual rainfall of Bangladesh. The investigation of long-term monsoon rainfall patterns at 12 sites in Bangladesh revealed no significant trend in seasonal total rainfall; nevertheless, certain trends in monthly rainfall were identified [46,47].

The study identified a rising temperature trend for Kutubdia and Sandwip, with increases of +0.029 °C and +0.044 °C, respectively, from 1977 to 2017. On the other hand, it was found that average minimum temperature in the Kutubdia region was documented from November to February, fluctuating between 6.2 °C and 13.4 °C, whilst the maximum temperature of 39.5 °C occurs in May [30]. Consequently, the correlation coefficient between year and temperature was positive throughout all research locations [40–49]. The variety of rainfall in both spatial and temporal dimensions is a significant element of Bangladesh's climate. This will result in a harsh amalgamation of intensified floods and prolonged droughts. Bangladesh has been identified as one of the most susceptible nations globally due to climate change. The rainfall trend from 1977 to 2017 is analyzed to forecast the temporal pattern of precipitation in Bangladesh. The authors determined that the rainfall trend in Kutubdia was 1.957 mm/year, while in Sandwip it was 0.875 mm/year. The correlation coefficient between the year and rainfall was positive for the study regions. Between 1961 and 1991, Bangladesh experienced 19 droughts. Significant droughts transpired in 1973, 1976, 1978, 1979, 1980, 1981, 1982, 1984, 1986, and 2000. In 1979, there was a substantial reduction in rainfall, resulting in a severe drought that inflicted extensive damage on crops. The repeated droughts of 1979 directly impacted approximately 42% of arable land, 44% of the populace, and diminished rice production by an estimated 2 million tons, marking it as one of the most severe in recent history [50,51]. The rising trends in annual maximum rainfall in Kutubdia and Sandwip upazilas are ultimately influenced by the trajectory of the south-western monsoon winds. This suggests that the severity of heavy rainfall may have escalated along the primary trajectory of the monsoon wind. Relative humidity (RH) is a significant climatic component that contributes to the development of many unstable conditions. Research on this parameter is crucial as temperature and relative humidity significantly influence cyclone development [51–53]. The research identified substantial variations in wind velocity throughout the examined regions. In 1977, at the commencement of the research area, the wind speeds recorded in Kutubdia and Sandwip were 1.9 m/s and 1.45 m/s, respectively.

In 2017, the average wind speeds in the two research sites were 5.5 m/s in Kutubdia and 5.7 m/s in Sandwip, respectively, and the data for the year 2015 was analyzed, revealing an average wind speed of 3.56 m/s at Sandwip [53]. The recent advancements in wind rotor aerodynamics enable energy extraction from wind speeds as low as 2.0 m/s. In 2011, the per capita electricity demand in Kutubdia was 138,250 MWh, equating to 378 MWh daily. The Sern and Eastern regions of Kutubdia are advantageous for wind energy production with huge turbines, since the wind power density at a height of 50 m or more exceeds 200 W/m^2 yearly, based on data from September 1996 to August 1997. At a height of 30 m, the coastal region of Kutubdia is deemed suitable for small turbines [54].

The authors discovered that cyclonic storm surges caused significant loss of life and property for the residents of Kutubdia and Sandwip Island [54]. The literature indicates that 31 cyclones have occurred in the Bay of Bengal, causing substantial damage to assets and human lives in the study areas [50–55]. Between 1960 and 2017, roughly 574,000 residents of the southeastern coast of Bangladesh were displaced from their homes and land due to cyclones. Residents of Kutubdia and Sandwip islands reported that 350,000 individuals have been compelled to displace and migrate from their homes between 1980 and 2018 due to natural disasters, including cyclones, tidal flooding, coastal erosion, and waterlogging issues [55,56]. One of the researchers discovered that Bangladesh experiences a heightened level of cloud cover from June to August, with July being the peak month. He stated that the cloud cover varies across different locations in Bangladesh. The geological position, humidity fluctuations, plant density, variations in wind speed, and temperature changes are critical characteristics influencing cloud formation and the variability of cloud cover [57].

The choice of study areas is predicated on their strategic significance in comprehending climate variability and coastal dynamics. These regions contain permanent meteorological stations that supply essential data on temperature, precipitation, wind patterns, and other environmental variables. Evaluating these characteristics is crucial for examining hydrodynamic alterations, sediment conveyance, and land-use modifications in the coastal ecosystem [58]. The region has pronounced seasonal fluctuations, featuring a monsoon-influenced climate marked by substantial rainfall from June to October, resulting in recurrent flooding and heightened silt deposition. In contrast, the dry season from November to April leads to diminished freshwater flow, exacerbating saline intrusion into agricultural areas and freshwater ecosystems. **Figure 2** presents a comprehensive map of the study area, depicting land elevation, significant rivers, and meteorological stations essential for climate observation. Comprehending the spatial distribution of these factors is essential for assessing the coastal zone's resilience and developing adaptive solutions to alleviate climate-induced threats (**Figure 2**).

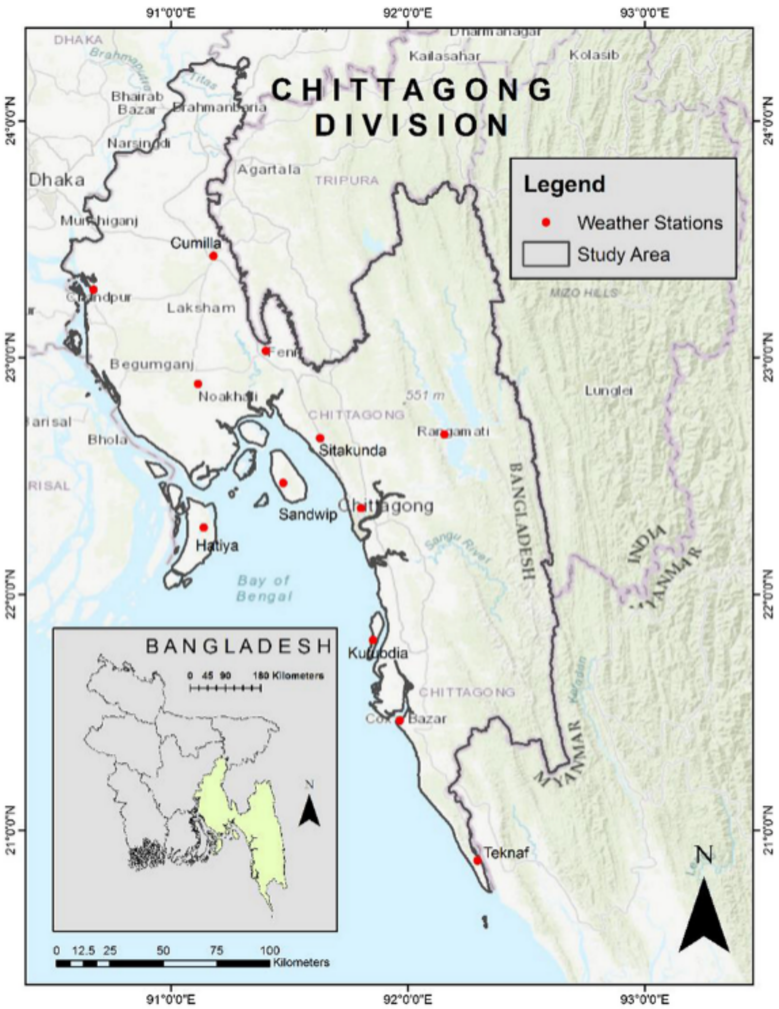

Figure 2. Geographical Location of the Study areas.

This study examines the relationship between daily temperature and rainfall data, sourced from meteorological stations, and their influence on land EA processes. In this research, daily temperature denotes the diurnal temperature range, determined by subtracting the daily minimum temperature from the daily high, a prevalent method for evaluating climate variability and its impact on landforms [50–52]. The correlation analysis investigates the link between temperature and rainfall using temporal records to deduce patterns of land erosion and accretion. To assess the impact of temperature and precipitation on land alterations, calibration was conducted utilizing empirical data of land erosion and accretion rates, adhering to recognized geomorphological methodologies [40,59]. The research employed temporal curves to represent the dynamics of landform alterations, integrating hydrological data to evaluate the impact of climatic variations on the physical landscape [42].

The subsequent subsections address the materials and procedures utilized in this investigation (**Figure 3**). This thorough method facilitates a more profound comprehension of how climatic elements, including temperature and precipitation, influence the current dynamics of land erosion rates, particularly in coastal areas.

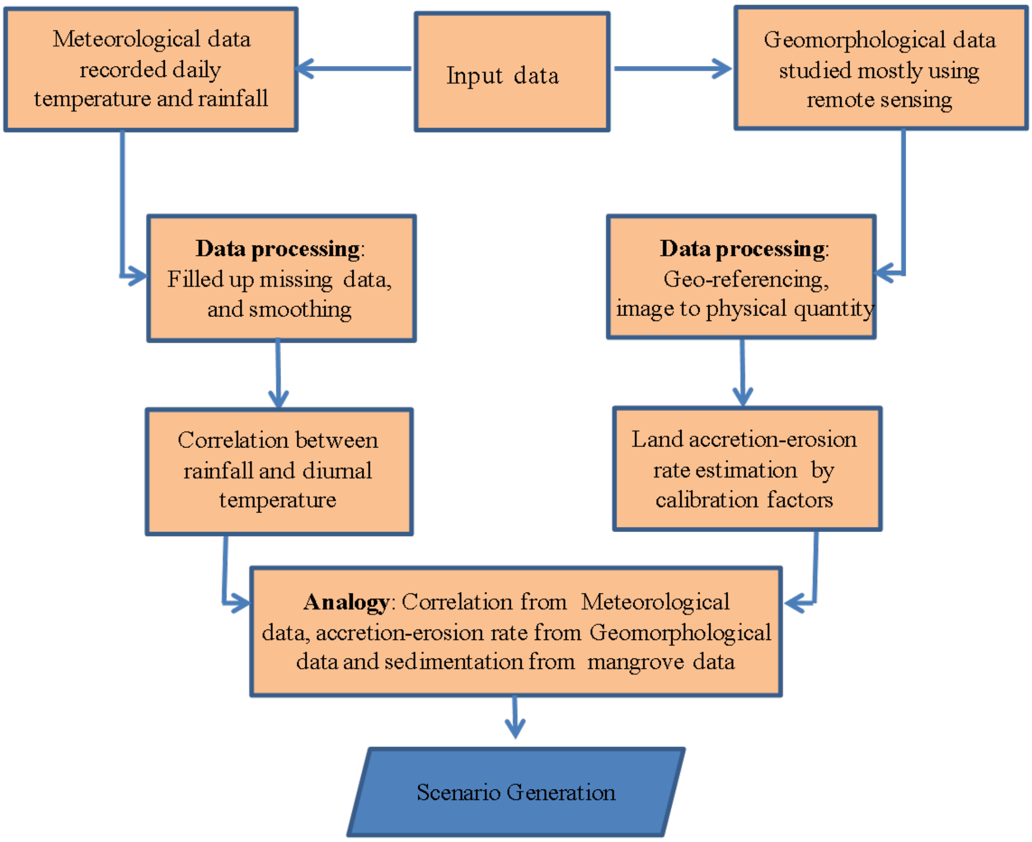

Figure 3. Conceptual flowchart illustrating the methodology of the proposed study, outlining the step-by-step process and key stages involved in the research.

2.2. The Information

To examine the correlation between rainfall and temperature in southwestern Bangladesh, daily minimum and maximum temperature, as well as rainfall data, were sourced from the Bangladesh Meteorological Department (BMD) for eight specified meteorological stations, encompassing a 33-year span from 1985 to 2017. Any absent data, comprising less than 1% of the overall dataset, were estimated via the cubic spline interpolation approach. Furthermore, land EA rates for the Kutubdia, Teknaf, and Cox's Bazar stations were obtained from prior research findings by the researcher [60–62].

Pearson, Kendall, and Spearman correlations are widely utilized statistical techniques for assessing the strength of associations between variables. The Pearson correlation is good for regularly distributed data, while the Kendall rank and Spearman correlations are preferable for variables that do not exhibit a linear connection. Given that climate data may not demonstrate linearity or normal distribution, all three methodologies were employed to analyze the relationships within the climate data. The correlations derived from the approaches exhibit analogous patterns, primarily varying in magnitude. Spearman's Rank Correlation Coefficient: A strong nonlinear link may exist despite the absence of, or a minimal linear correlation between, two variables. Spearman's rank correlation quantifies the strength and direction of the relationship between two ranked variables. It essentially represents uniform covariance and quantifies the monotonicity of the relationship between two variables. The Spearman rank correlation ranges from +1 to −1, where +1 indicates a perfect rank association, 0 signifies no rank association, and −1 denotes a perfect negative rank association. Conversely, Spearman's rank correlation coefficient is a nonparametric statistic employed to evaluate the strength and direction of a monotonic link between two ranked variables. In contrast to Pearson's correlation, which assesses linear links, Spearman's rank correlation is adept at identifying nonlinear associations, rendering it more resilient when the relationship between variables is not exactly linear [63]. It assesses the extent to which the correlation between two variables may be characterized by a monotonic function. Spearman's rank correlation coefficient (r_s) varies from +1 to −1, with +1 signifying a perfect positive correlation between ranks (i.e., an increase in one variable corresponds with an increase in the other); 0 denotes the absence of correlation; and −1 represents a perfect negative correlation (i.e., an increase in one variable corresponds with a decrease in the other).

The formula for Spearman's rank correlation coefficient can be described as follows (Siegel and Castellan, 1988) [64]:

$$r_s = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \tag{1}$$

where $d_i = rg\,(X_i) - rg(Y_i)$ is the difference between the ranks of each pair of observations observations and n is the total number of observations.

Equation (1) is especially advantageous when the prerequisites of normality or linearity, necessary for alternative correlation metrics, are not satisfied, offering a dependable measure for assessing ranked data across various applications [65].

Moving average method: The moving average technique is a prevalent method in time series analysis, mostly employed for data smoothing to discern underlying trends and patterns by mitigating the effects of short-term variations. It is commonly utilized in climate research to evaluate long-term meteorological fluctuations, encompassing precipitation and temperature trends. This strategy alleviates the impact of random fluctuations, rendering it a valuable instrument for comprehending seasonal and cyclical elements in climate data [66]. This study used the moving average method to improve the correlation analysis between rainfall and temperature, as climate patterns, including summer and winter seasons, are frequently influenced by variations in rainfall and mean temperature [67,68]. The method enhances clarity regarding cyclical or seasonal patterns by mitigating short-term fluctuations, therefore augmenting the precision of trend identification [69].

The widespread expression for the moving average technique was proposed by Brockwell and Davis [70] and moving average was done using Equation (2).

$$M_t = [X_t + X_{t-1} + X_{t-2} + \ldots + X_{t-N+1}]\,/N \tag{2}$$

where M_t is the moving average at time t, X_t represents the observed value at time t, and N is the period over which the average is calculated.

2.3. Calibration and Estimation of Land Erosion and Accretion

In a previous study investigating the relationship between rainfall and temperature in Southeast Bangladesh, researchers try to established a robust correlation between the erosion patterns seen on Sandwip and Hatiya islands from 1997 to 2010 and variations in rainfall and temperature [60]. The temperature in this analysis was characterized as the differential between the daily maximum and lowest, with a 7-day moving average utilized to refine the data prior to doing the correlation analysis. Although a distinct trend was identified, the investigation failed to determine the actual mass loss or gain of these islands. This study seeks to quantify land loss and gain by analyzing the relationship between rainfall and temperature using a calibrated methodology.

This study employed the Spearman rank correlation coefficient to examine the link between rainfall and temperature at eight meteorological stations: Chattogram, Cox's Bazar, Sitakund, Teknaf, Kutubdia, Sitakund, Sandwip, and Feni. Geographical location and mean climatic factors have been mentioned in **Table 1**.

Table 1. Summary of collected climate (i.e., temperature and rainfall) data.

Station Name	Latitude (Degree)	Longitude (Degree)	Altitude (m)	Mean Rainfall (mm)	Mean Temperature (°C)
Chattogram	22.3	91.8	5.5	243.26	30.17
Cox's Bazar	21.45	91.97	2.1	293.67	30.11
Teknaf	20.87	92.30	5	329.53	30.10
Kutubdia	22.4	92.5	2.7	235.35	29.77
Sitakund	23.1	91.6	7.3	257.68	30.15
Sandwip	22.48	91.43	2.1	289.8	29.4
Feni	23.0	91.4	6.3	257	30.25

Source: Bangladesh Meteorological Department.

In accordance with the previous study, temperature is characterized as the daily differential between the highest and minimum values. Prior to calculating the correlation coefficients for each year, a 7-day moving average was utilized to refine the data, resulting in more precise and interpretable correlations. The analysis encompassed the years 1985 to 2017, with correlations between rainfall and temperature continuously approximating 0.80. This corresponds with the physical expectation that augmented precipitation typically decreases temperatures, while diminished precipitation leads to elevated temperatures [70].

The robust connections derived from this study were then employed to estimate land erosion and accretion in the southwestern coastal area. Calibration was conducted by juxtaposing the correlation results with the available land change data for this region, obtained from multiple research studies [71–74]. **Table 2** presents the calibration data, wherein the accretion and erosion rates (DDD) for each year were divided by the correlation coefficient (rrr) to provide a calibration factor (D/rD/rD/r). The mean calibration factors were determined to be 90.27 for Kutubdia, −3220.22 for Teknaf, and −366.81 for Cox's Bazar.

Table 2. Calibration of correlations for estimating erosion and accretion of the coastal islands.

Erosion and Accretion Statistics of the Islands					Calibration of Correlation Using EA Statistics				
Location	**Duration**	**Year**	**EA rate (D) km^2/year**	**Ref.**	**Correlation* (r)**	**Duration of Changes in Correlation**	**Changes in Corr.**	**Cali. Factor (D/r) km^2/year**	**Mean Cali. Factor (k) km^2/year**
Kutubdia	1973–1988	1988	+3.4	Barua et al. [41]	−0.0904	-	-	-	90.27
	1988–2000	2000	+10.6		+0.1024	1988–2000	+0.1928	54.98	
	2000–2008	2008	−15.5		+.0059	2000–2008	−0.0965	160.62	
	2008–2016	2016	+4.3		+0.0838	2008–2016	+0.0779	55.20	
Sitakund	1978–1988	1988	−24.8	Roy et al. [69]	−0.0236				−3220.22
	1988–1998	1998	−16.8		+0.0019	1988–1988	+0.0255	−658.61	
	1998–2008	2008	−31.8		+0.0074	1988–2008	+0.0055	−5781.82	
	2008–2018	2018	31.2		-	-	-	-	
Cox's Bazar	1973–1984	1984	−8.1	Rahman et al. [61]	+0.0196	1973–1985	-	-	−366.81
	1984–1996	1996	+16.4		+0.0021	1984–1996	−0.0175	−937.14	
	1996–2006	2006	+4.1		−0.0487	1996–2006	−0.0508	−80.71	
	2006–2015	2015	−2.7		−0.0160	2006–2015	0.0327	−82.57	

Note: * Correlation of rainfall with the difference in daily temperatures from maximum to minimum.

The calibration parameters were subsequently utilized to assess land erosion and accretion at the five proximate stations—Chattogram, Kutubdia, Cox's Bazar, Sandwip, and Sitakund—throughout the study period. The subsequent sections give findings that provide novel insights into the correlation between climate variables and land transformation in the southwestern coastal region.

3. Results

Looking into Bangladesh's historical climate data from 1901 to 2022 shows that the environment is getting warmer, with temperatures rising and precipitation patterns changing [75]. Average temperatures have gone up during the past hundred years, with the biggest warming happening in the previous few decades. Rainfall patterns are becoming less regular, and disasters like floods and droughts are getting worse. Global climate change is causing these changes, which are making it very hard for Bangladesh's agriculture, water resources, and public health. While not all findings are presented, prior research investigated these links to comprehend coastal erosion and accretion. The stations comprised Feni, Chattogram, Cox's Bazar, Kutubdia, Sitakund, Teknaf, Sandwip, and Feni.

The correlations for the Feni and Kutubdia stations are depicted in **Figure 4**. Overall, the correlations for all stations were relatively high, with Spearman's rank correlation yielding values close to 0.80. However, Feni station showed a slightly different value of 0.74. These correlations indicate that the mainland and coastal areas exhibit similar climatic patterns, with minor variations (**Table 2**).

From the findings of **Table 2**, it is highlighted that Kutubdia, a significant offshore island situated on the south-eastern coast of Bangladesh, has garnered much attention due to its accelerated land loss to the sea, a situation that has become increasingly frequent in recent times as a result of rising sea levels. The whole island is mostly eroded, but most erosion is in the southern half of the island. Erosion is the main problem in the south and east segments of the islands. There is an accretion trend in the eastern part of the Kutubdia observed in the south segment and three transects in the east. This erosion could make it harder for farms to grow crops and for people to live. **Figure 5** shows the yearly EA rate (in km^2/year) from 1985 to 2017. The analysis uses the same calibration factor of 90.27, which is shown in **Table 1**. The findings show that land accretion rose significantly in 1997. Erosion happened faster than land formation in most other years during the study period, though.

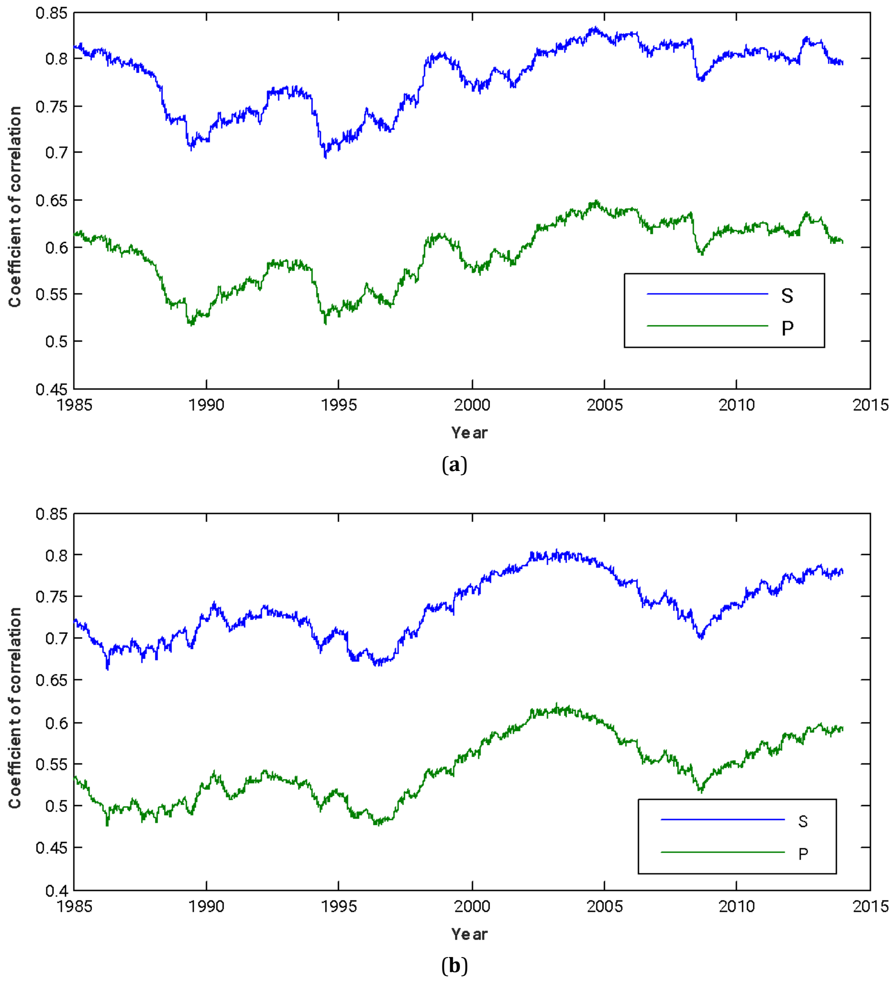

Figure 4. Estimated correlations using the Spearman (S) and Pearson (P) correlation techniques for (**a**) Feni and (**b**) Kutubia stations.

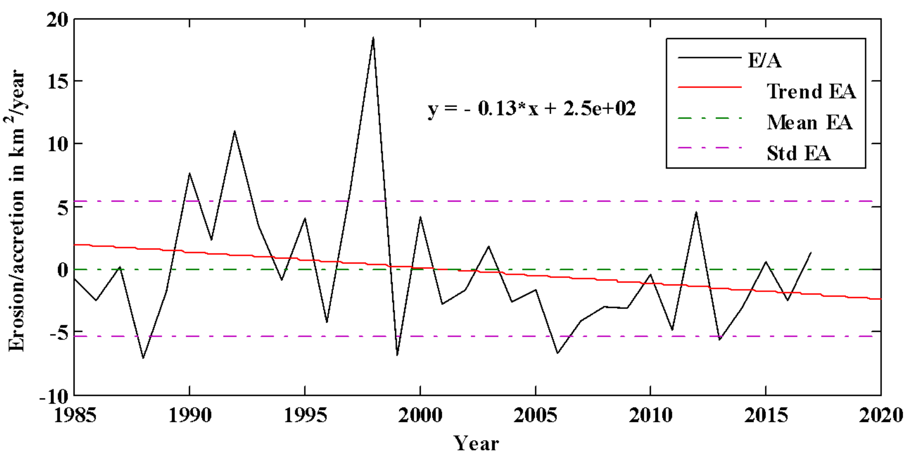

Figure 5. Calibrated correlation of EA rates, along with the linear trend, mean, and standard deviation (Std) of temperature and rainfall at Chattogram.

On the other hand, from the present study, the authors explored that various parts of Sandwip Island demonstrate cyclical accretion and erosion. The island's erosion and accretion were caused by both natural and human-induced factors. The physical factors include river discharge from the upstream Ganges-Brahmaputra-Meghna Rivers in the Meghna estuary, silt load, tidal influences, wave action, water currents, and bank structure. Moreover, human activities influence shoreline alteration and the hydrology of the canal. The sea depth surrounding the island displays analogous dynamics in relation to the erosion and accretion of the shoreline. There exists a correlation between coastal morphological changes and the erosion-accretion dynamics on this offshore island (**Figure 6**).

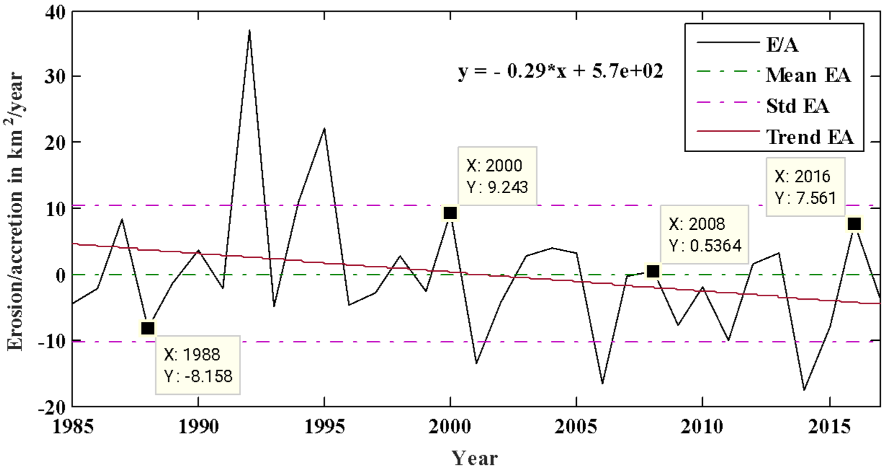

Figure 6. Calibrated correlation of EA rates, along with the linear trend, mean, and standard deviation (Std) of temperature and rainfall at Kutubdia.

The augmented erosion during this time can be ascribed to variables like intensified storm activity, diminished sediment supply, and potentially anthropogenic interventions such as river channelization or embankment construction.

The physical alterations in Sandwip signify considerable coastal erosion, an increase in developed areas, and changes in land usage. The southern and southwestern shores of the island underwent gradual erosion. Over the past three decades, a substantial section of arid land has been transformed into water bodies. Conversely, the regions of accretion on the northern and northeastern sides are comparatively limited and unstable. Enhanced tidal forces and evolving hydrodynamics have exacerbated coastal erosion, progressively eroding land [75]. Furthermore, a decrease in sediment supply from upstream rivers, caused by dam construction and embankments, has disturbed the normal equilibrium of accretion and erosion [76]. The effects of significant cyclones and storm surges have exacerbated the situation, as extreme weather events hasten land degradation.

Furthermore, the trend indicates that Chattogram is experiencing a net land loss at a rate of 0.1 km^2/year. This projected land loss, combined with erratic patterns in rainfall and temperature, could have a substantial negative impact on agricultural productivity and human livelihoods in the region. **Figure 7** depicts the yearly EA rate (in km^2/year) at Cox's Bazar from 1985 to 2017. The analysis uses a calibration factor of −366.81 (**Table 1**). The results show a general increase in land area, despite minor fluctuations in the yearly data. Notably, there was a significant land loss exceeding 55 km^2/year in 1997, contrasted by substantial gains of approximately 30 km^2/year in 1998 and 2011.

Cox's Bazar is gaining land at a pace of 0.6 km^2 per year overall. Because of this, Feni is not in danger of erosion. Instead, this beneficial land growth should support farming and other enterprises. **Figure 8** shows the yearly EA rate at Teknaf from 1985 to 2017, using a calibration factor of −3220.22 (**Table 1**). The data show a broad trend of land accretion, although there are big changes from year to year, sometimes more than ±175 km^2/year, which may not be completely accurate. Even though there have been big changes, the overall trend shows that land is slowly getting bigger. The rate of land gain was −25–25 km^2/year in 1988, but it grew to 31 km^2/year in 2018, which means that by 2018, there was a net gain of 56 km^2/year [77]. In 1992, the most land was lost, while in 2011, the most land was gained. These trends show that Teknaf is affected by land erosion in both good and bad ways, with yearly changes that are somewhat high. **Figure 9** shows the yearly EA rate for Sitakund from 1985 to 2017, which was calculated using a calibration factor of −366.81 (**Table 1**). The results show that the changes are mostly small, with the biggest one being a loss of 60 km^2 per year in 1997. Even though there are some differences, the overall trend shows that the terrain is steady, with a net land gain of 0.7 km^2/year. In 1999 and 2011, for example, the region had higher accretion rates, which shows that it can naturally generate land. The fact that EA changes are not very big and that land is always being added to shows that Sitakund is not in a lot of danger from climate-related changes in the shape of the land. Also, the region's infrastructure seems to be able to withstand coastal erosion, which reduces the possible social and economic effects.

These results show that the coastal dynamics along Bangladesh's South-Eastern Coast are not all the same. Some places are more likely to have land degradation and erosion, while others are more likely to have land accretion, which makes them more resistant to changes in the environment. This kind of variety shows how important it is to have localized coastal management plans that reduce the risk of erosion while taking advantage of natural processes that build up land to make it more stable and support sustainable development.

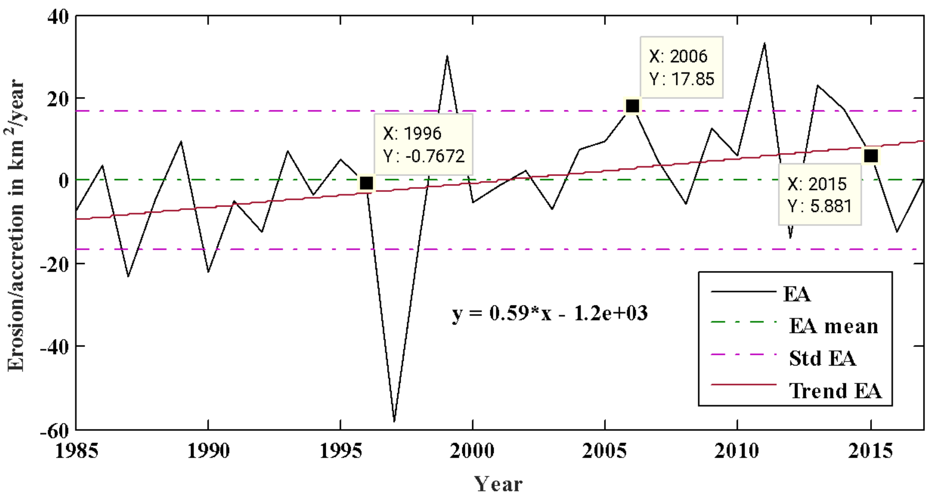

Figure 7. Calibrated correlation of EA rates, the linear trend, mean, and standard deviation (Std) of temperature and rainfall at Cox's Bazar.

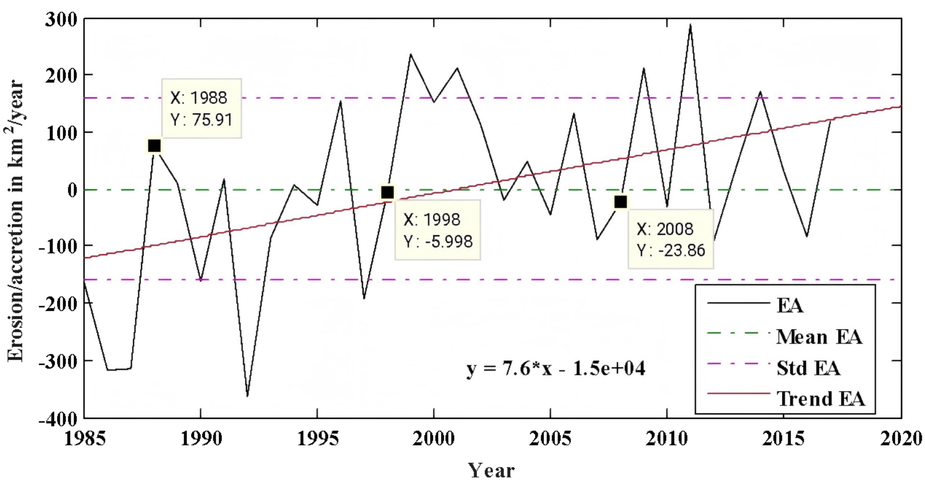

Figure 8. Calibrated correlation of EA rates, the linear trend, mean, and standard deviation (Std) of temperature and rainfall at Feni.

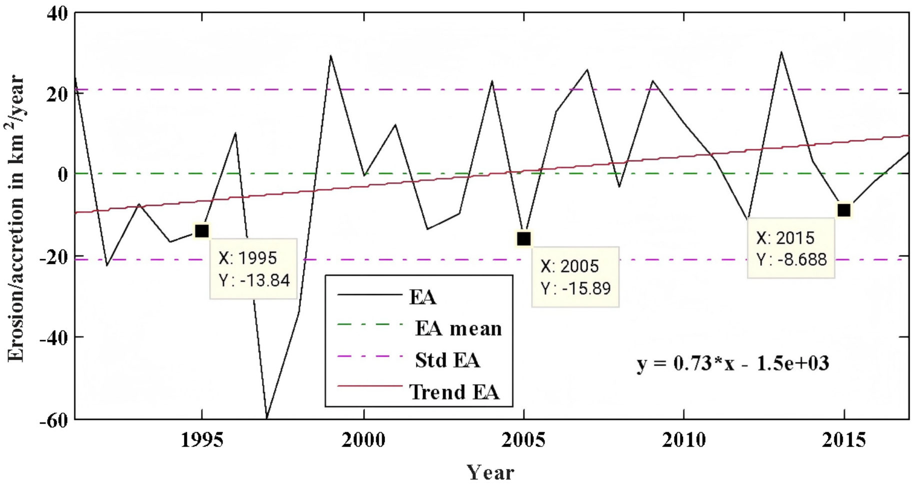

Figure 9. Calibrated correlation of EA rates, the linear trend, mean, and standard deviation (Std) of temperature and rainfall at Sitakund.

Researchers from Japan used the trap method to estimate sedimentation rates in mangroves in the field. They put the traps along the margin of the creek. On December 2–4, 1994, these data were collected over a transect through natural mangroves during three consecutive spring tide cycles. *Rhizophora sp*., *Bruguiera gymnorhiza*, and *Ceriops* sp. Talang was the most common mangrove species in the study. The mangrove trunks, including the roots, had a density of 30–40 m^2 and an average diameter of 4.0 cm. The mangrove forest went about 200 m inland from the creek's edge [28].

Conversely, Hoque et al. [38] concentrated on quantifying wave energy attenuation inside the forest, while Wolanski et al. [78] documented the selective retention of fine silt by mangroves. Hoque et al. [38] employed staggered cylinders of diverse heights (2.5–12.5 cm) to model wave attenuation, with each cylinder possessing a diameter of 0.6 cm and a spacing of 1.09 mm between adjacent cylinders. In this investigation, we employed the methodology of Furukawa et al. [28] to gather field data from the study areas (**Figure 10**). An investigation of sedimentation indicates a similarity between the mangrove forest areas and the findings of Furukawa et al. [28] in both a mangrove-lined bank (A–D) and an area devoid of mangroves (E). This indicates that sediment accumulates in mangrove forests due to their intricate root systems during storm surges, as wave energy is attenuated by the vegetation.

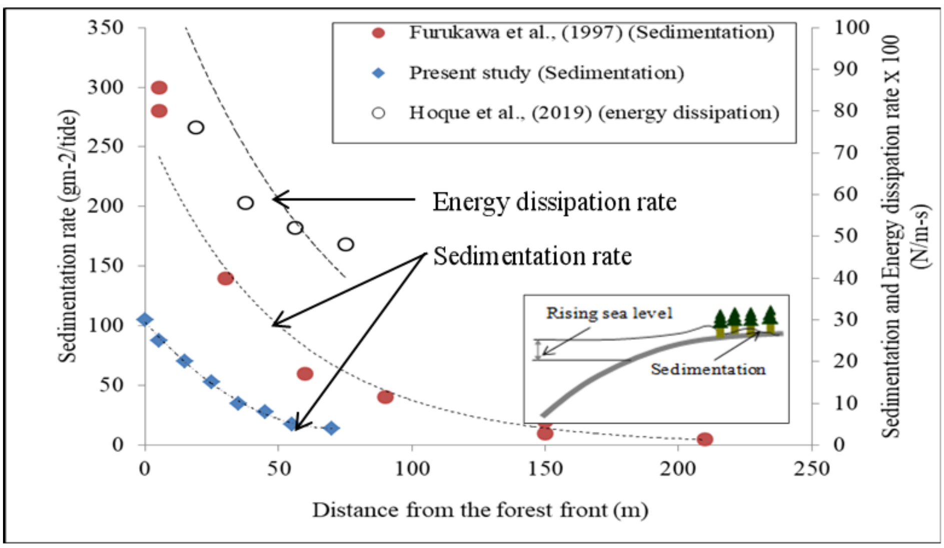

Figure 10. Study area's Sediment deposition within mangrove forests [38].

Figure 11 demonstrates that sediment accretion rates are strongly correlated with fluctuations in sea level. The equilibrium between sediment accretion and sea-level rise dictates the long-term stability and resilience of these ecosystems. Field surveys were conducted at Reju Khal to gather data along the river embankment of the Matamuhuri River in Cox's Bazar, Bangladesh, to examine the correlation between sea-level rise and sediment deposition. Conversely, Alongi [8] demonstrated that the graph depicting empirical measurements of accretion rate vs. regional mean sea-level rise revealed that average sedimentation rates exceeded the mean sea-level rise rate.

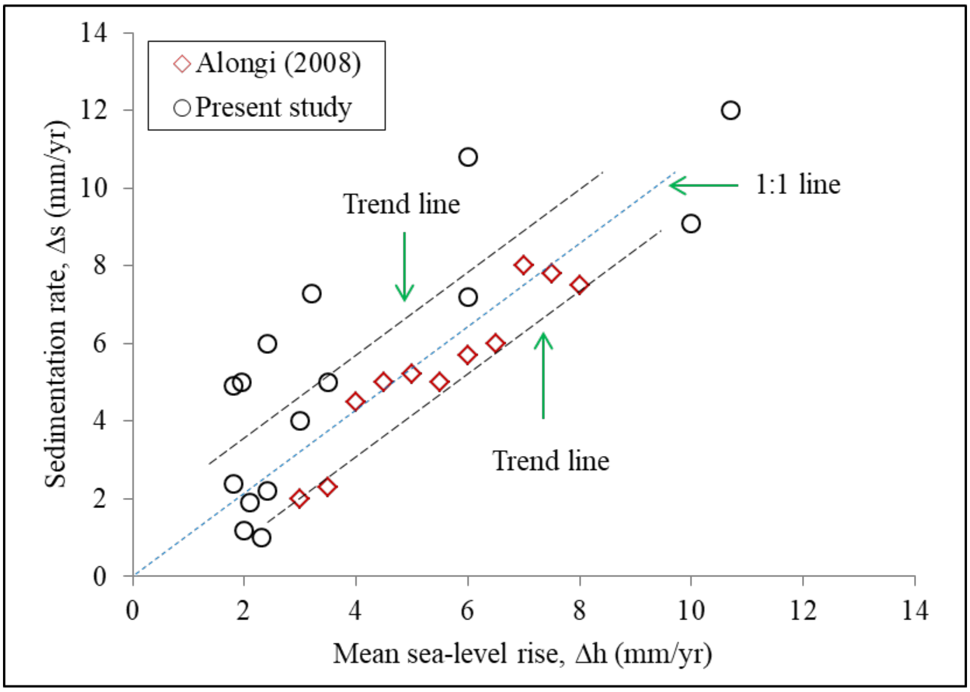

Figure 11. Study area at Reju Khal featuring mangrove forests and relationship between sea-level rise and sedimentation rates induced by the forests.

4. Discussion

The effects of climate change on coastal areas, such as sea-level rise, accelerated erosion, and ambiguity regarding erosion-accretion dynamics, have been thoroughly established [79,80]. These hazards have elicited considerable apprehension about the susceptibility of coastal regions. Nonetheless, not all research concurs on the magnitude of these concerns. Hassan et al. [36] posited that, in specific coastal areas of Bangladesh, land gain could exceed land loss, hence contesting the prevalent perception of extensive land loss attributed to coastal erosion. Bangladesh's coastline area had a net land gain of roughly 3,892 km^2, underscoring the intricacies of coastal dynamics and the necessity for a sophisticated comprehension from 1976 to 2016 [79]. Climate change and elevated sea levels have significantly contributed to the increased susceptibility of low-lying regions to inundation. Moreover, human activities, including unregulated coastal development and deforestation, have disrupted the sediment equilibrium, resulting in accelerated erosion [81]. Sandwip, which previously underwent considerable land accretion, especially in the eastern area, has since 2000 faced a pronounced transition to severe erosion, resulting in massive land loss and the displacement of coastal populations.

Mangrove forests are likely to be greatly affected by climate change because they are located in the dynamic intertidal zone. People talk a lot about how mangroves react to rising sea levels, but this ecosystem is also affected by a lot of other climate change stressors. These include more storms and waves, more unpredictable and dynamic rainfall patterns, and higher temperatures in the air and on the sea surface, especially at their latitudinal limits [82].

This study offers a comprehensive examination of erosion and accretion rates in southwestern Bangladesh, indicating a lack of significant evidence for considerable displacement hazards associated with these phenomena. It is essential to acknowledge that the geological processes of the region, such as weathering and erosion, necessitate more examination to evaluate their long-term consequences. Weathering, whether biological, chemical, or physical, significantly influences the formation of coastal landforms by disintegrating rocks in situ. Chemical weathering transpires when rainfall interacts with minerals in rocks, modifying their composition. Erosion entails the displacement of rock particles caused by factors such as wind, water, or ice. Weathering and erosion profoundly influence the formation of landforms, including mountains, valleys, and plains. Weathering significantly contributes to land formation, and climate change surely affects erosion and accretion patterns.

This study examined the relationship between rainfall, temperature, and the erosion-accretion cycle, emphasizing an indirect correlation among these climatic parameters and coastal dynamics. This association supports the findings of Hassan et al. [36], who identified evidence of land acquisition along the southwest coast of Bangladesh. The data in this study corroborate these findings, indicating that erosion-accretion dynamics are more intricate than previously believed, with specific areas exhibiting net land gain instead of land loss.

The present study investigated sediment deposition associated with sea-level rise and the function of mangrove forests in sediment retention. Different studies [75–78] indicate that mangroves may find it challenging to adapt to increasing sea levels in environments with insufficient sediment supply, such as low-lying islands. Conversely, Sikder et al. [79] suggested that mangroves in these habitats may acclimatise to elevated rates of sea-level rise. In specific protected coastal regions, the flooding of low-lying areas may result in the gradual proliferation of mangroves due to increasing sea levels [70]. Sovacool et al. [80] analyzed the relationship between land use/cover [LULC] changes and land surface temperature [LST] over two decades using remote sensing. It found significant impacts of LULC changes on LST, with built-up areas often showing increased temperatures and reduced green cover, leading to thermal issues. The research uses remote sensing data to map these changes and quantify their thermal impact, offering insights for sustainable land management and planning. They found that a reduction in green cover [vegetation] has been linked to a decrease in thermal comfort and increased surface temperatures.

Our research indicates that sediment traps positioned in the mangrove pioneer zone documented the highest sediment deposition rates. The elevated sedimentation rate is probably attributable to the significant decrease in current velocity on the mudflats, promoting sediment accumulation. The findings indicate that densely vegetated mangrove regions serve as sustainable sediment deposition zones, whereas the pioneer zone is characterized by dynamic fluctuations between high sedimentation and erosion phases. This indicates that mangrove forests are vital for sediment retention, which may be critical for the preservation of low-lying coastal regions such as Bangladesh, where storm surges are prevalent.

For the past 30 years, natural processes and human activities have worked together to create a complicated pattern of erosion and accretion on Sandwip, Kutubdia islands, including coastal areas of the South-Eastern Coast of Bangladesh. The study of changes along the coastline found that the western and southern parts of the shoreline eroded, while the eastern and northern areas showed more accretion from 1990 to 2023. The fact that erosion is so common on the coastal islands means that the ecology and local residents will continue to be at risk. To protect the livelihoods of the people of coastal areas and stop further land loss, it is important to use sustainable coastal management practices. These include planting mangroves in specific areas, strengthening erosion hotspots, restoring dunes, efficiently allocating resources for coastline restoration to the most important areas, managing sediment, and coming up with strategies for adapting to climate change. The erosion-accretion findings also assist in making sure that conservation and restoration programs are founded on facts, such as encouraging cooperation between local governments and international organizations [82–85]. The results of this study, albeit contextual, hold significant implications for coastal management in low-lying regions susceptible to storm surges. The interplay of sediment deposition, sea-level rise, and mangrove dynamics indicates that coastal ecosystems can significantly mitigate the effects of climate change. Nonetheless, ongoing surveillance and additional research are essential to comprehensively comprehend how these ecosystems might be utilized to safeguard at-risk coastal areas [86,87]. This study provides essential data to support the formulation of sustainable plans for managing the coastal dynamics of Bangladesh, especially regarding climate change and its related concerns. Alam et al. [4] found a significant increase in land surface temperature correlated with ongoing coastal infrastructure development in the region's mangrove ecosystem. The research highlights how the interruption of mangrove vegetation by development leads to a rise in temperatures, suggesting potential long-term environmental consequences for the South-Eastern Coast of Bangladesh. The present study explored that the study area directly influences and increases land surface temperature within the mangrove ecosystem. The study connects this temperature increase to the disruption of the mangrove vegetation caused by infrastructure development.

Vegetation in the mangrove forests of the South-Eastern coast of Bangladesh is steadily disappearing as the area becomes more built up, and the temperature of the land surface keeps rising over the years. They identified a robust positive link between Normalized Difference Built-up Index (NDBI) and Land surface temperature (LST), alongside a negative correlation between normalized-difference vegetation index (NDVI) and LST. Additionally, the constructed areas have a considerable impact on the vegetative cover of the Salimpur mangrove forest [88–90]. The relationship between built-up areas and vegetation cover was very negative. This means that when NDBI goes up, NDVI goes down, and as NDBI goes down, NDVI goes up. The present study assists coastal planners in comprehending the local context and formulating sustainable strategies for urban and vegetation management to equilibrate surface temperature.

5. Conclusions

This study shows that there is no strong link between the daily time series of rainfall and temperature in the south-eastern coastal area of Bangladesh. There isn't a substantial link between maximum, minimum, and average temperatures and meaningful rain. But when you use the moving average method and look at the difference between maximum and minimum temperatures, you find a moderate link of about 0.75. The disparities in these connections show that the climate is less stable on the islands than on the mainland. The calculated correlation patterns show that the climates in Chattogram, Cox's Bazar, Teknaf, Sitakund, and Feni on the mainland are very similar. On the other hand, coastal places like Kutubdia, Sandwip, and Maheskhali have climates that act a little differently, as seen by the differing correlation estimates. The results show that we need to quickly come up with good ways to manage the coast to stop erosion in places like Kutubdia that are at risk. Planting mangroves, strengthening embankments, and using nature-based solutions can all help stop land loss. Also, for a better understanding of long-term coastal stability, it is important to keep an eye on how sedimentation changes over time. This work is important because it helps us learn more about how the climate changes, how erosion happens, and how sedimentation happens in Bangladesh's coastal zone. These discoveries are very important for politicians, environmental planners, and researchers who are looking for ways to make coastal areas more resilient and adaptable. You can also use the same methods in this study to look at how the coast changes in other parts of the world. More research is needed to understand the geological processes in the area. Maheskhali, a port city, is a good place to live because of its climate and land qualities. This technique is simple and can be used to look at how land erosion and accretion affect coastal areas in other parts of the world.

Researchers should look at modelling sediment transport systems with high resolution, long-term changes in climate, and changes made by people that affect the stability of the coast. Adding the social and economic effects of land loss and gain to the analysis will give us a better idea of how vulnerable the coast is. Also, it will be important to keep an eye on mangrove ecosystems all the time to see how well they work at stabilizing sedimentation over time as the climate changes.

Recommendations

To lessen the bad effects of erosion, adaptive methods like artificial reefs, embankments, or reforestation should be looked into. Policies on sustainable development and land use could also help keep things from getting worse. The results also show that the south-eastern coastal island needs full monitoring procedures to keep track of and predict changes in its shape in the future. Some examples are using remote sensing technology, GIS, and hydrodynamic models to make predictions more accurate and help policymakers decide what to do. As climate change becomes a bigger danger, it will be important to focus on long-term environmental stability and resilience for coastal islands and adjacent places by using sustainable coastal management and adaptive measures.

Adding trees to a sturdy embankment helps minimize erosion by making the ground more stable with more root systems and adding a layer of protection against rain and runoff. When designing and building embankments, it is vital to think about the natural flow patterns and environmental circumstances. It is also important to keep them in good shape so that they work well over time. Adding other things like sustainable land management techniques, bioengineering of riverbanks, and sediment management can make erosion control initiatives even better and help the health of river ecosystems as a whole.

To protect the livelihoods of coastal inhabitants and stop more land loss, it is important to use sustainable coastal management practices. These include planting mangroves in specific areas, strengthening erosion hotspots, restoring dunes, allocating resources efficiently for coastline restoration to the most important areas, managing sediment, and adapting to climate change. The erosion-accretion findings also help make sure that decisions about conservation and restoration programs are based on facts. This includes encouraging cooperation between local government and international organization partners.

Author Contributions

P.B. was responsible for conceptualization the research, literature review, methodology framework and data analysis. N.N. was responsible for manuscript writing, editing the manuscript. Both authors have read and agreed to the published version of the manuscript.

Funding

This research has no funding opportunities.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data will be made available upon request.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Abedin, M.A.; Collins, A.E.; Habiba, U.; et al. Climate Change, Water Scarcity, and Health Adaptation in Southwestern Coastal Bangladesh. *Int. J. Disaster Risk Sci.* **2019**, *10*, 28–42.
2. Agrawala, S.; Ota, T.; Ahmed, A.U.; et al. Development and Climate Change in Bangladesh: Focus on Coastal Flooding and the Sundarbans. In *Organ. for Eco. Co-operation and Devel. (OECD) Report*; OECD: Paris, France, **2003**; pp. 1–49.
3. Ahasan, M.; Chowdhary, N.; Quadir, D. Variability and Trends of Summer Monsoon Rainfall over Bangladesh. *J. Hydro. Met.* **2021**, *15*, 1–17.
4. Alam, H.M.E.; Alam, M.W.; Hoque, M.E.; et al. The Impact of Coastal Development on Land Surface Temperature in the Mangrove Ecosystem of the Chattogram Coast in Bangladesh. *J. Coast. Cons.* **2022**, *26*, 23–33.
5. Langat, P.K.; Ghosh, M.K.; Roy, C.; et al. Mapping Coastal Dynamics Induced Land Use Change in Sandwip Island, Bangladesh. *Remote Sens.* **2024**, *16*, 4686.
6. Ahmed, T.; Jin, H.G.; Baik, J.J. Spatiotemporal Variations of Precipitation in Bangladesh Revealed by Nationwide Rain Gauge Data. *Asia-Pac. J. Atmos. Sci.* **2020**, *56*, 593–602.
7. Haque, A.; Nicholls, R.J. Floods and the Ganges-Brahmaputra-Meghna Delta. In *Ecosystem Services for Well-Being in Deltas*; Nicholls, R., Hutton, C., Adger, W., et al., Eds.; Palgrave Macmillan: Cham, Switzerland, 2018; pp. 147–159.
8. Alongi, D.M. Mangrove Forests: Resilience, Protection from Tsunamis, and Responses to Global Climate Change. *Estuar. Coast. Shelf Sci.* **2008**, *76*, 1–13.
9. Barua, P.; Barua, C. Women's Livelihood Vulnerability in the Light of Climate Change Effects in the Coastal Areas of Bangladesh. *Int. J. Eng. Env. Econ.* **2024**, *31*, 1–20.
10. Barua, P.; Mitra, A. Climate Resilience Aquaculture Development for Achieving Sustainable Development Goals. *Int. J. Energy Eng. Econ.* **2024**, *31*, 24–44.

11. Chowdhury, S.; Barua, P. Assessing the Climate-Induced Livelihood Vulnerability of Coastal People Using the Sustainable Livelihood Framework of Bangladesh. *Int. J. Eng. Env. Econ.* **2024**, *32*, 125–140.
12. Asian Development Bank. *Bangladesh: Climate Risk Country Profile*; Asian Development Bank: Washington, DC, USA, **2021**.
13. Bernard, A.; Mercier, D.; Huq, S. Bangladesh's Vulnerability to Cyclonic Coastal Flooding. *Nat. Haz. Earth Syst. Sci.* **2022**, *22*, 729–746.
14. Box, G.E.; Jenkins, G.M.; Reinsel, G.C.; et al. *Time Series Analysis: Forecasting and Control*, 5th ed.; John Wiley & Sons: Hoboken, NJ, USA, 2015.
15. Brammer, H. *The Geography of Soils of Bangladesh*; University Press Limited: Dhaka, Bangladesh, 1996.
16. Brammer, H. Bangladesh's Dynamic Coastal Regions and Sea-Level Rise. *Climate Risk Manag.* **2014**, *1*, 51–62. [CrossRef]
17. Brockwell, P.J.; Davis, R.A. *Introduction to Time Series and Forecasting*; Springer: New York, NY, USA, 2002.
18. Buishand, T.A.; Brandsma, T. Dependence of Precipitation on Temperature at Florence and Livorno (Italy). *Clim. Res.* **1999**, *12*, 53–63.
19. Barua, P.; Eslamian, S. Consequences of Coastal Erosion, Displacement and Community Relocation. In *Handbook of Climate Change Impacts on River Basin Management: Case Studies*; Eslamian, S., Bintul Huda, M., Ahmad Rather, N., et al., Eds.; CRC Press: Boca Raton, FL, USA, 2024; pp. 300–312.
20. Chatfield, C. *The Analysis of Time Series: An Introduction*, 6th ed.; Chapman and Hall/CRC: New York, NY, USA, 2003; pp. 1–352.
21. Chowdhury, M.R. The El Niño-Southern Oscillation (ENSO) and Seasonal Flooding – Bangladesh. *Theor. Appl. Climatol.* **2024**, *90*, 105–124.
22. Cloetingh, S.; Burov, E. Lithospheric folding and sedimentary basin evolution: a review and analysis of formation mechanisms. *Basin Res.* **2011**, *23*, 257–290.
23. Dehghan Rahimabadi, P.; Liu, B.; Azarnivand, H.; et al. The Nexus between Land Use/Cover Changes and Land Surface Temperature: Remote Sensing Based Two-Decadal Analysis. *J. Arid Env.* **2024**, *225*, 105–130.
24. Easterling, D.R.; Horton, B.; Jones, P.D. Maximum and Minimum Temperature Trends for the Globe. *Science* **1997**, *277*, 364–367.
25. Eckstein, D.; Künzel, V.; Schäfer, L.; et al. *Global Climate Risk Index 2020*; Germanwatch eV: Bonn, Germany, 2019; pp. 1–42.
26. Ellison, J.C. Mangrove Retreat with Rising Sea Level, Bermuda. *Estuar. Coast. Shelf Sci.* **1993**, *37*, 75–87.
27. Ferdous, M.G.; Baten, M.A. Climatic Variables of 50 Years and Their Trends over Rajshahi and Rangpur Division. *J. Environ. Sci. Nat. Resour.* **2012**, *4*, 147–150.
28. Furukawa, K.; Wolanski, E.; Mueller, H. Currents and Sediment Transport in Mangrove Forests. *Estuar. Coast. Shelf Sci.* **1997**, *44*, 301–310.
29. Friess, D.A.; Chen, L.; Cormier, N.; et al. Mangrove Forests and Climate Change: Impacts and Interactions. In *Climate Change and Estuaries*; Kennish, M.J., Pearl, H.W., Crosswell, J.R., Eds.; CRC Press, Taylor & Francis Group: Boca Raton, FL, USA, 2023; pp. 381–400. [CrossRef]
30. Ghosh, M.; Kumar, L.; Roy, C. Climate Variability and Mangrove Cover Dynamics at Species Level in the Sundarbans, Bangladesh. *J. Sustainability* **2017**, *9*, 805.
31. Hamrick, A.M.; Martijn, H.H. Fifty Years' Weather in Kansas, MO, 1889-1983. *Mon. Wea. Rev.* **1941**, *44*, 53.
32. Hasan, M. Impacts of Climate Change on Coastal Bangladesh: Accretion and Erosion Trends. *Earth Sci. Rev.* **2016**, *159*, 47–59.
33. Hossain, M.S.; Yasir, M.; Wang, P.; et al. Automatic Shoreline Extraction and Change Detection: A Study on the Southeast Coast of Bangladesh. *Mar. Geol.* **2021**, *441*, 106–126.
34. Hasan, M. Land Mass Change along the Bangladesh Coastline. The University of Texas at Austin, Austin, TX, USA, 2016.
35. Hasan, M.; Matin, N. Estimation of Areal Changes along the Coastline of Bangladesh due to Erosion and Accretion. *Int. J. Eng. Sci.* **2019**, *2*, 111–117.
36. Hassan, S.M.T.; Syed, M.A.; Mamnun, N. Estimating Erosion and Accretion in the Coast of Ganges-Brahmaputra-Meghna Delta in Bangladesh. In *Proceedings of the 6th International Conference on Water and Flood Management (ICWFM 2017)*, Dhaka, Bangladesh, 4–6 March 2017; pp. 115–124.
37. Hauke, J.; Kossowski, T. Comparison of Values of Pearson's and Spearman's Correlation Coefficients on the Same Sets of Data. *Quaest. Geograph.* **2011**, *30*, 87–93.
38. Hoque, A.; Kumar, D.; Paul, A.K.; et al. Sedimentation in Dune Forests, Mangrove Forests and CC Block System and Associated Topographic Changes. *J. Bangladesh Acad. Sci.* **2019**, *30*, 45–67.

39. Hoque, M.; Nandi, S.; Ghosh, H. Wind Resource Assessment for Southern Part of Bangladesh. *As. J. Eng. Env.* **2016**, *11*, 1–9.
40. Houghton, J. *Global Warming*, 1st ed.; Cambridge University Press: New York, NY, USA, 2009.
41. Barua, P.; Rahman, S.H.; Mitra, A. Coastal Erosion Pattern and Rehabilitation of Climate Displaced Communities of 3 Coastal Islands in and Around the South-Eastern Coast of Bangladesh. *Glob. J. Earth Sci. Eng.* **2024**, *11*, 68–100.
42. Hu, S.; Karim, Z.; Asaduzzaman, M.; et al. *Vulnerability and Adaptation to Climate Change for Bangladesh*; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1999.
43. Hyndman, R.J.; Athanasopoulos, G. *Forecasting: Principles and Practice*, 3rd ed.; OTexts: Melbourne, Australia, 2018.
44. Islam, M.J.; Abdullah, M.S.; Alam, M. Flooding Crisis in Bangladesh: Urgent Measures Required. *Biodiversity* **2024**, *25*, 95–98. [CrossRef]
45. Islam, M.N.; Tamanna, S.; Noman, M.; et al. Climate Change Impact and Adaptation Strategies in Bangladesh to Strengthen Regional Cooperation. In *Bangladesh II: Climate Change Impacts, Mitigation and Adaptation in Developing Countries*; Springer Climate: Cham, Switzerland, 2021; pp. 421–458.
46. Islam, M.R.; Shamsuddoha, H. Socioeconomic Consequences of Climate Induced Human Displacement and Migration in Bangladesh. *Int. J. Sociol.* **2017**, *32*, 277–298.
47. Jihan, M.A.T.; Popy, S.; Kayes, S. Climate Change Scenario in Bangladesh: Historical Data Analysis and Future Projection Based on CMIP6 Model. *Sci. Rep.* **2025**, *15*, 7856–7870.
48. Khan, E.; Hussain, N. Coastline Dynamics and Raising Landform: A Geo-Informatics Based Study on the Bay of Bengal, Bangladesh. *Indonesia J. Geogr.* **2018**, *50*, 41–48.
49. Kreyling, J.; Beier, C. Complexity in Climate Change Manipulation Experiments. *Bioscience* **2013**, *63*, 763–767.
50. Latif, M.; Roeckner, E.; Botzet, M.; et al. Reconstructing, Monitoring, and Predicting Multidecadal-Scale Changes in the North Atlantic Thermohaline Circulation with Sea Surface Temperature. *J. Clim.* **2024**, *27*, 1605–1614.
51. Li, Z.; Xue, Y.; Fang, H. Modulation of Environmental Conditions on the Significant Difference in the Super Cyclone Formation Rate During the Pre- and Post-Monsoon Seasons Over the Bay of Bengal. *Clim. Dynam.* **2021**, *57*, 2811–2822.
52. Madden, R.A.; Williams, J. The Correlation between Temperature and Precipitation in the United States and Europe. *Mon. Wea. Rev.* **1978**, *106*, 142–147. [CrossRef]
53. Mallick, M. Cyclone Shelters and Their Locational Suitability: An Empirical Analysis from Coastal Bangladesh. *Dis. Mang.* **2022**, *58*, 654–671.
54. MOEF. *National Adaptation Programme of Action*; Ministry of Environment and Forest, Government of the People's Republic of Bangladesh: Dhaka, Bangladesh, 2005.
55. Mondal, M.S.; Jalal, M.R.; Khan, M.; et al. Hydro-Meteorological Trends in Southwest Coastal Bangladesh: Perspectives of Climate Change and Human Interventions. *Amer. J. Clim. Change* **2013**, *2*, 62–70.
56. Pandey, P.K.; Das, L.; Jhajharia, D.; et al. Modelling of Interdependence Between Rainfall and Temperature Using Copula. *Mod. Earth Syst. Environ.* **2018**, *4*, 867–879.
57. Parkinson, R.W.; DeLaune, R.D.; White, J.C. Holocene Sea-Level Rise and the Fate of Mangrove Forests Within the Wider Caribbean Region. *J. Coast Res.* **1994**, *10*, 1077–1086.
58. Rahman, M. Governance Matters: Climate Change, Corruption, and Livelihoods in Bangladesh. *J. Cli. Cha.* **2018**, *147*, 313–326.
59. Rahman, S.M.; Ahmad, M.M.; Alam, M.S. From Strategy to Execution: The Case of Local Climate Fund in Bangladesh. *Int. J. Environ. Policy Dec. Making* **2016**, *2*, 1–18.
60. Rahman, S.M.; Ahmed, N.; Hasan, M. Rainfall-Temperature Nexus in Southeast Bangladesh: Impacts on Coastal Erosion. *J. Clim. Stud.* **2023**, *47*, 120–135.
61. Rahman, S.M.; Rahman, M.A.; Sultana, R.; et al. Rainfall-Temperature Nexus Over the Mainland and Islands in Southeast Bangladesh. *Dew-Drop* **2023**, *9*, 81–91.
62. Rakib, Z.B. Extreme Temperature Climatology and Evaluation of Heat Index in Bangladesh During 1981–2010. *J. Presi Univ.* **2013**, *2*, 84–95.
63. Rashid, H.E. *Geography of Bangladesh*, 2nd ed.; University Press Ltd.: Dhaka, Bangladesh, 1991.
64. Siegel, S.; Castellan, N.J. *Nonparametric Statistics for the Behavioral Sciences*, 2nd ed.; McGraw-Hill: New York, NY, USA, 1988.
65. Rehfeld, K.; Laepple, T. Warmer and Wetter or Warmer and Dryer? Observed Versus Simulated Covariability of Holocene Temperature and Rainfall in Asia. *Earth Planet. Sci. Lett.* **2016**, *436*, 1–9.

66. Reinhardt, L.; Jerolmack, D.J.; Cardinale, B.J. Dynamic Interactions of Life and Its Landscape: Feedbacks at the Interface of Geomorphology and Ecology. *Earth Surf. Proc. Landf.* **2010**, *35*, 78–101.
67. Richmond, B.M.; Mieremet, B.; Reiss, T.E. Yap Islands Natural Coastal Systems and Vulnerability to Potential Accelerated Sea-Level Rise. *J. Coast Res.* **1997**, *24*, 153–173.
68. Rouf, M.; Uddin, M.; Debsarma, S.; et al. Climate of Bangladesh: An Analysis of Northwestern and Southwestern Part Using High Resolution Atmosphere-Ocean General Circulation Model (AOGCM). *J. Agric.* **2012**, *9*, 143–154.
69. Roy, B.; Penha-Lopes, A.G.P.; Uddin, M.S.; et al. Sea Level Rise Induced Impacts on Coastal Areas of Bangladesh and Local-Led Community-Based Adaptation. *Int. J. Dis. Risk Reduct.* **2022**, *73*, 102905.
70. Saenger, P.; Siddiqi, N.A. Land from the Sea: The Mangrove Afforestation Program of Bangladesh. *Ocean Coast. Manag.* **1993**, *20*, 23–39.
71. Saha, C.K. Dynamics of Disaster-Induced Risk in Southwestern Coastal Bangladesh: An Analysis on Tropical Cyclone Aila 2009. *Nat. Hazards* **2015**, *75*, 727–754.
72. Sammonds, P.; Shamsudduha, M.; Ahmed, B. Climate Change Driven Disaster Risks in Bangladesh and Its Journey Towards Resilience. *J. Br. Acad.* **2021**, *9*, 55–77.
73. Shahid, S. Rainfall Variability and the Trends of Wet and Dry Periods in Bangladesh. *Int. J. Climatol.* **2010**, *30*, 2299–2313.
74. Shahid, S. Trends in Extreme Rainfall Events of Bangladesh. *Theor. Appl. Climatol.* **2011**, *104*, 489–499.
75. Shahid, S.; Bin, H.; Katimon, K. Changes in Diurnal Temperature Range in Bangladesh During the Time Period 1961–2008. *Atmos. Res.* **2012**, *128*, 260–270.
76. Shahid, S.B.; Gani, M.R.; Gani, N.D. 32 Years of Changes in River Paths and Coastal Landscape in Bangladesh, Bengal Basin. *J. Sedi. Environ.* **2024**, *9*, 1035–1053.
77. Sheskin, D.J. *Handbook of Parametric and Nonparametric Statistical Procedures*, 3rd ed.; Chapman and Hall/CRC: New York, NY, USA, 2003.
78. Wolanski, E.; Nhan, N.H.; Spagnol, S. Sediment Dynamics During Low Flow Conditions in the Mekong River Estuary, Vietnam. *J. Coast Res.* **1998**, *14*, 472–482.
79. Sikder, M.; Baqee, H.; Begum, S. *Bangladesh II: Climate Change Impacts, Mitigation and Adaptation in Developing Countries*; Islam, M.N.; van Amstel, A., Eds.; Springer: Cham, Switzerland, 2021.
80. Sovacool, B.K.; D'Agostino, A.L.; Rawlani, A.; et al. Improving Climate Change Adaptation in Least Developed Asia. *Environ. Sci. Policy* **2012**, *21*, 112–125.
81. Subash, N.; Sikka, A.K. Trend Analysis of Rainfall and Temperature and Its Relationship Over India. *Theor. Appl. Climatol.* **2014**, *117*, 449–462.
82. Barua, P.; Rahman, S.H.; Mitra, A.; et al. Review on Coastal Erosion, Displacement and Resettlement Strategies of South Asian Countries. *Glob. J. Env. Eng.* **2020**, *7*, 52–72.
83. Ratna, F.; Hoque, E.; Barua, P.; et al. Trends of Climatic Parameters and Resilience Practices of Climate Displaced People of Southern Coast of Bangladesh. *Earth Sci. Malays.* **2022**, *6*, 103–113.
84. Vidal, J. Sea Change: The Bay of Bengal's Vanishing Islands. Available online: https://www.theguardian.com/global-development/2013/jan/29/sea-change-bay-bengal-vanishing-islands (accessed on 15 June 2025).
85. Woodroffe, C.D. *Coasts: Form, Process and Evolution*; Cambridge University Press: Cambridge, UK, 2002.
86. World Bank. *Floods in Bangladesh: Damage and Needs Assessment and Proposed Recovery Program*; World Bank Group: Washington, DC, USA, 2004.
87. World Bank. Bangladesh: Enhancing Coastal Resilience in a Changing Climate (English). Available online: http://documents.worldbank.org/curated/en/099552209012279085 (accessed on 15 June 2025).
88. Zar, J.H. Significance Testing of the Spearman Rank Correlation Coefficient. *J. Amer. Stat. Assoc.* **1972**, *67*, 578–580.
89. Zhao, W.; Khalil, M.A.K. The Relationship Between Precipitation and Temperature Over the Contiguous United States. *J. Clim.* **1993**, *6*, 1232–1236.
90. Zhou, L.; Dickinson, R.E.; Dirmeyer, P.A. Spatiotemporal Patterns of Changes in Maximum and Minimum Temperatures in Multi-Model Simulations. *Geophys. Res. Lett.* **2009**, *36*, L02702.