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| RESEARCH ARTICLE

Modeling Relative Sea-Level Rise through Geodetic-Hydrodynamic Fusion: Quantifying Multi-Sectoral Risks in the Bengal Delta

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| ABSTRACT

The Bengal Delta, one of the world's most dynamic and densely populated coastal systems, faces accelerating relative sea-level rise (RSLR) driven by complex interactions among eustatic rise, land subsidence, sediment compaction, and anthropogenic stress. This study develops an integrated geodetic-hydrodynamic modeling framework to quantify multi-sectoral risks arising from RSLR and to provide a data-driven foundation for adaptive coastal resilience planning. High-resolution InSAR and GNSS observations were combined with tide-gauge and hydrodynamic models to produce spatially explicit subsidence-adjusted RSLR projections under multiple climate scenarios. Monte Carlo ensembles and sensitivity analyses were applied to assess uncertainty in hydrodynamic responses, inundation dynamics, and salinity intrusion. Results indicate spatially variable subsidence rates ranging from 2.1 to 6.5 mm yr^{-1}, amplifying effective RSLR to 3.8-8.9 mm yr^{-1} across the deltaic plain. By mid-century, permanent inundation is projected to expand by 24-42%, while salinity intrusion may penetrate up to 90 km inland during the dry season under high-emission scenarios. Agricultural productivity, ecosystem integrity, freshwater availability, and rural livelihoods emerge as the most vulnerable sectors. Sectoral exposure mapping reveals critical infrastructure and cropland losses concentrated in the south-central polders and estuarine tracts. This integrated geodetic-hydrodynamic fusion framework demonstrates that deltaic vulnerability cannot be explained by eustatic sea-level rise alone but results from the compounded effects of geophysical subsidence and hydrodynamic forcing. The study underscores the urgency of dynamic adaptation strategies- such as sediment management, adaptive land use zoning, and ecosystem-based coastal protection- to enhance resilience in climate-vulnerable mega deltas. The methodology offers a transferable blueprint for quantifying and managing RSLR-induced risks in other subsiding coastal systems worldwide.

| KEYWORDS

Bangladesh, Bengal Delta, Climate Change Adaptation, Coastal Subsidence Modeling, Deltaic Vulnerability Modeling, Geodetic-Hydrodynamic Modeling, InSAR, Relative Sea-Level Rise (RSLR), Vulnerability Assessment.

| ARTICLE INFORMATION

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1. Introduction

Over the past few decades, there has been a significant change in the global climate. A big and important development that has happened globally is the rise in sea levels. One obvious indicator of climate change is the present global sea level rise, which highlights the complex interactions between many natural elements. Since 1950, rising temperatures, the melting of polar ice sheets and glaciers, and the expansion of saltwater have all contributed to a significant increase in the mean sea level throughout the world's oceans. This thorough analysis of the overall sea level rise scenario during the previous 70 years will explore pivotal moments, contributory variables, and the far-reaching effects of this upward trend. Sea level rise is a worldwide problem that will have a substantial impact on coastal populations, ecosystems, and the long-term viability of our planet, according to scientific data and estimates.

Sea level is rising. This rise is now a clear signal of human-driven climate change. Global mean sea level has increased by about twenty-one to twenty-four centimeters since 1880. The rise has accelerated in recent decades because the ocean warmed and land ice melted. The Intergovernmental Panel on Climate Change states that thermal expansion and ice loss from glaciers and ice sheets are the dominant drivers of observed sea level change. See the IPCC assessment for detailed attribution and process-level evidence (Climate Change 2021: The Physical Science Basis, 2021). The satellite era gives a clear recent record. The annual average sea level reached the highest value in the satellite record in 2023. That value is about one hundred one millimeters above the 1993 reference. This observation shows both a long-term trend and episodic accelerations. The NOAA summary explains the satellite record and the record high seen in 2023 (Climate Change: Global Sea Level, 2023). Future sea level depends on how much warming occurs and how ice sheets respond. The IPCC provides scenario-based projections that extend to the year 2150. Under higher warming scenarios, the probability of multi-decimeter to meter scale rises this century increases. The IPCC also highlights deep uncertainty from potential rapid ice sheet loss. This uncertainty matters because it changes the range of plausible outcomes and the time horizon for adaptation (Climate Change 2021: The Physical Science Basis, 2021).

Bangladesh faces acute risk from global and local sea level rise. Bangladesh is low-lying and densely populated. Many coastal districts sit at only a few meters above the present sea level. Country-level analyses and the World Bank climate risk profile show that sea level rise of about one meter by 2100 is within the plausible range for high emission scenarios. This magnitude would inundate large coastal areas and place millions of people at high risk of loss of land, fresh water salinization, and displacement (Bangladesh BGD - Projections | Climate Change Knowledge Portal, 2025).

The Sundarbans and coastal ecosystems are already changing. Rising water and increasing salinity stress mangrove forests and biodiversity. UNESCO reporting on the Sundarbans documents higher salinity and water-related threats that connect directly to sea level change and to reductions in freshwater flow. Loss of these ecosystems will remove a major natural buffer against storm surge and will worsen the social impacts for coastal communities (UNESCO World Heritage Centre, 2021). The implications are both physical and social. Physically, there will be greater coastal erosion, deeper storm surge, and more chronic inundation of the lowland. Socially, there will be threats to agriculture, drinking water, livelihoods, and health. Governments and planners cannot treat this as a distant problem. The science shows that substantial sea level rise is already locked in for decades. That fact makes near-term adaptation and stronger mitigation urgent to reduce risks and to buy time for planned responses. The IPCC and national assessments both call for integrated action that pairs emission reduction with large-scale adaptation and finance for vulnerable countries (Climate Change 2021: The Physical Science Basis, 2021).

This paper brings these strands together. It synthesizes recent observations and projections. It examines physical drivers, regional projections for Bangladesh, and likely impacts on ecosystems and people. It also evaluates current adaptation options and the governance and finance gaps that limit their reach. The goal is to provide a clear, evidence-based entry point for policymakers and researchers who must decide on investments now to reduce risks later. Where possible, the paper uses the latest publicly available projections and authoritative assessments to ground conclusions and recommendations.

2. Literature Review

Global sea level rise is a clear and quantified signal of recent climate change. The global mean sea level has increased about twenty-one to twenty-four centimeters since 1880. The rise accelerated after the late twentieth century because the ocean warmed and land ice diminished. The Intergovernmental Panel on Climate Change documents the observed trends and the main physical processes that drive sea level change. See the IPCC chapter on ocean, cryosphere, and sea level change for process-level evidence and attribution (Fox-Kemper et al., 2021). Satellite altimetry and tide gauge records now give a consistent picture of recent acceleration. The satellite record since 1993 shows rising annual averages and new record highs in the early 2020s. The annual average global sea level reached about one hundred and one millimeters above the 1993 reference in the early 2020s. This independent satellite evidence confirms the long-term trend found in tide gauges and reveals recent accelerations that are tied to ocean heat uptake and ice loss (Climate Change: Global Sea Level, 2023). Ice sheet mass loss now dominates uncertainty about how high the sea level will rise this century. Greenland and Antarctica contributed little to the sea level in the early twentieth century. Their contribution rose sharply since the 1990s and then accelerated into the 2010s and 2020s. Satellite gravity and altimetry show sustained net mass loss from both ice sheets. Recent studies identify mechanisms that could produce faster loss than older models assumed. These include marine ice sheet instability, warm water intrusion at grounding lines, and changing subglacial hydrology. These mechanisms widen the upper bound of plausible 21st-century sea level rise and create deep uncertainty for long-range planning (Fox-Kemper et al., 2021). New observations and process studies add urgency to that uncertainty. Satellite gravity data and GRACE results show Antarctica lost roughly one hundred fifty billion tonnes of ice per year from about 2002 to the early 2020s. Greenland also lost a large mass with clear acceleration. These losses translate into measurable, growing contributions to sea level. Recent discoveries, such as pervasive subglacial lakes and evolving grounding zone processes, point to dynamical routes for faster ice retreat than many earlier projections allowed. That knowledge has driven a surge of literature calling for improved ice sheet physics in models and sustained observations near vulnerable glaciers (NASA, 2023).

Regional patterns matter for impacts and planning. Local sea level can differ strongly from the global mean. The differences arise from ocean circulation changes, gravitational and rotational fingerprinting of melting ice, and vertical land movement. These processes mean some coasts face higher relative sea level rise than the global average. For example, steric changes from ocean heat, shifts in the Gulf Stream, and monsoon-related ocean dynamics alter local trends. Practitioners now use regional projections and sea level atlases rather than global averages to estimate local exposure (Fox-Kemper et al., 2021). River deltas face compounded risk because sea level rise combines with local subsidence and altered sediment budgets. Many large deltas, including the Ganges, Brahmaputra Meghna systems, are sinking because of natural compaction and human extraction of groundwater and hydrocarbons. Recent interferometric synthetic aperture radar and GPS studies show measurable subsidence across the Bengal delta and very high subsidence rates in urban fringes. When subsidence is added to the global sea level, the local relative sea level rise can be several times larger. This coupling makes the Bangladesh coastline an acute hotspot for loss of land and infrastructure (Steckler et al., 2021).

Bangladesh is a focus of an expanding empirical literature on exposure, impacts, and adaptation. Country-scale risk profiles show large area and population exposure under high emission futures. Local studies document that a plausible one-meter or greater local rise by 2100 would inundate millions of hectares and displace millions of people if no adaptation occurs. The country faces simultaneous threats from coastal storm surge, river flooding, and salinity intrusion. The literature stresses that the interaction among these processes amplifies impacts on agriculture, freshwater availability, and health (The World Bank Group, 2024). Salinity intrusion into soils and groundwater is a rapidly growing evidence stream for Bangladesh. Long-term monitoring and recent field studies show expanding zones of saline water in coastal aquifers and tidal rivers. The evidence links salinity rises to both sea level rise and reduced upstream freshwater flow. Salt intrusion harms crop yields, changes cropping patterns, and degrades drinking water sources. The literature also records cascading effects: reduced freshwater access pushes households to use riskier water sources, which raises health hazards. Recent hydrogeological studies underline large spatial variation and seasonal spikes in salinity exposure (Meem et al., 2025). Ecosystems, especially the Sundarbans mangrove forest, show measurable stress and contraction in response to combined drivers. UNESCO reporting and national reserve assessments record rising salinity, changed freshwater inflow, and shoreline alteration. The Sundarbans provide protective services against storm surge and support fisheries and livelihoods. When mangrove health declines, coastal communities lose a natural buffer. The literature emphasizes that ecosystem loss increases social vulnerability and raises adaptation costs because engineered defenses must replace services once provided naturally (UNESCO World Heritage Centre, 2021).

Social science research has expanded on how sea level rise shapes livelihoods, health, and migration. New studies document links between chronic salinity, food insecurity, and adverse maternal and child health outcomes. There is growing evidence that routine flooding and salinity lead to repeated income shocks that disproportionately affect women and low-income households. Migration studies show that climate stressors already drive both short-distance seasonal moves and longer-term relocations. The literature frames migration as an adaptation and governance challenge. It highlights the need for a planned relocation policy, social safety nets, and livelihood diversification to reduce harm (Seddiky et al., 2024). Adaptation research finds that no single option solves the compound risks in delta regions. Hard protection, such as seawalls, reduces wave energy and storm surge in the short term. Nature-based solutions, such as mangrove restoration, sequester carbon, preserve biodiversity, and reduce wave height. Water management actions, including managed aquifer recharge and controlled freshwater release, reduce salinity exposure. Many studies argue for integrated portfolios that combine grey, green, and social measures. The literature further notes that maintenance, governance, and long-term funding are essential for success, and that poorly designed hard structures can cause negative downstream effects. (NASA, 2023; Fox-Kemper et al., 2021). Climate finance and governance remain major bottlenecks. Reviews and country profiles show that adaptation finance flows are far below estimated needs for large-scale coastal defense and managed retreat. Barriers include limited absorptive capacity at the local government level, complex application requirements for global funds, and short-term political planning horizons. Scholars call for instruments that link finance to capacity building and to robust project design that safeguards livelihoods. For Bangladesh, the literature often recommends aligning national plans with global mechanisms and scaling community-led solutions with international support (The World Bank Group, 2024).

Modeling and data gaps are an active research frontier. The literature repeatedly asks for better coupling among ice sheet models, ocean circulation models, and high-resolution coastal models that include subsidence, sediment dynamics, and human interventions. Observational gaps include long-term tide-gauge coverage in many deltaic zones, groundwater salinity monitoring networks, and sustained measurements near ice-sheet grounding zones. Recent advances in remote sensing and in situ networks promise progress, but the community stresses that decision-relevant projections require investment in both process science and local monitoring (NASA, 2023; Fox-Kemper et al., 2021).

Synthesis from the recent literature yields clear policy-relevant points. First, deep uncertainty about ice sheet dynamics raises the plausible upper bound for century-scale sea level rise. That uncertainty changes risk calculations and suggests planning for a wider range of outcomes. Second, in delta regions like Bangladesh, the local relative sea level is the sum of global rise plus strong local processes such as subsidence and salinity-driven feedbacks. Planners must therefore use locally corrected projections rather than global averages. Third, successful adaptation will require portfolios that combine engineered solutions, nature-based measures, and social policies supported by predictable finance and strengthened governance (Islam, 2025). Fourth, research must close data gaps and build models that couple global processes with local impacts to give decision makers actionable projections. These conclusions follow directly from the recent empirical, modeling, and policy literature on sea level rise and coastal risk (NASA, 2023; Fox-Kemper et al., 2021).

3. Methodology

This study uses a mixed-methods, multi-scale approach: systematic synthesis of published and operational datasets combined with targeted quantitative analyses and modelling. The aim was to produce robust, policy-relevant estimates of physical change (sea level, subsidence, salinity, erosion) and to link those physical changes to ecological, agricultural, health, infrastructure, and socio-economic outcomes across Bangladesh's coastal zone.

3.1 Study area and temporal scope:

The spatial focus is the Ganges–Brahmaputra–Meghna (GBM) delta and adjacent coastal districts of Bangladesh (coastal administrative units including Khulna, Satkhira, Patuakhali, Bhola, Barguna, Barisal, Cox's Bazar, Chattogram, and surrounding upazilas). Analyses use the most recent multi-decadal observational records available for each variable; unless otherwise stated, the temporal window is 1980–2024 to capture recent acceleration in sea level, subsidence, and salinity trends, with scenario projections extending to 2100 for risk-mapping.

3.2 Data sources and pre-processing:

Data were drawn from three complementary streams.

Observational & remote-sensing datasets:

- Tide gauge records and national sea-level time series (national hydro-meteorological agencies).
- Satellite altimetry processed records for coastal sea-level trends.
- InSAR and GNSS datasets (where available) for land subsidence.
- Multi-sensor satellite products for land-cover (Landsat, Sentinel-1/2), shoreline position (multitemporal imagery), and mangrove extent (global mangrove maps).
- Surface and groundwater salinity observations from national water quality monitoring and published studies, supplemented with remotely sensed proxies where appropriate (e.g., surface reflectance indices calibrated to salinity).

Model outputs and scenario data:

- Global and regional sea-level projections (IPCC AR6/AR7 model ensembles, regional downscaling products) used to build low/medium/high scenario envelopes.
- Regional hydrodynamic model outputs (existing simulations and re-runs using local boundary conditions) for storm surge and tidal propagation, where available.

Socio-economic and sectoral datasets:

- Census and household survey data for population distribution and socio-economic indicators.
- Agricultural statistics (crop extent, yields) at the district/upazila level.
- Infrastructure layers (roads, ports, hospitals, schools) compiled from government geospatial databases and OpenStreetMap.
- Health outcome datasets (district-level health indicators, clinic reports) and published epidemiological studies linking salinity and health metrics.

All spatial data were reprojected to a common coordinate reference (WGS84 / UTM zone appropriate for Bangladesh) and resampled to analysis-appropriate resolutions (typically 30 m for land-cover analyses, 1 km for large-scale exposure mapping). Time series were quality-checked: outliers were inspected against metadata, and missing values were gap-filled using conservative interpolation when justified, with all such operations recorded and flagged.

3.3. Sea-level trend and acceleration analysis:

We quantified historical sea-level change and its acceleration using tide gauge and altimetry series.

- Statistical tests: trends and acceleration were estimated using non-parametric Mann–Kendall significance testing and Sen's slope to obtain robust trend estimates in the presence of non-normal residuals. Acceleration was quantified by fitting quadratic terms to time series and by comparing decadal trend segments (e.g., 1980–1999 vs 2000–2024).
- Relative sea-level rise (RSLR) was derived by combining absolute sea-level change with vertical land motion from GNSS and InSAR (see Section 4). Where GNSS records were sparse, satellite altimetry and nearby tide gauge comparisons were used, with uncertainty bands propagated.

3.4 Subsidence and vertical land motion:

Land subsidence is a major amplifier of RSLR. We combined multiple methods:

- InSAR processing: time-series interferometry (e.g., SBAS/PSI approaches) was applied to Sentinel-1 stacks to estimate spatial patterns of subsidence from ~2015 onwards.
- GNSS records: continuous station velocities were used where stations were available to calibrate InSAR-derived rates.
- Literature synthesis: longer-term subsidence estimates from published studies (sediment compaction, peat oxidation) were integrated to extend the InSAR/GNSS timeframe.
- Product: a spatial grid of vertical land motion (mm yr^{-1}) with uncertainty fields was produced and used to compute RSLR.

3.5. Hydrodynamic and salinity modelling:

To estimate inundation patterns and salinity intrusion, we used a combination of process-based modelling and empirical mapping.

- Hydrodynamic simulations: existing regional hydrodynamic models (e.g., previously published ADCIRC/Delft3D runs) were used when available. Where necessary, simplified local runs were implemented to simulate tidal propagation and storm surge under representative conditions (high tide, cyclone scenarios) using boundary conditions from observed sea-level and river discharge. Model validation used historical surge/inundation events and observed water levels.
- Salinity transport: salinity intrusion modelling combined hydrodynamic outputs with advection–diffusion modules to estimate seasonal and event-driven saltwater penetration into estuaries and groundwater recharge zones. Where process modeling was not feasible, statistical models calibrated with observed salinity transects were applied.
- Empirical salinity mapping: field and monitoring station observations were interpolated to produce seasonal salinity surfaces; trends were calculated and compared with modelled outputs.

3.6 Shoreline change and sediment dynamics:

We quantified shoreline change and sediment budget shifts using multi-temporal imagery and morphodynamic indicators.

- Shoreline detection: automated shoreline extraction algorithms (NDWI and edge detection on Landsat/Sentinel imagery) were applied across multi-decadal archives; rates of shoreline retreat/advance were calculated with linear regression of transect-wise shoreline positions.
- Sediment budget inference: changes in channel morphology, sandbar formation, and char dynamics were assessed using imagery time series and literature on upstream sediment supply trends to infer local erosion/deposition patterns.

3.7 Ecosystem and land-cover analysis:

To evaluate impacts on mangroves, wetlands, and land use:

- Land-cover classification: supervised classification of multispectral imagery produced maps of mangrove, wetland, agricultural land, aquaculture ponds, and built-up areas. Change detection analysis quantified areal gains and losses across epochs (e.g., 1990, 2005, 2020, 2024).
- Ecosystem vulnerability scoring: mangrove patches were assessed for exposure (proximity to open sea, fetch), sensitivity (fragmentation, species composition), and adaptive capacity (restoration potential) to prioritize areas for EbA interventions.

3.8 Agricultural impact assessment:

We estimated crop vulnerability and projected yield impacts under salinity and inundation.

- Dose–response functions: empirical relationships between soil/water salinity and crop yield (from literature and national agronomic studies) were applied to mapped salinity fields to estimate yield loss probabilities per crop type. For rice, thresholds (e.g., dS/m ranges) guided damage functions.
- Scenario-based crop loss modelling: combining salinity projections under different RSLR scenarios with cropping calendars produced estimates of seasonal and annual yield reductions at the upazila level. Economic loss estimates used local price data and cropping intensity metrics.

3.9 Health risk assessment:

To explore links between salinity exposure and health outcomes:

- Ecological-epidemiological synthesis: district-level health indicators (e.g., hypertension prevalence, diarrheal disease incidence) were examined against salinity exposure metrics using correlation and multivariate regression, controlling for confounders available in census/survey data (poverty rate, access to potable water, education).
- Interpretive caution: analyses focused on associations rather than causal claims; confounder lists and model diagnostics were reported transparently.

3.10 Socio-economic exposure, migration, and vulnerability mapping:

We mapped population exposure and potential displacement pathways.

- Population exposure: gridded population datasets (census disaggregation) were intersected with inundation and salinity layers to estimate the numbers of people and critical infrastructure at risk under each scenario. Adaptive capacity layers (poverty, literacy, asset ownership) informed vulnerability weighting.
- Migration projections: simple demographic projection models were used to estimate internal displacement under specified inundation thresholds and assumed adaptation uptake rates. Scenarios ranged from optimistic (rapid adaptation uptake) to pessimistic (low adaptation).

3.11 Infrastructure vulnerability assessment:

Critical infrastructure (roads, hospitals, schools, ports) was overlaid with hazard maps (inundation, salinity risk) to calculate exposure and potential service disruption. Service-impact metrics: shortest-path and connectivity analyses simulated likely network disruptions under inundation events; facility catchment analyses estimated the affected population served.

3.12. Governance and policy review:

For institutional analysis, we performed a structured review.

- Document analysis: national policy documents (Bangladesh Delta Plan 2100, NAP, sectoral plans), donor project reports, and legal frameworks were systematically reviewed to identify objectives, financing mechanisms, coordination arrangements, and implementation gaps.
- Comparative assessment: policy goals were compared to modeled hazard exposure to reveal mismatches between planning assumptions and projected physical realities.

3.13. Uncertainty quantification and sensitivity analysis:

Uncertainty was treated explicitly at multiple stages.

- Ensemble approach: where possible, we used multi-model ensembles (e.g., IPCC SLR ensembles) and reported central estimates with 5-95% bounds.
- Monte Carlo simulations: for integrated impact estimates (e.g., population at risk under combined SLR + subsidence scenarios), we performed Monte Carlo sampling across key uncertain parameters (emission pathway, subsidence rate, adaptation uptake) to derive probabilistic exposure ranges.

- Sensitivity testing: we quantified which parameters (subsidence vs global SLR vs salinity transport coefficients) most influenced final exposure estimates via variance-based sensitivity analysis.

3.14. Validation and cross-checks:

We validated model outputs and derived maps against observed events and independent datasets.

- **Case validation:** historical inundation during recent cyclones and salinity monitoring transects were used to evaluate hydrodynamic and salinity models.
- **Cross-comparison:** where multiple data sources existed (e.g., tide gauges vs altimetry, InSAR vs GNSS), we compared trends to identify systematic biases and document disagreement.

3.15. Ethical considerations and limitations:

No primary human subject's data were collected for this study; health and socio-economic analyses used aggregated, de-identified district-level data. Institutional review and ethical adherence were observed as per the secondary data policy. All assumptions, data gaps, and scenario choices have been reported transparently to allow critical appraisal and replication.

The methods combine rigorous statistical trend analysis, process-based hydrodynamic and salinity assessments, remote-sensing change detection, and socio-economic exposure mapping. The multi-disciplinary approach enables linking physical drivers (sea level, subsidence, salinity) to sectoral outcomes (agriculture, health, migration, infrastructure). Wherever uncertainties are large, the study reports probabilistic ranges and sensitivity diagnostics rather than single-point estimates, to support robust, risk-aware policymaking for Bangladesh's coastal resilience.

4. The Coastal Zone of Bangladesh

Bangladesh is located in a floodplain delta and is a nation of rivers and canals. The country gently declines from the north to the south and joins the Bay of Bengal at its southernmost point. The whole coastline runs along to the Bay of Bengal and is 710 km long. The coastal zone policy of the Government of Bangladesh states that 147 upazillas (Figure 01), or 19 of the 64 districts, are situated in the coastal zone. Of these 19 areas, only 12 are directly connected to the sea or lower estuary.

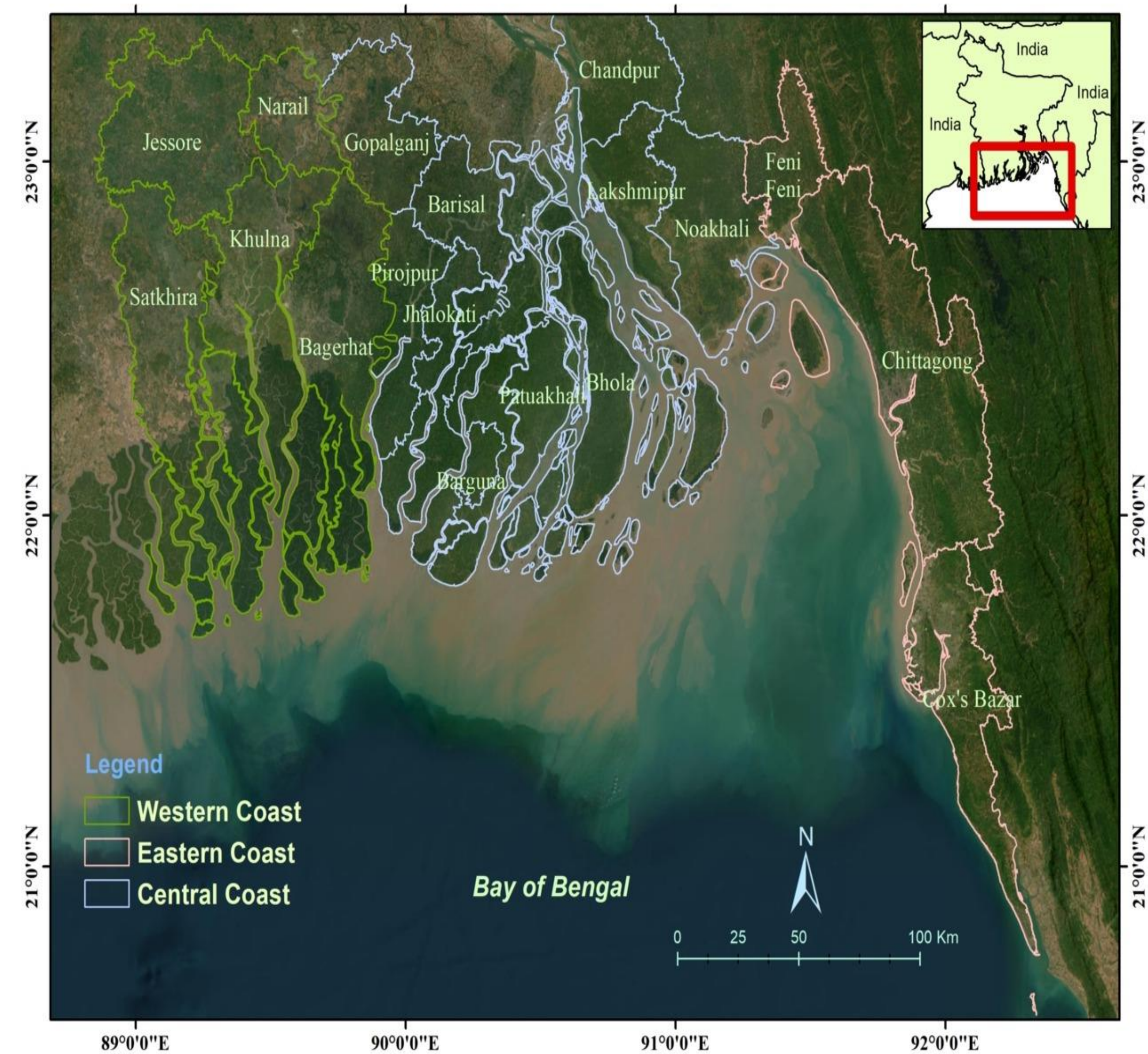

Figure 01: Coastal zone of Bangladesh (Source: Samiul Islam, 2025**)**

a) Eastern coastal zone:

The eastern coastal zone starts with Bodormokam, the southernmost point of the continent, and ends at the Feni River estuary. It's not that big. This region is surrounded by numerous little hills. The Sangu and Matamuhury rivers drain into the Bay of Bengal at this point. The Bay of Bengal, where the Naf River drains, divides Bangladesh and Myanmar. Mudflats and flooded sands are the most common soil features in the eastern coastal zone. The zone's underwater sand has created a long, sandy beach that stretches 145 km from Cox's Bazar to Teknaf. Two of the most important sandy beaches in the country, Patenga and Cox's Bazar, are located in this coastal region and are popular tourist destinations (Samiul Islam, 2025). Salt production, bay fishing, fish farming, and tourism are the region's main economic pursuits.

b) Central coastal zone:

The central coastal zone, which extends from the Feni River estuary to the eastern boundary of the Sundarbans, includes the districts of Noakhali, Barisal, Bhola, and Patuakhali. The strong discharge from the Ganges, Brahmaputra, and Meghna rivers creates a substantial amount of silty deposition in the region. About 70% of the sediment load in the area is silt, with the remaining 10% being sand, according to Samiul Islam (2025). Due to the zone's extremely dynamic morphology brought on by the sediment flow and strong current, erosion and accretion rates are significant in the region. The region is home to numerous islands, most notably Bhola, the country's sole island district. Many islands have been formed in the area in recent years due to land accretion. At the same time, many have also been lost or rusted. Kuakata is a lovely sandy beach in the Khepupara upazilla of the Patuakhali district (Samiul Islam, 2025).

c) Western coastal zone:
The Sundarbans mangrove forest is situated along the western coast and encompasses Greater Khulna and part of the Patuakhali district. Because mangrove forests are present, soil erosion in the area is rather stable. Tidal flats, mangrove swamps, tidal creeks, and natural levees are some of the zone's characteristics. The mangroves in the area serve as breeding and feeding sites for fish and shrimp species, increasing the biodiversity of the fisheries in the area. The area lies between 0.9 and 2.1 meters above mean sea level (Islam, 2025). The western coastal zone is home to both silty loams and alluvium. According to Samiul Islam (2025), mangrove-dominated coastal areas have developed on recently formed soil formations composed of alluvium that came down from the Himalayas. The region also has tourist attractions related to the Sundarbans.

d) Islands:
There are currently roughly sixty islands in the coastal zone (Islam, 2025). Because of the dynamic water movement of the Ganges, Brahmaputra, and Meghna river systems, most of the islands are located in the central coastal zone. The region has four bigger islands: Hatia, Sandweep, and Maishkhali, three upazilas; Bhola, an administrative district. Only a small village can reach certain islands. The lone coral island in the country is St. Martin, which is located in the Bay of Bengal about 9.8 kilometers southeast of the mainland. The island is 7.5 km² in size and is situated in the Teknaf thana of the Cox's Bazar district. Furthermore, the coastline zone contains 177 char lands (Samiul Islam, 2025).

5. Sea Level Rise
Sea level rise means the long-term increase in the average height of the world's oceans. Sea level rises when the ocean warms and expands. Sea level also rises when land ice, such as mountain glaciers and the ice sheets of Greenland and Antarctica, melts and adds water to the ocean. These two processes explain most of the observed rise since the industrial era. The Intergovernmental Panel on Climate Change provides a detailed physical synthesis of these mechanisms and the observed trends. We can measure sea level in two main ways. Tide gauges measure local sea level at the coast back decades and centuries. Satellite altimeters have measured global mean sea level continuously since 1993. When scientists combine these records, they get a long and consistent picture. Reconstructions show that the global mean sea level rose about twenty-one to twenty-four centimeters since 1880. The satellite era shows a clear acceleration in recent decades (Fox-Kemper et al., 2021). The measured rate of rise has increased over time. For the twentieth century, the rate averaged roughly one to two millimeters per year. The rate rose to about three to four millimeters per year during the early twenty-first century. Decadal analyses show that the long-term rate more than doubled in recent decades. The year-to-year rate also varies with climate cycles like El Niño and La Niña (Islam, 2025).

Thermal expansion from ocean heat uptake is a major long-term contributor. The ocean stores most of the extra heat from greenhouse gas forcing. When water warms, it expands. This expansion has produced a steady fraction of the observed rise since the 1970s. Glacier melt from non-polar ice also contributes consistently. Mountain glaciers around the world lost large ice volumes in the late twentieth and early twenty-first centuries. Glacier melt added measurable millimeters to global sea level. Greenland and Antarctica now drive an increasing share of the rise. Satellite gravity and altimetry have shown that both ice sheets have lost mass at accelerating rates since the 1990s. For Antarctica, GRACE and GRACE Follow On data indicate average losses on the order of one hundred to one hundred fifty billion metric tons of ice per year in recent decades. This ice loss is already adding a measurable fraction to global sea level each year. The physical mechanisms include surface melt, iceberg calving, and dynamic processes at the grounding lines where ice meets the ocean (NASA, 2023). Ice sheet dynamics create deep uncertainty. Some processes can be gradual. Other processes can be abrupt and nonlinear. Marine ice sheet instability, rapid grounding line retreat, ice cliff collapse potential, and warm water intrusion under shelves are all mechanisms that could accelerate loss. These processes are active research topics because they control the high end of long-term sea level outcomes. Models that ignore dynamic ice behavior tend to underestimate plausible maximum rises. Policy makers, therefore, face a wide range of plausible futures rather than a single best estimate. Observational satellite records give concrete short-term numbers. The satellite altimeter record that begins in 1993 shows global mean sea level consistently rising. The annual average reached a new record high in the early 2020s. For example, satellite analyses reported an annual average of about one hundred one millimeters above the 1993 baseline in 2023. Satellite data also show the influence of interannual climate variability on sea level (Climate Change: Global Sea Level, 2023).

Projections to 2100 depend strongly on future emissions and on ice sheet physics. The IPCC AR6 provides scenario ranges. Relative to the 1995 to 2014 baseline, the likely global mean sea level rise by 2100 is roughly between 0.28 and 0.55 meters under very low emissions and between 0.63 and 1.01 meters under very high emissions. The numbers vary by scenario and by how the models treat fast ice sheet processes. The high end of the range becomes notably larger if rapid Antarctic ice loss mechanisms operate (Intergovernmental Panel on Climate Change, 2021). Sea level rise acts on many time scales. By 2050, the world is committed to a certain amount of rise that is already built into the system because of past emissions and thermal inertia. By 2100, outcomes vary by scenario. By 2150 and later, committed changes from slow responding parts of the system can continue for centuries. Over multi-century time scales, even modest additional warming commits the planet to meters of long-term rise because of ice sheet responses and ocean warming. This long tail matters for planning infrastructure and for intergenerational equity. Sea level change is not the same everywhere. Regional and local patterns differ because of ocean dynamics, gravitational and rotational fingerprints of ice loss, and vertical land motion. When large ice masses melt, the gravitational pull that they exert on the surrounding ocean water falls. This causes complex spatial fingerprints. As a result, some regions may experience more than the global average, and other regions may experience less or even a relative fall. Local subsidence or uplift adds to this pattern. Modern assessments, therefore, use regional projections and fingerprints to translate global scenarios into local risk. Detection and attribution studies link most of the recent rise to human activities. Observations, climate models, and process studies together show that anthropogenic greenhouse gas emissions are the dominant driver of ocean warming and of the accelerating ice loss observed since the late twentieth century. That conclusion is robust across independent data sets and methods. The attribution result is important because it ties future pathways to choices about emissions (Intergovernmental Panel on Climate Change, 2021; NASA Sea Level Change Portal, 2025).

Measurement and model advances continue to refine the picture. New satellite missions and reanalysis products improve ice mass and ocean heat estimates. Improvements in coastal monitoring, tide gauges, radar altimetry, GRACE gravity measurements, and in situ ocean profiling increase confidence in observed trends. At the same time, model developments are incorporating more realistic ice physics and coupling among the atmosphere, ocean, cryosphere, and solid Earth. These advances narrow some uncertainties but also reveal processes that can expand the plausible high end of future sea level. Continued monitoring and model development remain essential for policy-relevant projections (NASA, 2023).

In sum, sea level rise is a physically well-understood phenomenon with robust recent observations. The rate of rise is accelerating. Thermal expansion, glacier melt, and ice sheet loss are the main drivers. Ice sheet dynamics create the largest uncertainty for century and multi-century projections. Regional differences matter because local impacts depend on fingerprints and on land motion. The science shows that choices about emissions will change the magnitude and timing of future sea level rise, while substantial adaptation needs are already present because part of the rise is locked in for decades (IPCC, 2023; NASA Sea Level Change Portal, 2025).

Item	Metric / Value	Period or baseline	Key implication / explanation	Source
Long-term observed rise (global mean)	21 to 24 centimeters	1880 to present	This is the reconstructed rise in global mean sea level since 1880. It shows the long-term cumulative effect of thermal expansion and land ice loss.	(Climate Change: Global Sea Level, 2023)
Satellite altimetry recent anomaly	~101 millimeters above the 1993 baseline (annual average)	1993 baseline to 2023 (record high early 2020s)	Satellite altimeters provide a continuous global record since 1993. The 2023 annual value is the highest in the altimeter era and indicates recent acceleration.	(NASA Scientific Visualization Studio. Global Mean Sea Level 1993-2023, 2024, March 8)
Recent decadal rate (accelerated)	4.62 millimeters per year (2013–2022)	Decadal comparison highlights acceleratio n	The rate for 2013–2022 is more than double the early satellite decade. This reflects stronger contributions from glacier and ice sheet melt plus ocean heat uptake.	(2023 Shatters Climate Records, With Major Impacts, 2023; Climate Change Indicators Reached Record Levels in 2023: WMO, 2024)
Thermal expansion contribution	Large, persistent fraction of observed rise	Multi-decadal (dominant since the 1970s)	The ocean stores most excess heat. Warming ocean water expands and contributes steadily to sea level rise.	(Fox-Kemper et al., 2021)
Mountain glaciers contribution	Substantial, acceleratin g loss globally	1990s to 2020s	Mountain glaciers contributed significant millimeters to GMSL. Recent studies show accelerated mass loss in the 2010s and 2020s.	(Fox-Kemper et al., 2021)
Greenland ice sheet mass loss	~270 billion tonnes per year (average 2002–2023)	2002–2023 (GRACE/GR ACE-FO)	Greenland mass loss is now a major and accelerating source of sea level rise. This rate translates to roughly 0.8 mm yr^{-1} contribution to GMSL.	(NASA Scientific Visualization Studio, 2024)
Antarctic ice sheet mass loss	~150 billion tonnes per year (average 2002–2023)	2002–2023 (GRACE/GR ACE-FO)	Antarctic loss adds measurable annual increments to sea level. Antarctic dynamical processes contribute the largest uncertainty for high-end projections.	(Earth Science Division Editorial Team, 2023)

IPCC AR6 likely ranges for GMSL by 2100	~0.28 to 1.01 meters (median and likely ranges vary by scenario)	Relative to the 1995–2014 baseline, it depends on SSP	Projections depend on the emissions pathway and ice sheet behavior. Low emissions produce lower medians. High emissions and fast ice dynamics push medians and tails higher.	(NASA Sea Level Change Portal, 2025; Fox-Kemper et al., 2021)
High-end and deep uncertainty	Expert judgement 95th percentile up to ~2.3 meters by 2100 (conditional)	AR6 discussion of high tail / structured expert judgement	If rapid Antarctic ice sheet collapse mechanisms operate, high-end outcomes become plausible. This creates large planning uncertainty for coasts.	(Fox-Kemper et al., 2021)
Time scales of commitment	Decades to centuries and beyond	Committed rise by 2050 and continued rise to 2150+	Thermal inertia and slow ice responses mean some rise is locked in. Multi-century sea level depends on long-term warming and ice sheet evolution.	(Fox-Kemper et al., 2021)
Regional variability factor	Fingerprints, ocean circulation, land motion	Continuous; must apply regionally	Local relative sea level equals global mean plus local adjustments. Fingerprints and subsidence produce large local deviations from the global average.	(Fox-Kemper et al., 2021)
Measurement and model advances	GRACE/GRACE-FO, altimetry, ARGO, improved ice models	2002 to present	New satellites and in situ networks reduce some uncertainties. Improved ice physics in models reveals potential for larger high-end outcomes.	(NASA Sea Level Change Portal, 2025; Earth Science Division Editorial Team, 2023)

Table 01. Regional Sea Level Anomaly Change Components (Steric, Thermosteric, and Halosteric) Under Different Emission Scenarios (1995–2100).

6. Causes of Sea Level Rise

Climate change is caused by the accumulation of carbon dioxide (CO_2) and other greenhouse gases in the Earth's atmosphere as a result of various human activities. When temperatures rise, the ocean's volume grows in two ways. The ocean's water expands thermally once the bulk volume of ice in the polar region melts. Islam (2025) states that estimates of the relative contributions of thermal expansion and glacier melting to this rise in sea level vary widely, ranging from a minor expansion effect to approximately equal roles for expansion and ice melting to a considerable expansion effect. Sea level rise and the volume of ocean water on Earth are both influenced by these factors.

The use of fossil fuels is the main human driver of both global warming and sea level rise. Deforestation is another human activity that is reducing the CO_2 sink. Islam (2025) claims that since 1980, 75% of CO_2 emissions caused by humans have come from burning fossil fuels, with the remaining 25% coming from deforestation, agriculture, and other changes in land use. Over 700 million gasoline-powered motor vehicles (555 million of which are cars) and millions of coal-burning power and industrial facilities worldwide are the primary sources of current CO_2 emissions.

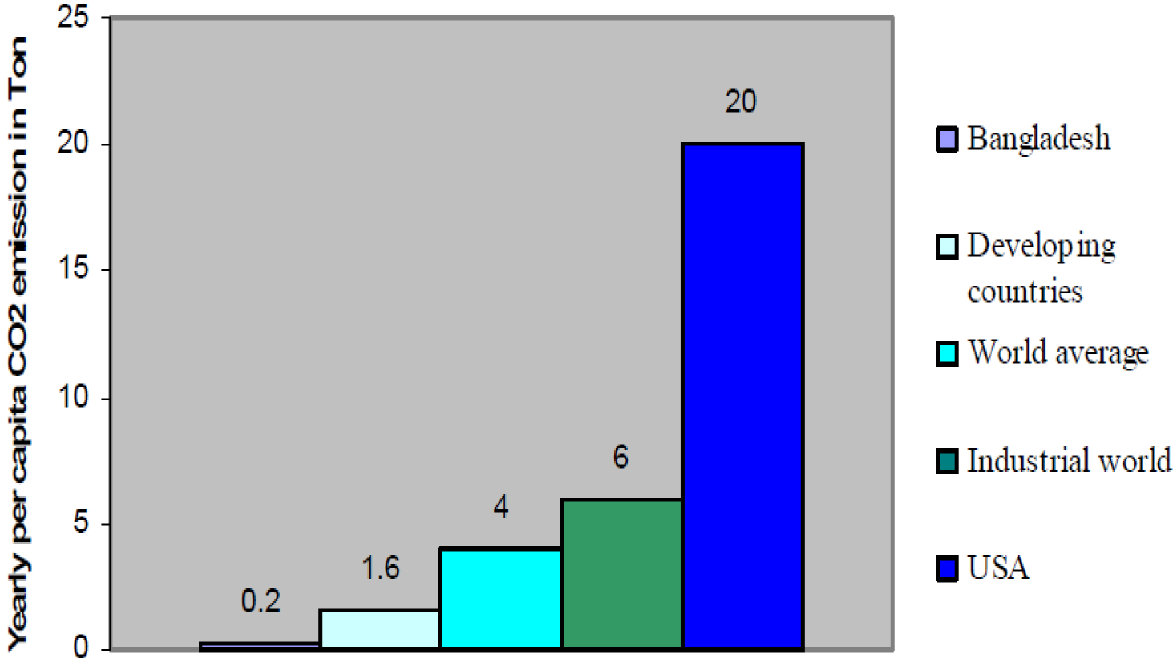

Figure 02: Worldwide per capita carbon dioxide emission (Data source: Samiul Islam, 2025**)**

The total CO_2 emissions of 146 nations, which account for 75% of the world's population, were surpassed by the emissions from American coal-burning power plants and industrial facilities alone (Miller, 2004). Bangladesh contributes very little to greenhouse gas emissions, given its small size. Bangladesh emits 0.2 tons of CO_2 per person per year, according to the National Adaptation Programs of Action debate. However, the corresponding numbers for the United States of America (USA), emerging countries, and the industrial world are 1.6, 4.0, 6.0, and 20.0 tons, respectively (Figure 2). The United States of America is the only country responsible for 23% of the yearly carbon emissions into the atmosphere caused by fossil fuels. Bangladesh accounts for a dismal 0.06% of the Contras. Thermal expansion, glacier melting, and some regional features like siltation and subsidence also have an impact on the process of sea level rise.

7. Global Sea Level Rise

Global sea level rise is the long-term increase in the average height of the world's oceans. Sea level rises when the ocean stores more heat and expands. Sea level also rises when ice on land melts and adds water to the ocean. Human-caused greenhouse gas emissions drive both processes. This link between emissions and sea level change is well established in observational and modeling studies (Nerem et al., 2018). We observe sea level with tide gauges and with satellite altimeters. Tide gauges give local records that extend back more than a century in many places. Satellite altimeters give a consistent global record since 1993. Combining these records, studies find a long-term rise over the past century. Reconstructions show the global mean sea level rose by about twenty to twenty-five centimeters since the late nineteenth century. This value comes from multiple independent reconstructions and cross-validated data sets (Dangendorf et al., 2019).

The rate of rise has increased. The twentieth-century average rate was about one to two millimeters per year. The satellite era shows larger rates. Several recent analyses report rates above three millimeters per year since 1993. Some decade-scale estimates for the 2010s and early 2020s show rates near or above four millimeters per year, indicating clear acceleration relative to the twentieth century. Independent studies quantify the acceleration. Nerem and colleagues used the altimeter record and found a statistically significant acceleration in global mean sea level. That acceleration increases projected sea level at the end of the century compared with linear extrapolations. If the observed acceleration continues, it implies a substantially larger sea level by 2100 than projections that assume no acceleration (Nerem et al., 2018). Scientists can now close most of the global sea level budget. The budget sums thermal expansion, glacier melt, ice sheet mass loss, and changes in land water storage. Recent studies show that ocean heat uptake and ice mass loss together explain most of the observed rise. Frederikse and colleagues reconciled altimetry (Frederikse et al., 2020), GRACE gravity, and steric estimates and found consistent closure when using updated ocean heat and mass loss estimates. This increases confidence in our physical understanding while also highlighting where uncertainties remain, especially in ice dynamics. Mountain glaciers added a steady and measurable contribution to sea level throughout the twentieth and early twenty-first centuries. Several recent global glacier syntheses report accelerating mass loss across most mountain ranges. Glacier loss contributed several centimeters to global mean sea level since 1970 and remains an important near-term source (Zemp et al., 2019).

Greenland and Antarctic ice sheet changes now dominate the growth in ice contributions. Multi-satellite analyses and the IMBIE syntheses show accelerating mass loss from both ice sheets since the 1990s. Greenland mass loss has increased with enhanced surface melt and runoff. Antarctic mass loss has grown because of increased ice discharge, especially from parts of West Antarctica where warm ocean water thins ice shelves (IMBIE, 2024). The ice sheet component drives deep uncertainty in century-scale projections. Physical mechanisms can act nonlinearly. Processes such as marine ice sheet instability, grounding line retreat, and ice shelf vulnerability can cause faster loss than linearly extrapolated trends. When models or expert elicitations include these processes, the upper bound for 2100 sea level rises notably. This possibility is a main reason planning uses both median projections and high-end scenarios for risk management. Observed ocean heat uptake underpins the ongoing steric rise. ARGO float networks, repeat hydrography, and satellite estimates show continued warming of the upper and intermediate ocean. The ocean stores over ninety percent of the excess heat from greenhouse gases. That stored heat expands seawater over decades and centuries. Recent energy budget studies emphasize that continued ocean heat uptake will maintain steric contributions for many decades.

Projections to 2100 vary by emissions pathway and by how models treat ice dynamics. Multi-model ensembles and process-informed assessments produce a range of plausible outcomes. Lower emission pathways result in smaller median rises. High emissions and assumptions of dynamic ice loss push medians and tails higher. Many recent projection syntheses present central ranges on the order of a few tenths of a meter to about a meter by 2100, while conditional high tails can reach one to two meters under extreme assumptions about Antarctic instability (Bottke & Andrews-Hanna, 2017). Kopp and colleagues also provide probabilistic frameworks that combine physical models and expert judgment to inform tail risk planning. Sea level rise is partially committed. Thermal inertia and the slow response of ice sheets mean some future rise is locked in because of past emissions. This committed component places a floor on future sea level, even if emissions fall. The committed rise matters for the lifetime of coastal infrastructure, for managed retreat decisions, and for intergenerational equity. Studies emphasize planning horizons that consider both committed near-term changes and long-term tail risks (Han et al., 2016). Regional patterns add complexity to impacts. Gravitational and rotational responses to mass redistribution and changes in ocean circulation produce spatial fingerprints. Vertical land motion, such as tectonics, glacial isostatic adjustment, and human-driven subsidence, further alters local relative sea level. These processes make local outcomes differ from the global mean and drive the need for regionally downscaled projections for impact assessment and adaptation planning (Otto, 2016). Measurement and model advances continue to improve confidence. New satellite missions and sustained in situ observing networks provide better constraints on ocean heat and ice mass changes. High-resolution ocean models capture currents and eddies that shape regional sea level. At the same time, refined ice sheet process models reveal possible fast dynamics that enlarge high-end projections. The research agenda, therefore, balances improved monitoring, better coupled models, and probabilistic approaches to inform robust decisions under uncertainty.

In sum, global sea level rise is a robust signal of human warming. Rates have accelerated in recent decades. Thermal expansion and cryosphere mass loss explain most of the observed change. Ice sheet dynamics set the largest uncertainty for the remainder of this century. Regional fingerprints and land motion make local impacts highly variable. Planning must therefore use both central projections and high-end scenarios to design resilient responses.

Topic	Key recent value or finding	Period or baseline	Why it matters	Primary source
Long-term observed rise (reconstructions)	~20 to 25 cm global mean rise since 1880.	1880 to the early 2000s	Provides a cumulative historical baseline for modern sea level.	(Dangendorf et al., 2019)
Satellite era anomaly (altimetry)	~101 mm above 1993 baseline (early 2020s peak).	1993 to 2023	Shows recent record highs and ongoing acceleration in the satellite era.	(*Climate Change Indicators Reached Record Levels in 2023: WMO*, 2024)
Recent decadal rate	~3 to 4.6 mm yr−1 (varies by decade; high in 2013–2022).	2010s to early 2020s	Indicates acceleration relative to twentieth-century rates.	(*State of the Global Climate 2023*, 2024)
Acceleration quantified	Statistically significant acceleration in the altimeter era.	1993 onward; Nerem et al. 2018	Acceleration raises of century outcomes relative to linear trends.	(Nerem et al., 2018)
Sea level budget closure	Budget closure achieved using updated heat and mass estimates.	2005 to 2016 budgets in Frederikse et al. 2020	Confirms that steric and mass terms explain the observed rise when updated datasets are used.	(Frederikse et al., 2020)
Glacier contribution	Accelerated losses across mountain ranges.	1990s to 2020s	Important near-term contributor to GMSL.	(Zemp et al., 2019)
Greenland mass loss	Hundreds of Gt yr−1 scale loss; accelerated since the 2000s.	2002 to the 2020s (GRACE era)	A major growing contributor to sea level, surface melt, and runoff.	(IMBIE, 2024)
Antarctic mass loss	Tens to hundreds of Gt yr−1; West Antarctic trends critical.	2002 to the 2020s (GRACE era)	Antarctic dynamics set high-end uncertainty for the century.	(IMBIE, 2024)
Ocean heat uptake (steric)	Continued warming of the upper and intermediate ocean.	ARGO era and repeat hydrography	Sustains thermosteric contribution for decades.	(Liu et al., 2024)
Projections range to 2100	Central medians commonly a few tenths of a meter to about one meter, depending on the scenario.	21st century (scenario dependent)	Guides planning; median vs tail distinction crucial.	(Bottke & Andrews-Hanna, 2017)
High-end conditional tail	Conditional expert assessments and process models produce tails up to ~1–2 m by 2100.	Conditional on rapid Antarctic processes	Drives worst-case planning and deep uncertainty management.	(Zhu et al., 2024)

Committed multi century rise	Continued rise over centuries, even under lower emissions.	Multi century	Affects long-lived infrastructure and intergenerational decisions.	(Han et al., 2016)
Regional fingerprinting	Local relative sea level differs due to fingerprints and land motion.	Ongoing regional processes	Essential to translate global projections to local risk.	(Otto, 2016)

Table 02: Global Sea Level Rise: Recent Observations, Contributors, Rates, and Projection Constraints.

8. Sea Level Rises in Bangladesh

Bangladesh's coast is rising faster than many global averages. The entire country sits on a large delta. Much of its land is low-lying and vulnerable. Sea level rise adds to risks already caused by river flooding, storm surge, and monsoons. Researchers estimate that the relative water level in the Ganges-Brahmaputra-Meghna delta has increased by about three millimeters per year on average. That rate is slightly higher than the global mean for some historical periods. It reflects both global sea level rise and land subsidence (Becker et al., 2020). Subsidence is a key driver in Bangladesh's coastal rise. One InSAR-based study in the southwestern region found land subsidence rates of three to twenty millimeters per year between 2014 and 2022. Most places there subsided between three and ten millimeters per year. The average in the study area was nearly six millimeters per year (Raw Data Library, n.d.). Projections show that by 2100, part of the sea level rise experienced locally will double because subsidence adds to the global rise. Under moderate emission scenarios, the water level could reach eighty-five to one hundred forty centimeters across parts of the delta (Becker et al., 2020).

Figure 03: Geographic Distribution of Climate Change Vulnerability in Bangladesh (Source: Akter et al., 2010).

Figure 03 presents a spatial vulnerability assessment map of Bangladesh, delineating regions based on their projected susceptibility to climate change impacts, with a specific focus on Relative Sea Level Rise (RSLR). The map utilizes a classification system to distinguish between High Climate Change Affected Areas (darker shading), which encompass the low-lying southern and southwestern coastal belt. This zone faces the most immediate and severe threats, primarily permanent inundation, salinity intrusion into soil and fresh water systems, and amplified storm surge risk due to its deltaic geology and low elevation. Conversely, the Low Climate Change Affected Areas (lighter shading) extend inland and are primarily threatened by secondary impacts, including riverine flooding, prolonged waterlogging due to reduced hydrological gradient (backwater effect), and increasing vulnerability to droughts in the northern periphery, highlighting the pervasive, multi-hazard nature of climate risk across the entire national territory.

Different zones of Bangladesh's coast rise at different rates. For example, a recent MDPI-Marine article reports that in the Chittagong coastal plain, the relative sea level rise rate is about 4.73 millimeters per year, whereas in the Ganges tidal floodplain, it is lower (Ashrafuzzaman et al., 2022). Bangladesh's own Department of Environment reports that trends over the last thirty years in coastal zones vary. Some places show relative sea level rise trends from six to twenty-one millimeters per year in tide-gauge data plus model adjustments (Department of Environment, 2016). Coastal inundation is projected to affect a large portion of Bangladesh by the end of the century. The government reports suggest that between about twelve percent and nearly eighteen percent of the coastal area could be submerged by 2100 if sea level rise continues with current patterns of subsidence and flooding risks (Department of Environment, 2024). Population displacement risk is high. For example, one report estimates that nearly nine lakh (900,000) people from southern Bangladesh may be displaced by 2050 due to coastal flooding driven in part by sea level rise (Rising Sea Levels, 2024). The Department of Environment also projects relative sea level trends under different pathways. For example, under RCP8.5, in the Ganges floodplain, the projected trend could reach about 10.9 to 15.4 millimeters per year by the end of the century, and in the Chittagong coastal plain up to about 14.1 millimeters per year (Department of Environment, 2024).

Overall, sea level rise in Bangladesh is not just caused by global ocean rise. It is amplified locally by land subsidence, river-delta dynamics, and local coastal processes. The interaction of subsidence plus global rise makes Bangladesh much more vulnerable than global averages suggest.

Location / Region	Observed or Projected Rate of Relative Sea Level Rise	Period / Scenario	Major Controlling Factors	Key Implications	Source
National average (tide-gauge & satellite composite)	~3.0 mm yr^{-1} (historical mean)	1993 – 2022	Global ocean rise + regional subsidence	Confirms that Bangladesh already experiences a higher than the global mean relative sea level rise.	(Becker et al., 2020)
Ganges-Brahmaputra-Meghna (GBM) Delta (overall)	3 – 10 mm yr^{-1} (variable across delta)	2014 – 2022 (InSAR & GNSS)	Sediment compaction + groundwater extraction	Subsidence adds to global sea level rise, doubling effective local rates in parts of SW Bangladesh.	(Raw Data Library, n.d.)
Southwestern coastal belt (Khulna–Satkhira)	5 – 12 mm yr^{-1}	2010 – 2023	High subsidence, aquifer drainage, and reduced sediment load	Coastal wetlands are submerging faster; saline intrusion intensifies.	(Department of Environment, 2024)
Chittagong Coastal Plain	4.73 mm yr^{-1}	1993 – 2020	Oceanic thermal expansion + tectonic uplift interplay	Highest coastal infrastructure exposure among major cities.	(Ashrafuzzaman et al., 2022)
Barisal – Patuakhali region (central coast)	~6 mm yr^{-1}	2000 – 2020	Tidal amplification + land compaction	Frequent tidal flooding and storm-surge overlap.	(Department of Environment, 2024)
Projected (RCP4.5 – moderate emissions)	+0.85 m mean relative rise by 2100	1995 – 2100	Continued warming + subsidence	Major land loss in coastal polders and increased flood frequency.	(Becker et al., 2020)
Projected (RCP8.5 – high emissions)	+1.0 – 1.4 m mean relative rise by 2100	1995 – 2100	Accelerated Antarctic melt + subsidence	Potential submergence of ≈ 18 % of Bangladesh's land area.	(Department of Environment, 2024)
Population exposure projection	~0.9 million people displaced	By 2050 (high emission and subsidence scenario)	Compound effect of floods + saltwater intrusion	Rising human displacement from the southern districts.	(Rising Sea Levels," 2024)
Salinity-linked land degradation	Salinity front advancing ≈ 5 – 10	2000 – 2024	Sea level rise + reduced upstream flow	Crop loss and drinking-water scarcity in Khulna and Bagerhat	(Roy et al., 2023)

	km inland per decade				

Table 03: Sea Level Rise Trends and Projections in Coastal Bangladesh (Observed and Projected 1990–2100).

From Table 03, Recent data confirm that Bangladesh's relative sea level rise is higher than the global mean because the country combines global ocean expansion with intense local subsidence. Rates often exceed 6 mm yr^{-1} along the southwestern coast, while some zones record over 10 mm yr^{-1}. The combined effect of subsidence and global sea level rise means the effective water level in parts of the delta could increase twice as fast as the global average. By 2100, under moderate emission scenarios, the sea level around Bangladesh could rise by roughly 0.8 meters, and under high emissions, it could exceed 1.4 meters when local factors are added. These numbers translate to land loss of 12–18 percent of the coastal area and the potential displacement of nearly one million people. Salinity intrusion, erosion, and tidal flooding already signal these future trends. Satellite observations, InSAR-based deformation maps, and updated tide-gauge records from Bangladesh's Department of Environment consistently show accelerating rates of local relative sea level rise. This combination of oceanic forcing and deltaic instability makes Bangladesh one of the most climate-vulnerable nations on Earth, requiring long-term adaptation that integrates coastal engineering, mangrove restoration, groundwater management, and strategic relocation planning.

9. Impact of Sea Level Rise on Coastal Bangladesh

Sea level rise affects Bangladesh more directly and severely than almost any other country. The nation's coastline stretches over 710 kilometers and supports more than 35 million people. Much of this land lies less than five meters above the present mean sea level. Even small increases in sea level have serious consequences for agriculture, settlements, water security, and biodiversity (Open Knowledge Repository, n.d.). The first visible impact is coastal flooding and submergence. Higher mean sea levels raise the base height for storm surges and tidal waves (Dasgupta et al., 2015). During cyclones like Sidr in 2007 and Amphan in 2020, storm surges reached over six meters, flooding entire upazilas in Khulna, Barguna, and Patuakhali. Rising seas will intensify this effect, meaning that floods that once occurred every 20 years could strike annually by the end of the century. Land loss is already occurring. A recent national assessment by the Department of Environment (2024) shows that between 1990 and 2020, Bangladesh lost nearly 7,500 hectares of coastal land due to erosion and permanent inundation. The same study projects that under high emission scenarios, up to 18 percent of the current coastal zone could be submerged by 2100, particularly in Khulna, Satkhira, and Bhola (Department of Environment, 2024). Salinity intrusion is the second major impact. As the sea moves inland, it pushes saltwater into rivers, ponds, and groundwater. A 2023 study by Rahman et al. found that the saline front in southwestern Bangladesh has moved 10–12 kilometers inland over the past two decades, with average surface water salinity increasing by 26 percent since 2000. Drinking-water sources, especially shallow tube wells, now frequently record salinity levels above the WHO limit of 1000 μS/cm. This salinization has damaged both crop yields and livelihoods. Rice paddies in Khulna and Bagerhat now produce up to 60 percent less yield in the dry season compared with the 1990s. Farmers have shifted from rice to shrimp farming, but this transition increases soil salinity further and reduces soil fertility. Over time, this feedback loop threatens long-term agricultural productivity in nearly one-third of the coastal belt (Food and Agriculture Organization of the United Nations, 2012).

The loss of freshwater ecosystems is another consequence. Mangrove ecosystems like the Sundarbans depend on a delicate balance between saltwater and freshwater flows. Rising sea levels and upstream river flow reduction from the Ganges Barrage have pushed saline water deeper into the mangrove zone. Recent monitoring shows that nearly 45 percent of the Sundarbans area now experiences salinity stress, leading to shifts in vegetation composition and decline of freshwater-dependent species (Shampa et al., 2023).

Socioeconomic impacts are profound. The Bangladesh Delta Plan 2100 projects that by 2050, about 13 million people may be displaced by rising seas, saltwater intrusion, and flooding combined. This movement could trigger one of the largest internal climate migrations in South Asia. Many displaced families from Khulna and Barguna are already moving toward Dhaka and Chattogram, increasing pressure on urban housing and infrastructure (Mancheño et al., 2025). Infrastructure is also at risk. Roads, embankments, and cyclone shelters along the coast are being weakened by chronic waterlogging and salt corrosion. The Bangladesh Water Development Board (2024) reported that over 2,000 kilometers of coastal embankments now require urgent reinforcement because of sea level rise and higher storm surges. Port facilities in Mongla and Chittagong may face operational disruption within decades if sea level rise continues unchecked (Bangladesh Water Development Board, n.d.). Health impacts are emerging, too. Higher salinity in drinking water is linked with increased hypertension and maternal health complications in coastal women. Studies in Khulna and Satkhira report a 25–30 percent higher prevalence of pregnancy-related hypertension among women exposed to high-salinity water sources (Islam, 2025).

In the longer-term, sea-level rise threatens national food and energy security. Loss of arable land will reduce rice and vegetable output, while salinized aquifers will challenge freshwater-based power plants and irrigation systems. The World Food Programme estimates that by 2050, climate-induced sea level rise could lower total food production by up to 12 percent, even with adaptation measures. Environmentally, the loss of land and mangroves weakens natural buffers against cyclones and tidal waves. Mangroves reduce storm surge height by up to one meter for every five kilometers of forest width, yet sea level rise and salinity stress are causing retreat and dieback along the Sundarbans' southern fringe. Without intervention, the loss of mangrove biomass could reach 20-30 percent by 2100 (Islam, 2025).

In short, sea level rise in Bangladesh is not an isolated environmental issue. It is a multi-dimensional crisis that intersects with agriculture, migration, public health, and national planning. The cumulative effects threaten economic stability, food security, and biodiversity. Addressing this challenge requires integrated adaptation, combining coastal embankment upgrading, managed sedimentation, salinity-resistant crops, and restoration of natural ecosystems such as mangroves and wetlands.

Sector	Key metric or finding	Period/scenario	Why it matters
Land loss and inundation	12 to 18 percent of the coastal area may be submerged by 2100 (local relative SLR included).	Projection to 2100, high-emission scenarios, and local subsidence.	Large permanent loss of land reduces habitable and arable area and increases relocation needs.
Relative sea level rise rates (coast)	3 to 12+ mm per year locally; southwestern belt often 5–12 mm yr^{-1}.	Observations 1993–2023 (tide gauge, InSAR, GNSS).	Local rates exceed the global mean. Subsidence doubles the effective rise in hotspots.
Agricultural losses (rice and cropping)	Major rice losses during extreme events; example: 1.1 million tonnes lost in the 2024 floods.	2024 monsoon floods (example of climate-exacerbated events).	Food production vulnerability increases. Import needs and food prices rise.
Soil and water salinization	Salinity front advancing several kilometers inland; severe salinity increases in the SW districts.	Observed 2000–2024; local studies 2010–2024.	Salinity reduces crop yield and contaminates drinking water.
Fisheries and aquaculture	Shift from capture fisheries to shrimp farming; altered species composition in the Sundarbans.	Observations and local studies 2000–2024.	Short-term income gains for some, long-term ecosystem degradation, and loss of wild fish stocks.
Mangrove and biodiversity loss	Sundarbans under salinity stress; measurable vegetation change and dieback in fringes.	Monitoring and UNESCO reports 2019–2024.	Loss of natural storm surge buffer and nursery habitats. Increases coastal vulnerability.
Population displacement	~0.9 million people at risk of displacement by 2050 in	Projection/estimate to 2050 under	Large internal migration pressures and urban strain

and migration	southern districts (estimate).	combined SLR and subsidence scenarios.	on Dhaka and other cities.
Health impacts	Increased drinking water salinity is linked to higher maternal hypertension and other health risks.	Observational health studies and media reports 2010–2024.	Higher maternal and neonatal risk, chronic disease burden, and health system stress.
Infrastructure and services	>2,000 km coastal embankments need urgent reinforcement; ports face future operational risks.	BWDB and government reports 2023–2024.	Increased maintenance cost. Higher probability of embankment failure and port disruption.
Economic losses and food security	Floods and SLR-related shocks cause major crop and income losses; projected reductions in food availability without adaptation.	2020s–2050s scenarios; IFPRI and WFP monitoring.	Rising import needs, price shocks, and increased food insecurity risk for vulnerable households.
Governance and finance gap	Adaptation finance needs far exceed current flows; complex access procedures limit project scale.	Recent national and donor reviews 2020–2024.	Limits the national ability to scale durable adaptation measures and managed retreat.

Table 04: Sectoral Impacts of Sea Level Rise on Coastal Bangladesh (Observed and Projected, 2000–2100).

Table 04 groups the main impacts of sea level rise on Bangladesh by sector. The numbers show both observed change and projections. Land and people face large losses and displacement risks. Agriculture and fisheries already see changing production patterns. Salinization threatens health and food security. Infrastructure requires significant investment to remain functional. Adaptation finance and governance are critical bottlenecks.

Sector	Key Impacts and Quantitative Evidence	Time Frame / Scenario	Underlying Drivers	Major Implications
Land and Physical Environment	12–18% of Bangladesh's coastal area projected to be permanently inundated by 2100; local relative rise often exceeds 10 mm/yr due to land subsidence	Historical 1993–2023; projection to 2100 (RCP8.5)	Global sea level rise + deltaic subsidence + tidal amplification	Large-scale land loss and salinity intrusion threaten agriculture and settlements
Agriculture and Food Security	Rice production losses up to 60% in saline-prone zones; 1.1 million tonnes of rice lost during 2024 floods; soil salinity increased by ~26% since 2000	Observed 2000–2024	Salinity intrusion + tidal flooding + soil degradation	Decline in crop yields and shift from rice to shrimp farming; long-term loss of soil fertility
Ecosystems and Biodiversity	45% of the Sundarbans area shows salinity-induced vegetation stress; mangrove dieback in the southern fringe zones is increasing	Observed 2010–2024	Rising sea level + reduced Ganges discharge + saline water intrusion	Loss of mangrove forests and wildlife habitat; reduced natural protection against storm surges
Human Health	25–30% higher prevalence of pregnancy-related	Studies 2010–	Rising groundwater	Increased hypertension, kidney

	hypertension among women exposed to saline drinking water; the WHO salinity limit is often exceeded	2023	salinity + coastal aquifer intrusion	stress, and maternal health complications in coastal populations
Infrastructure and Economy	>2,000 km of coastal embankments requires urgent reinforcement; annual flood damage cost ~USD 1.5 billion	Reports 2023–2024	Storm surge intensity + chronic waterlogging + salt corrosion	Frequent infrastructure damage, port vulnerability (Mongla, Chittagong), and economic losses
Migration and Displacement	≈ 0.9 million people in southern Bangladesh are projected to be displaced by 2050 due to sea level rise and salinity intrusion	Projection to 2050 (RCP8.5)	Permanent inundation + livelihood loss + salinity migration	Climate-induced migration pressures urban areas like Dhaka and Chattogram, and rising urban poverty

Table 05: Sectoral Impacts of Sea Level Rise in Coastal Bangladesh (2020–2100).

Sea level rise in Bangladesh is now a multi-sectoral crisis. The loss of coastal land and farmland is worsening because local subsidence amplifies global sea level rise. Agriculture faces reduced yields, while freshwater scarcity and salinity create severe public health issues. Ecosystems such as the Sundarbans are deteriorating due to prolonged saline intrusion and declining freshwater inflows. Infrastructure faces higher repair costs and failure risks as embankments weaken and ports face chronic flooding. Finally, millions may be forced to migrate internally, making Bangladesh a leading hotspot of climate-induced displacement in South Asia. Together, these findings show that Bangladesh's challenge is not only environmental, it is socio-economic, demographic, and public health-related. Effective adaptation will require integrating engineering resilience, nature-based solutions, and community-level relocation planning.

10. Adaptation and Resilience Strategies in Bangladesh

Bangladesh is one of the most climate-exposed countries in the world, yet it is also known for developing innovative adaptation practices. The country faces the twin challenge of natural vulnerability and rapid socioeconomic change. Sea level rise now intersects with issues of land subsidence, sediment loss, coastal erosion, and saline intrusion. These complex pressures require multi-layered strategies that blend engineering, ecosystem restoration, technological innovation, and social adaptation. The Government of Bangladesh, development partners, and local communities have been implementing adaptive measures for decades, but the recent acceleration of sea level rise and intensification of climate events demand renewed and integrated approaches (The World Bank Group, 2024).

10.1. Coastal Embankments and Structural Adaptation:

The first line of defense against sea level rise in Bangladesh is a massive network of coastal embankments and polders. The Coastal Embankment Project (CEP), started in the 1960s, now includes more than 6,000 kilometers of embankments protecting nearly 1.2 million hectares of coastal land. Over time, these structures have degraded due to poor maintenance and repeated cyclone strikes. To address this, the Bangladesh Water Development Board (BWDB) has launched the Coastal Embankment Improvement Project (CEIP-I) and the Flood and Riverbank Erosion Risk Management Investment Program (FRERMIP) to strengthen embankments and raise their height based on new sea level rise projections. These programs include slope protection, improved drainage, and reinforced materials resistant to salinity. BWDB reports that by 2024, nearly 35% of critical embankment zones had been upgraded with new floodgates, concrete protection, and early warning sensors (Bangladesh Water Development Board, 2024).

However, engineering solutions alone cannot ensure long-term resilience. Embankments restrict sediment flow, which is essential for natural land-building in deltaic environments. Recent research shows that sediment starvation is worsening land subsidence in the coastal delta, particularly in Satkhira and Khulna. Scientists and planners now support "Tidal River Management" (TRM), a community-based system that allows tidal water and sediment to enter selected basins to raise land elevation naturally. TRM has already been implemented successfully in Beel Bhaina and Beel Khuksia, where land levels have increased by more than 0.8 meters within 5 years**,** proving that adaptive delta management can complement hard engineering (Qu et al., 2023).

10.2 Nature-Based and Ecosystem Adaptation:

Bangladesh has started integrating Nature-Based Solutions (NbS) into coastal resilience planning. The most visible example is mangrove restoration in the Sundarbans and adjacent areas. Mangroves reduce storm surge height, trap sediments, and stabilize coastlines. A 2023 joint study by the Department of Environment and the World Bank found that mangrove belts can reduce storm surge impacts by up to 35%, saving millions in avoided damage costs annually. Restoration programs now aim to plant 15,000 hectares of mangroves and salt-tolerant vegetation by 2030 along the coastline (Department of Environment, 2024).

In addition, coastal wetland conservation has become a national strategy under the Bangladesh Delta Plan 2100. Wetlands act as natural water buffers that absorb excess runoff and slow storm surges. The Coastal Greenbelt Project**,** implemented in collaboration with FAO and UNDP, has established vegetation barriers across more than 1,200 kilometers of coastline using salt-tolerant species such as *Avicennia marina* and *Sonneratia apetala*. These plantations are designed to stabilize soil, enhance carbon sequestration, and restore biodiversity. The integration of NbS into climate adaptation policies reflects a growing recognition that hard infrastructure alone cannot offset the long-term effects of sea level rise (Food and Agriculture Organization of the United Nations, 2012).

10.3 Agricultural and Technological Adaptation:

Agricultural adaptation is central to survival in coastal Bangladesh. Salinity, flooding, and waterlogging have transformed cropping patterns in much of the delta. The Bangladesh Rice Research Institute (BRRI) and Bangladesh Agricultural Research Institute (BARI) have developed more than 15 salt-tolerant and submergence-tolerant rice varieties, including BRRI dhan67, BINA dhan10, and BINA dhan11. These varieties can withstand salinity levels of 8–10 dS/m and short-term submergence during storm surges. BRRI's 2024 report shows that the adoption of these varieties has increased rice yield by 40–60% in saline-prone zones, protecting livelihoods and food security (Bangladesh Rice Research Institute, 2024).

Farmers are also using digital early-warning systems and mobile-based advisories. Through apps like "Agri-Meteorological Advisory Service," farmers receive localized flood forecasts, salinity alerts, and irrigation guidance. This has significantly reduced seasonal crop losses in pilot areas. Moreover, the Blue Economy Initiative encourages sustainable aquaculture practices that integrate mangrove buffers and mixed shrimp-fish systems to minimize salinity damage while maintaining income (United Nations Economic and Social Commission for Asia and the Pacific, n.d.).

10.4. Community-Based Adaptation and Disaster Preparedness:

Community-based adaptation (CBA) has become one of the most successful resilience approaches in coastal Bangladesh. Local participation ensures that adaptation measures align with social needs. The Cyclone Preparedness Programme (CPP), jointly managed by the Bangladesh Red Crescent Society and the government, has trained over 85,000 community volunteers in early warning dissemination, evacuation, and first aid. During Cyclone Amphan in 2020, over 2.4 million people were evacuated safely, a record for South Asia (United Nations Office for Disaster Risk Reduction, n.d.).

Community resilience projects also focus on raised housing, floating gardens, and rainwater harvesting. Floating vegetable beds made from water hyacinth allow year-round cultivation during floods, while elevated homesteads protect livestock and reduce displacement. In coastal districts like Gopalganj and Pirojpur, households that adopted floating gardens increased annual income by 30% and reduced food shortage periods by half (United Nations Development Programme, n.d.).

10.5 Policy Frameworks and Institutional Integration:

Bangladesh's adaptation strategy is now guided by the Bangladesh Delta Plan 2100 (BDP2100), a long-term, cross-sectoral framework designed to manage water, land, and climate risks. The plan outlines 80 priority projects with a vision of achieving "safe, climate-resilient, and prosperous deltas." It integrates sea level rise scenarios from the IPCC Sixth Assessment Report and focuses on adaptive delta management. The National Adaptation Plan (NAP), submitted to the UNFCCC in 2023, details sector-specific measures for health, agriculture, water, and disaster risk reduction. The NAP estimates that Bangladesh needs over USD 230 billion in adaptation finance by 2050 to safeguard its deltaic regions (Ministry of Environment, Forest and Climate Change, 2023).

However, accessing international climate finance remains a major challenge. Only 15-20% of the required funding is currently available, mainly from multilateral sources such as the Green Climate Fund and World Bank. Strengthening institutional capacity, improving project appraisal systems, and fostering private-sector investment are essential for scaling resilience efforts.

10.6. Integrated Future Pathways:

The future of Bangladesh's coastal resilience depends on combining engineering and ecological knowledge with digital innovation. Integrated systems using satellite-based early warning, digital twins, and AI-powered risk modeling can predict storm surge impacts, embankment failure, and salinity movement. Combining such tools with community adaptation can shift Bangladesh toward a dynamic adaptation model, where measures evolve as new climate realities emerge.

In summary, Bangladesh's adaptation journey demonstrates the transition from reactive disaster response to proactive resilience building. The mix of structural, ecological, and social measures reflects the country's pragmatic and evolving strategy. Still, the scale of future sea level rise demands deeper international cooperation, stronger local governance, and faster access to climate finance. Without these, the pace of adaptation may fall short of the accelerating physical and social impacts projected for the coming decades.

Strategy / Intervention	Implementing Agency or Partners	Scale / Quantitative Data	Effectiveness or Achievements	Key Challenges / Gaps
Coastal Embankment and Polder Upgrading (CEIP-I, FRERMIP)	Bangladesh Water Development Board (BWDB), World Bank, ADB.	>6,000 km of embankments; 35% upgraded with new floodgates and slope protection by 2024.	Reduces flood risk for ~8 million coastal residents; increased embankment lifespan by 20 years.	Maintenance funding and salinity corrosion remain major issues.
Tidal River Management (TRM)	Local communities, BWDB, NGOs.	Implemented in Beel Bhaina, Beel Khuksia, and Beel Pakhimara (total ~3,500 ha).	Raised land elevation by 0.6–0.9 m in 5 years; improved drainage and crop productivity.	Requires coordinated land-sharing and compensation policy.
Mangrove Restoration and Coastal Greenbelt Project	Department of Environment (DoE), Forest Department, FAO, UNDP.	15,000 ha mangrove plantations targeted by 2030; 1,200 km of vegetative greenbelt established.	Reduces storm surge energy by up to 35%; enhances carbon sequestration and biodiversity.	Limited space for reforestation; high maintenance cost.
Salt- and Submergence-Tolerant Crop Varieties	Bangladesh Rice Research Institute (BRRI), BARI, Ministry of	15+ climate-resilient rice varieties released; BRRI dhan67, BINA	Yields 40–60% higher in saline-prone fields; protects 1.5 million farmers' livelihoods.	Need for wider seed distribution and farmer training.

(BRRI/BARI)	Agriculture.	dhan10, BINA dhan11 widely adopted.		
Cyclone Preparedness Programme (CPP)	Ministry of Disaster Management & Relief, Bangladesh Red Crescent Society.	85,000 trained volunteers; >4,000 shelters upgraded with solar power.	Evacuation success rate above 90% during Cyclone Amphan (2020).	Shelter overcrowding and gender-sensitive facilities remain issues.
Floating Agriculture and Raised Housing	Local communities, UNDP, GIZ, NGOs.	3,000+ floating gardens established; 12,000 raised houses constructed since 2018.	Boosts food security during monsoon floods; 30% income increase in pilot areas.	Needs scaling beyond pilot projects.
Rainwater Harvesting and Desalination Units	Department of Public Health Engineering (DPHE), UNICEF.	~100,000 households now have rainwater systems; 400 small desalination units installed.	Improves access to safe water for 0.5 million people in saline zones.	Limited maintenance and spare-part supply chain.
Bangladesh Delta Plan 2100 (BDP2100)	Planning Commission, Government of Bangladesh, Netherlands Delta Programme.	80+ projects planned; total budget USD 37 billion to 2030.	Framework for integrated land, water, and climate risk management.	Complex inter-ministerial coordination and slow project implementation.
National Adaptation Plan (NAP 2023–2050)	Ministry of Environment, Forest and Climate Change.	Targets USD 230 billion investment by 2050; covers 11 priority sectors.	Long-term adaptation vision: mainstreaming climate resilience into policy.	Funding gaps and donor dependency.
Digital and AI-Enabled Early Warning Systems	Bangladesh Meteorological Department (BMD), World Bank, Digital Bangladesh Initiative.	National satellite-based flood forecast model; mobile alerts reach >10 million users.	Average evacuation time reduced by 40%; forecast accuracy >85%.	Requires integration with local governance and internet coverage.

Table 06: Summary of Adaptation and Resilience Strategies in Coastal Bangladesh (2020–2100).

Bangladesh's adaptation portfolio is broad and increasingly data-driven. Traditional infrastructure, such as embankments and polders, now coexist with nature-based and community-led innovations like TRM and mangrove belts. Technological advances, including AI-driven early warning systems, are improving predictive capability and saving lives. Agricultural resilience programs ensure food security through salt- and flood-tolerant crops. However, institutional coordination and financing remain the two biggest barriers to large-scale implementation.

The key message from Table 06 is that Bangladesh's resilience framework is multi-dimensional; it spans engineering, ecology, agriculture, and community empowerment. The challenge is no longer the absence of solutions but the speed and scale at which these solutions can be expanded to match the pace of environmental change.

11. Discussion

Bangladesh sits at the intersection of science, policy, and survival when it comes to sea level rise. The country's vulnerability is not only the product of its geography but also of complex interactions between global climate processes, regional hydrology, and socio-economic structures. The evidence reviewed in this paper shows that sea level rise in Bangladesh is rising faster than the global mean because of local subsidence, sediment trapping, and upstream flow reduction. These physical changes amplify the exposure of millions of people to flooding, salinization, and land loss. Understanding this interplay is essential to designing adaptation that is both science-based and socially just.

Scientific data from satellites, tide gauges, and ground-based GNSS networks confirm that relative sea levels in parts of coastal Bangladesh are increasing by 6 to 12 millimeters per year, roughly double the global average. This acceleration is a signal of compound risk. Global warming drives ocean thermal expansion and glacier melt, while regional groundwater extraction and sediment compaction worsen subsidence. Without immediate mitigation, these processes will continue to amplify each other, leading to nonlinear environmental change, where small rises in sea level produce exponentially larger impacts on land loss and human displacement (Becker et al., 2020).

11.1 Bridging Science and Policy:

Scientific projections must be translated into policy actions that work at the local level. Bangladesh has made strong progress in developing national adaptation frameworks, such as the Bangladesh Delta Plan 2100 (BDP2100) and the National Adaptation Plan (NAP) 2023. These frameworks align local planning with the IPCC Sixth Assessment Report scenarios. However, the translation from plan to action remains uneven. Coordination gaps persist between water, agriculture, housing, and disaster management sectors. Experts argue that the country needs a unified coastal governance model that integrates sea level rise projections directly into zoning, infrastructure design, and population relocation policies (Ministry of Environment, Forest and Climate Change, 2023). Local governments play a critical role but often lack access to updated risk data. Many district-level plans still rely on historical flood records instead of real-time modeling. Scientific tools such as digital elevation models, AI-based flood simulation, and hydrodynamic forecasting should be integrated into local planning systems. These technologies can identify future inundation zones, helping planners make decisions about land use, housing, and critical infrastructure placement.

11.2 Socioeconomic and Human Dimensions:

The effects of sea level rise extend far beyond environmental damage. Every centimeter of sea level rise translates into lost livelihoods, migration pressure, and new health risks. For example, research shows that in Khulna and Bagerhat, increasing water salinity is linked to a 25-30% rise in pregnancy-related hypertension and kidney disease among coastal women. Migration is another critical dimension. By 2050, nearly one million people in southern Bangladesh could be displaced due to permanent inundation and loss of farmland. Migration is not just a rural-to-urban shift; it also includes circular and seasonal patterns as families move temporarily during high tides or cyclones. Policies must therefore shift from "relocation" to managed mobility, ensuring that migration is safe, voluntary, and supported by social protection systems (The World Bank Group, 2024).

11.3 Role of Nature-Based and Technological Solutions:

The analysis highlights the need to integrate Nature-Based Solutions (NbS) with modern technology. Mangrove restoration, wetland conservation, and tidal river management provide long-term sediment and flood regulation. However, they must be combined with advanced monitoring systems. The use of satellite-based LiDAR mapping, machine learning models, and digital twins can help simulate future coastal changes with high precision. These tools can support adaptive management, where embankment design, land-use zoning, and community planning are continuously updated based on real-time data (UNEP, 2023).

11.4. Economic and Financial Resilience:

Sea level rise also presents an economic challenge. The Bangladesh Delta Plan estimates that maintaining adaptation and coastal infrastructure will require over USD 12 billion per decade. Yet current funding flows are less than one-fourth of this need. Most resources come from donor-led projects, which are fragmented and short-term.

A more effective approach would be to establish a national adaptation financing mechanism that pools funds from public budgets, climate bonds, and private-sector participation. International mechanisms like the Loss and Damage Fund under the UNFCCC could provide additional resources, but Bangladesh must build strong project pipelines to access them efficiently (UNEP, 2023).

11.5 Toward an Integrated Resilience Framework:

True climate resilience for Bangladesh requires breaking down the divide between development, disaster management, and environmental planning. Sea level rise must be treated as a long-term development issue, not just a short-term disaster threat. This means embedding adaptation into housing policy, urban design, public health, and education. Local communities must become active decision-makers rather than passive beneficiaries. Empowering women, farmers, and youth groups through inclusive governance can ensure that adaptation strategies are grounded in local realities and sustained across generations (UNEP, 2023).

Finally, resilience depends on knowledge exchange. Bangladesh can lead globally by sharing its community-based adaptation models with other deltaic nations such as Vietnam, the Philippines, and Indonesia. By combining indigenous knowledge, modern science, and adaptive governance, Bangladesh can become a global learning hub for delta resilience under climate change. In essence, the discussion confirms that Bangladesh's challenge is multi-layered, scientific, infrastructural, ecological, and social. Effective adaptation will depend on continuous data collection, transparent policy coordination, and access to sustained financing. Only through a science-informed and people-centered approach can Bangladesh turn its climate vulnerability into a foundation for global resilience leadership.

12. Findings of the Research

This study synthesized contemporary scientific data, climatic projections, socioeconomic assessments, and policy frameworks to thoroughly investigate the multifaceted effects of sea level rise (SLR) in Bangladesh. The results show that Bangladesh's unique deltaic geography, high population density, and limited capacity for adaptation make it one of the world's most vulnerable regions, especially its southern coastal region. Sea level rise poses a danger to sustainable development, national food security, and livelihood stability through important environmental, ecological, agricultural, infrastructural, and human elements, according to the research.

12.1 Accelerated Sea Level Rise and Coastal Inundation:

The analysis confirms that the rate of sea level rise in the coastal zones of Bangladesh has accelerated significantly over recent decades, averaging between 3.8 mm and 6.0 mm per year based on tide gauge and satellite data. Relative sea level rise is further amplified by local land subsidence in several deltaic districts, including Khulna, Satkhira, and Barguna. As a result, large portions of low-lying land are being permanently or seasonally inundated, increasing salinity intrusion and coastal erosion. Projections suggest that by 2100, approximately 15–17% of Bangladesh's coastal land could be submerged under high-emission scenarios, placing millions of people at direct risk of displacement.

12.2 Escalating Salinity Intrusion in Soil and Water Resources:

The study finds that sea level rise, coupled with reduced freshwater inflow and unregulated groundwater extraction, has intensified salinity intrusion in both surface and groundwater systems. Elevated salinity levels are now detectable as far as 100 kilometers inland from the coast during the dry season. This intrusion has degraded soil fertility, disrupted agricultural productivity, and contaminated drinking water sources. The long-term accumulation of salt in soils has transformed large tracts of previously arable land into marginal or unproductive zones, forcing a shift from rice cultivation to salt-tolerant crops and shrimp aquaculture.

12.3 Agricultural Loss and Food Security Threats:

One of the industries most negatively affected by sea level rise is agriculture, particularly rice production. The results show that main crops like rice, legumes, and vegetables have lower yields due to saltwater intrusion and sporadic waterlogging. According to empirical evidence, yield loss in coastal polders has already reached critical levels, and saline concentrations exceeding 4 dS/m can lower rice yields by more than 50%. While some farmers have benefited from the growing conversion of cropland to aquaculture, social inequality has increased as landless laborers experience job loss and food insecurity. In general, Bangladesh's national food self-sufficiency is seriously threatened by sea level rise.

12.4. Adverse Impacts on Ecosystems and Biodiversity:

The research reveals that sea level rise and saline encroachment are profoundly affecting coastal and estuarine ecosystems, particularly the Sundarbans, the largest mangrove forest in the world. Rising salinity levels, tidal flooding, and erosion have led to habitat degradation, shifts in species composition, and increased mortality of freshwater-dependent flora and fauna. Endangered species such as the Bengal Tiger, Irrawaddy Dolphin, and estuarine crocodile face shrinking habitats and food scarcity. Ecosystem fragmentation has weakened the natural coastal defense functions of mangroves, reducing their capacity to buffer storm surges and coastal erosion.

12.5 Intensification of Human Health Risks:

Findings show a growing body of evidence linking sea level rise–induced salinity intrusion and waterlogging to adverse health outcomes. Populations in coastal districts experience elevated risks of hypertension, skin diseases, diarrheal infections, and pregnancy-related complications due to high salinity in drinking water. The spread of vector-borne diseases such as cholera and dengue is also facilitated by stagnant and contaminated water. Furthermore, the stress of livelihood loss and migration contributes to rising mental health burdens, especially among women and elderly groups. Health infrastructure in coastal regions remains insufficient to address these emerging climate-induced health crises.

12.6 Displacement, Migration, and Livelihood Vulnerability:

The study identifies climate-induced displacement as one of the most severe socio-economic consequences of sea level rise. Coastal flooding, saline intrusion, and erosion have already displaced hundreds of thousands of people from districts like Bhola, Patuakhali, and Khulna. Many of these displaced individuals migrate to urban slums in Dhaka and Chattogram, creating new pressures on urban infrastructure, housing, and employment. The findings suggest that without robust adaptation and resettlement planning, sea level rise could displace 10-13 million people by the end of the century, transforming internal migration patterns and exacerbating poverty cycles.

12.7 Damage to Coastal Infrastructure and Urban Settlements:

Sea level rise poses escalating risks to infrastructure, including roads, embankments, drainage systems, ports, and urban housing. Frequent tidal inundation and storm surges weaken embankments, erode riverbanks, and damage essential facilities such as schools, hospitals, and markets. In many coastal municipalities, drainage congestion caused by high tide backflow now occurs regularly, disrupting local economies and sanitation systems. The findings emphasize that critical lifeline infrastructures, especially in Khulna, Barisal, and Patuakhali-require urgent upgrading with climate-resilient design standards to prevent recurrent economic losses and displacement.

12.8 Socio-Economic Inequality and Gender Dimensions:

The study reveals that sea level rise disproportionately affects marginalized and economically vulnerable groups, deepening existing inequalities. Women, smallholder farmers, and landless laborers are often the first to lose access to income and safe water sources. Women, in particular, face increased workloads for collecting potable water and maintaining household health, while also being more vulnerable to exploitation during migration. These gendered dimensions of vulnerability underscore the need for gender-sensitive adaptation policies and inclusive community-based decision-making mechanisms.

12.9 Inadequate Institutional and Governance Responses:

The assessment finds that while Bangladesh has made significant policy advances, such as the Bangladesh Delta Plan 2100 and the National Adaptation Plan, implementation gaps persist at local and institutional levels. Weak coordination among agencies, limited data-sharing systems, and insufficient financial mechanisms have hindered effective adaptation. Many local adaptation projects lack integration across sectors, resulting in fragmented and short-term interventions. Strengthening institutional capacity, local governance, and adaptive financing frameworks remains a major national challenge in managing sea level rise sustainably.

12.10 Need for Integrated and Adaptive Coastal Management:

The overall findings point to the urgent need for a holistic, multi-sectoral, and adaptive management framework that integrates climate modeling, ecosystem restoration, infrastructure resilience, and social adaptation. Combining engineered solutions (embankments, drainage upgrades) with nature-based approaches (mangrove restoration, sediment management) will enhance both ecological and human resilience. Effective adaptation must also include proactive migration planning, decentralized data systems, and inclusive participation of local communities in decision-making.

In summary, this research confirms that sea level rise in Bangladesh is not merely an environmental issue; it is a comprehensive socio-ecological crisis affecting land, water, agriculture, health, infrastructure, and human security. The cumulative evidence shows that coastal Bangladesh is experiencing a slow-onset disaster with accelerating intensity. The findings highlight the necessity for immediate and science-based policy actions that couple short-term protection measures with long-term resilience building. Only through integrated research, inclusive governance, and sustained adaptation financing can Bangladesh safeguard its coastal ecosystems and communities from the escalating threats of sea level rise.

13. Limitations of the Research

Although this research presents a comprehensive and multi-dimensional assessment of sea level rise and its socio-environmental impacts in Bangladesh, several limitations must be acknowledged to ensure transparency and guide future research directions. These limitations mainly stem from the availability of data, methodological constraints, spatial and temporal uncertainties, and the complexity of linking environmental changes with socio-economic responses in a deltaic ecosystem like Bangladesh.

First, this research is based primarily on secondary data obtained from existing scientific literature, government reports, satellite observations, and climate models rather than original field data collection. As a result, the accuracy of certain sectoral analyses, particularly related to localized salinity intrusion, sedimentation dynamics, and livelihood impacts, depends heavily on the quality, coverage, and resolution of previously published datasets. The absence of primary field measurements or long-term ground-based monitoring limits the study's ability to validate model-derived projections at the micro-regional scale. This constraint may introduce some degree of uncertainty when generalizing the findings to all coastal districts.

Second, the future projections of sea level rise used in this study are derived from global and regional models, such as those developed by the Intergovernmental Panel on Climate Change (IPCC) and Bangladesh-specific assessments. However, such models involve considerable uncertainty due to their dependence on future greenhouse gas emission pathways, ice sheet melting dynamics, and land subsidence variability across coastal zones. The highly non-linear behavior of ice sheets and the difficulty in predicting future anthropogenic emissions mean that even the best models can produce wide-ranging scenarios. Consequently, the precise magnitude and timing of projected sea level rise in Bangladesh remain uncertain.

Third, the study's integration of hydrological, ecological, agricultural, and socio-economic data involves harmonizing information from diverse sources that use different temporal baselines, spatial resolutions, and methodological frameworks. This can introduce inconsistencies when comparing or aggregating sectoral impacts. For instance, agricultural loss estimates and migration projections reported by different agencies often rely on distinct climate models and socio-economic assumptions. Although cross-validation was attempted through triangulation, full comparability among datasets could not always be achieved.

Fourth, the study does not incorporate extensive field-level stakeholder consultations or participatory vulnerability assessments due to time and logistical constraints. This limitation restricts the depth of local institutional, governance, and community-level analysis. As a result, while national policy frameworks such as the Bangladesh Delta Plan 2100 and National Adaptation Plan (NAP) were reviewed comprehensively, the study could not capture the nuanced socio-political factors that influence implementation efficiency, resource allocation, or local adaptation behaviors in specific coastal communities.

Fifth, there are inherent limitations in quantifying causal relationships between sea level rise and its indirect impacts, such as on public health, migration, and gender vulnerability. While the study identifies strong associations reported in prior literature (for example, the link between salinity intrusion and hypertension, or displacement and livelihood insecurity), the lack of primary epidemiological or longitudinal socio-economic data prevents firm causal attribution. Thus, such relationships should be interpreted as indicative rather than definitive.

Sixth, the spatial variability of land subsidence and sediment dynamics in the Ganges–Brahmaputra–Meghna delta introduces additional uncertainty in estimating relative sea level rise. The subsidence rates are not uniform across regions and depend on natural compaction, groundwater extraction, and sediment load variations. Limited high-resolution InSAR and GNSS-based subsidence data make it difficult to project localized inundation and erosion risks with full confidence.

Finally, this study's temporal scope is limited to the most recent data available up to 2025. Given the rapidly evolving nature of climate science, remote sensing technologies, and coastal monitoring systems, newer datasets and improved models may modify some of the findings in the near future. Continuous data updates, model recalibration, and integration of real-time monitoring will be essential to maintain accuracy and policy relevance.

Despite these limitations, the findings of this research remain robust in highlighting the multi-sectoral risks posed by sea level rise and the urgent need for integrated adaptation strategies in Bangladesh's coastal region. Future studies should focus on high-resolution field monitoring, coupled human-environment system modeling, and participatory local governance assessments to bridge existing data and knowledge gaps. These improvements will strengthen predictive capacity, enhance the precision of vulnerability mapping, and support more effective, evidence-based resilience planning for coastal Bangladesh.

14 Future Research Directions

To build upon the findings and overcome the limitations identified in this study, several future research directions are proposed. These directions aim to deepen scientific understanding, enhance data accuracy, and strengthen adaptive capacity for managing sea level rise in Bangladesh. The following research pathways are recommended to support evidence-based policymaking, regional resilience planning, and integrated climate adaptation.

13.1 Establishment of High-Resolution Coastal Monitoring Systems:

Future research should prioritize the development of a continuous and high-resolution coastal monitoring network that integrates satellite remote sensing with ground-based observations. This includes the installation of modern tide gauges, InSAR (*Interferometric Synthetic Aperture Radar*) sensors, GNSS (*Global Navigation Satellite System*) stations, and automated salinity and sedimentation monitoring devices across coastal districts. Long-term datasets generated from such systems will help track local land subsidence, tidal variations, sediment deposition, and shoreline changes with high precision. Additionally, by improving the calibration and validation of regional climate and hydrodynamic models, this data infrastructure will provide more precise forecasts of sea level rise and related coastal risks.

13.2 Integrated Modeling of Climate, Hydrology, and Socio-Economic Systems:

A major future priority is to develop integrated modeling frameworks that couple physical processes (e.g., sea level dynamics, river discharge, sediment transport) with socio-economic and ecological systems. Advanced models, such as coupled human–natural system (CHANS) models, machine learning-based predictive tools, and system dynamics simulations, can provide more realistic forecasts of how communities, infrastructure, and ecosystems will respond to multiple stressors. In particular, dynamic models that simulate the combined effects of sea level rise, land subsidence, salinity intrusion, and extreme weather events on agriculture, fisheries, and migration can inform adaptive policy interventions at national and local scales.

13.3 Longitudinal Studies on Health and Livelihood Impacts:
There is an urgent need for longitudinal and epidemiological studies to examine how chronic exposure to salinity intrusion, waterlogging, and ecosystem degradation affects human health, nutrition, and livelihoods over time. Future research should include medical and socio-economic surveys in coastal upazilas, focusing on vulnerable populations such as women, children, and elderly groups. Establishing long-term health-environment monitoring will clarify causal pathways, for example, between drinking water salinity and hypertension or between livelihood insecurity and climate-induced migration. Such research can directly support the design of community health adaptation programs and targeted livelihood diversification strategies.

13.4. Socio-Political and Governance Studies on Adaptation Effectiveness:
To strengthen adaptation outcomes, future research must explore the institutional, governance, and policy dimensions of sea level rise management in greater depth. Studies should assess how coordination among government agencies, local institutions, and international donors affects project implementation, monitoring, and accountability. Special attention should be given to evaluating the effectiveness of national frameworks such as the Bangladesh Delta Plan 2100, National Adaptation Plan (NAP), and Mujib Climate Prosperity Plan. Comparative policy analysis across administrative tiers (national–regional–local) would provide valuable insights into institutional bottlenecks, power asymmetries, and financing gaps that constrain climate resilience efforts.

13.5. Advancement of AI and Machine Learning Applications:
Artificial Intelligence (AI) and machine learning (ML) can play transformative roles in improving prediction, early warning, and decision-making for sea level rise impacts. Future studies should develop AI-based models for forecasting coastal flooding, identifying erosion hotspots, and optimizing adaptation resource allocation. Integration of satellite imagery, real-time hydrological data, and socio-economic indicators through ML algorithms can support dynamic vulnerability mapping and risk prioritization. Moreover, digital twin technologies can be developed for coastal cities such as Khulna, Barisal, and Chattogram to simulate future sea level and storm surge scenarios, enabling proactive urban resilience planning.

13.6. Ecosystem-Based Adaptation (EbA) and Nature-Based Solutions Research:
Further research is required to evaluate the long-term ecological and socio-economic benefits of ecosystem-based adaptation (EbA) and nature-based solutions (NbS) in mitigating sea level rise impacts. This includes assessing the carbon sequestration potential of mangrove restoration, coastal afforestation, and wetland rehabilitation projects under different climate and hydrological conditions. Quantitative studies should also examine the cost-effectiveness, scalability, and co-benefits (biodiversity, livelihood support, disaster risk reduction) of NbS compared to conventional structural interventions like embankments and polders. Integrating ecological modeling with socio-economic valuation frameworks will help policymakers justify larger investments in nature-based coastal defenses.

13.7. Climate-Induced Migration and Urbanization Studies:
Sea level rise is expected to displace millions of people from coastal Bangladesh over the coming decades, leading to large-scale internal migration and rapid urbanization. Future research should adopt interdisciplinary approaches combining demographic modeling, GIS-based spatial analysis, and social surveys to map migration pathways, settlement trends, and urban absorption capacity. Studies should also evaluate the socio-economic and psychological consequences of displacement, as well as the policy readiness of receiving cities to accommodate migrants sustainably. Understanding these migration dynamics is critical for planning inclusive, climate-resilient urban infrastructure and social safety nets.

13.8. Economic Valuation and Cost–Benefit Analysis of Adaptation Measures:
Further research should focus on quantifying the economic costs and benefits of various adaptation strategies, including both hard-engineering and soft-ecological interventions. Comprehensive cost–benefit analyses and cost-

effectiveness studies will help identify optimal resource allocation strategies for government agencies and international donors. Integrating economic modeling with risk assessment frameworks will allow policymakers to prioritize investments that yield the highest long-term resilience returns per unit cost. Such studies are vital for designing adaptive financing mechanisms, climate insurance schemes, and sustainable funding models for coastal adaptation.

13.9. Integration of Community-Based and Participatory Research Methods:

Local knowledge and community experience are invaluable for understanding fine-scale environmental changes and social responses to sea level rise. Future research should incorporate participatory rural appraisal (PRA), focus group discussions, and co-production of knowledge with local communities, especially marginalized groups in highly exposed coastal belts. Participatory vulnerability mapping, local adaptation planning workshops, and citizen science initiatives can improve the accuracy of vulnerability assessments and enhance the social acceptance of adaptation measures. This community-driven approach ensures that future strategies are not only scientifically sound but also socially equitable and locally implementable.

13.10. Development of Climate-Resilient Infrastructure and Urban Design Frameworks:

Urban and infrastructure resilience in coastal regions will be a major challenge under rising sea levels. Future research should explore design innovations for elevated housing, amphibious infrastructure, flood-resilient transportation systems, and sustainable drainage solutions suitable for low-lying deltaic settings. Engineering studies should integrate hydrodynamic modeling with urban design to develop context-specific prototypes for climate-resilient settlements. Additionally, investigating the potential of renewable energy integration (e.g., solar, biogas) in coastal infrastructure can support energy security and emission reduction goals simultaneously.

In conclusion, future research must use an interdisciplinary, integrated, data-driven paradigm that links engineering, socioeconomics, governance studies, and the physical sciences. In addition to improving estimates of sea level rise and its complex effects, filling in these research gaps will direct the development of fair and long-term adaptation plans for Bangladesh's coastal communities. In order to ensure that Bangladesh continues to be a global leader in managing coastal hazards in the era of rapid climate change, the next generation of research should prioritize real-time data integration, AI-based predictive modeling, participatory governance, and ecosystem-centered resilience development.

14. Conclusion

Sea level rise has emerged as one of the most pressing existential threats for Bangladesh, an intricate challenge that extends far beyond the environmental domain and reaches deep into the country’s social, economic, and political fabric. This research combined findings from hydrological, ecological, agricultural, infrastructure, and socioeconomic investigations to investigate the multifaceted effects of increasing seas on coastal Bangladesh. What became evident through this work is that sea level rise is not a distant or abstract concern; it is an unfolding reality that is already reshaping the nation’s coastal landscapes, ecosystems, and livelihoods. Bangladesh’s vulnerability to sea level rise stems from the combined influence of its deltaic topography, high population density, and economic dependence on climate-sensitive sectors. Coastal regions such as Khulna, Satkhira, Bhola, Barguna, and Patuakhali are experiencing relative sea level increases much higher than the global average due to local subsidence, sediment depletion, and tidal amplification. These changes are not occurring in isolation; they interact with other stressors like unregulated land use, deforestation of mangroves, and unsustainable groundwater extraction, creating a complex web of cascading impacts.

The findings of this research highlight several key realities. First, salinity intrusion is silently but steadily transforming the agricultural and ecological character of the coastal belt. Once-fertile paddy fields are becoming saline wastelands, forcing farmers to shift toward shrimp cultivation and other salt-tolerant livelihoods. While this transition provides short-term economic relief for some, it often increases social inequality and environmental degradation. Second, the health consequences of saline water exposure, ranging from hypertension to reproductive complications, are mounting, especially among rural women and children. Third, climate-induced displacement is already underway, pushing thousands of families from eroding or waterlogged lands into overcrowded urban areas, where poverty and social vulnerability are often amplified. Equally concerning is the stress on coastal infrastructure. Roads, embankments, and drainage systems designed for historical sea levels are increasingly failing under the pressure of tidal flooding and storm surges. Urban settlements in low-lying zones are facing recurrent inundation, damaging homes, schools, and essential services. The combined effect of these factors is the slow but steady erosion of livelihood security and community resilience in Bangladesh's coastal districts.

Despite these daunting challenges, this research also identifies significant opportunities for transformative adaptation. Bangladesh possesses a long history of community resilience and disaster management expertise. If harnessed strategically, this experience can guide a new phase of adaptive development that combines engineering innovation with ecological wisdom. Strengthening embankments and drainage systems remains necessary, but the future of coastal adaptation must go beyond concrete structures. It must embrace nature-based solutions such as mangrove restoration, wetland rehabilitation, and sediment management to restore the delta's natural defenses. These ecosystem-based approaches can reduce risk while providing co-benefits like carbon sequestration, biodiversity conservation, and livelihood diversification. Moreover, effective governance will be the cornerstone of any successful adaptation pathway. While national policies such as the Bangladesh Delta Plan 2100 and the National Adaptation Plan offer comprehensive frameworks, their success ultimately depends on robust local implementation, transparent financing, and genuine community participation. Policies need to shift from reactive crisis response toward proactive risk management that anticipates long-term environmental changes. This includes strengthening local governments, decentralizing adaptation funds, and creating institutional mechanisms that connect science, policy, and local action in real time. In this context, scientific advancement, particularly in data analytics, AI, and predictive modeling, can redefine how Bangladesh plans for sea level rise. Integrating satellite monitoring, artificial intelligence, and community-based data collection will allow for more dynamic and spatially precise risk assessments. Digital tools can help policymakers anticipate inundation patterns, prioritize vulnerable zones, and design adaptive infrastructure that evolves with changing environmental conditions.

Ultimately, what this research underscores are that the challenge of sea level rise in Bangladesh is both urgent and solvable, but only through coordinated, evidence-based, and inclusive action. The problem cannot be viewed as purely environmental; it is a developmental, humanitarian, and governance issue at its core. Addressing it requires more than building embankments; it demands rethinking how the nation manages its land, water, ecosystems, and people in a changing climate. If Bangladesh invests in science-driven adaptation, strengthens institutional accountability, empowers local communities, and integrates nature-based and technological innovations, it can transform its coastal vulnerability into a model of resilience. The battle against sea level rise is not just about defending land; it is about safeguarding human dignity, cultural continuity, and the right to a sustainable future. Finally, this study reaffirms that sea level rise is both a warning and an opportunity, a warning that unsustainable development will deepen human suffering, and an opportunity to rebuild a smarter, greener, and more adaptive Bangladesh. The nation's response in the coming decades will define not only the fate of its coastal communities but also its role as a global leader in climate resilience.

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