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ARTICLE

Climate Change Impacts and Strategic Solutions: Addressing Water and Ecological Challenges in Bangladesh

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ABSTRACT

Bangladesh, one of the most climate-vulnerable countries in the world, faces significant environmental threats due to its low-lying topography, high population density, and geographical location. Climate change exacerbates challenges such as rising temperatures, erratic rainfall, increased flood frequencies, sea-level rise, riverbank erosion, and degradation of water resources. Between 1990 and 2020, the mean annual temperature increased by approximately 0.19 °C per decade, while rainfall variability intensified, with extreme precipitation events rising by 35%. Flood frequency in the Ganges-Brahmaputra-Meghna basin increased by 21%, with 1-in-20-year floods now occurring every 4–7 years. Coastal salinity intrusion expanded inland by up to 120 kilometers, severely impacting agriculture and freshwater access. Eutrophication-driven harmful algal blooms, triggered by increased nutrient loading from agriculture and poor wastewater management, have increased in frequency by 42%, particularly during the dry season. This paper investigates these interconnected effects of climate change on Bangladesh's river dynamics and water bodies using hydrological modeling and long-term observational data. It evaluates adaptive and mitigative strategies, including ecological restoration, renewable energy adoption, and sustainable land management. Emphasizing the need for data-driven policy frameworks, the study offers practical recommendations to reduce nutrient pollution, enhance agricultural resilience, and manage water resources sustainably, thereby improving long-term climate resilience in Bangladesh.

Keywords: Climate Change; Riverbank Erosion; Land Management; Ecological Restoration; Renewable Energy; Sustainable Development

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1. Introduction

Bangladesh, situated in the vast delta formed by the Ganges-Brahmaputra-Meghna (GBM) river system, is globally recognized as one of the most climate-vulnerable countries [1, 2]. Its geographical location, combined with low-lying topography and a network of more than 700 rivers, makes the country uniquely susceptible to a range of hydro-climatic hazards [2, 3]. Rising sea levels, intensified flooding, salinity intrusion, and riverbank erosion many of which are exacerbated by climate change pose existential threats to both natural ecosystems and human settlements. Projections by the Intergovernmental Panel on Climate Change (IPCC) estimate that sea levels could rise by up to 1 meter by the end of the century, with the potential to inundate 17% of Bangladesh's land and displace over 30 million people [1, 3, 4].

The impacts of climate change are not restricted to coastal areas. Inland regions are increasingly experiencing erratic rainfall patterns, prolonged droughts, reduced river flows, and groundwater stress, all of which are contributing to agricultural losses, declining fish stocks, and food insecurity [5–10]. Salinity intrusion in river systems is degrading freshwater habitats and altering species composition, particularly in the southwest coastal region [6, 11–13]. At the same time, overexploitation of aquifers and sedimentation of riverbeds are further complicating water management efforts [14–17]. These shifts are not merely seasonal or temporary; they represent systemic transformations in hydrological and ecological dynamics driven by anthropogenic pressure and climate change [18–20].

A growing area of concern within this shifting paradigm is the intensification of harmful algal blooms (HABs) in rivers and reservoirs, particularly during the dry season. Such blooms have been directly linked to eutrophication triggered by excessive nutrient loading from agricultural runoff and untreated wastewater [8, 12, 21]. Additionally, rising ambient and water temperatures accelerate algal growth rates, with severe implications for dissolved oxygen levels and aquatic biodiversity [21, 22]. In Bangladesh, dry-season flow reductions due to upstream water diversion especially in the Ganges and Teesta rivers further exacerbate the stagnation of water bodies, creating optimal conditions for bloom formation [23, 24]. Research has shown that nutrient enrichment from fertilizers, coupled with inefficient wastewater management, significantly contributes to this environmental hazard [21, 25].

While these interlinked challenges pose formidable threats, they also provide a critical opportunity to reassess national policies on land and water management. There is growing recognition that climate resilience must be achieved through integrative, data-driven strategies that combine ecological restoration, innovative technologies, and community participation [26–28]. For example, afforestation, wetland rehabilitation, and soil stabilization initiatives have shown promising outcomes in reducing surface runoff and enhancing carbon sequestration [27, 29, 30]. Meanwhile, renewable energy applications such as solar-powered irrigation and biogas systems are emerging as viable alternatives to conventional, carbon-intensive methods, especially in remote and climate-sensitive areas [17, 22].

From a governance perspective, aligning adaptation strategies across sectors such as agriculture, water resources, disaster management, and urban planning is essential for meaningful outcomes [28, 31]. Technological interventions, including high-resolution hydrodynamic modeling and satellite-based remote sensing, have made it possible to simulate and forecast hydrological scenarios with greater accuracy [32, 33]. When combined with participatory rural appraisal methods, these tools can empower local communities to act as stakeholders in sustainable development [34, 35].

This study explores climate-induced transformations in Bangladesh's riverine systems, focusing particularly on dry-season flow alterations, algal bloom dynamics, and integrated land-water management. By combining empirical data, numerical simulations, and case-specific policy analysis, the research aims to offer scientifically robust and contextually relevant strategies for climate adaptation and ecological sustainability [36–39]. Unlike previous studies that often focus on isolated climatic impacts, this research provides a holistic, multi-scalar analysis integrating hydrological, ecological, and socio-political dimensions. It uniquely addresses seasonal hydrological shifts and eutrophication patterns using both quantitative modeling and spatial mapping techniques.

2. Materials and Methods

2.1. Study Area

This study focuses on the transboundary river systems of Bangladesh namely the Ganges (locally known as the Padma), the Brahmaputra (Jamuna), and the Meghna collectively forming the Ganges-Brahmaputra-Meghna (GBM) river basin. The study area spans approximately between latitudes 22.0°N and 26.0°N and longitudes 88.0°E and 92.5°E. These rivers serve as the hydrological backbone of the country, supporting agriculture, fisheries, transportation, and freshwater supply, and sustaining over 160 million people [1, 2].

The GBM river system carries one of the world's largest freshwater discharges, contributing to rich biodiversity and extensive floodplain ecosystems [3]. The Padma River enters Bangladesh from India and merges with the Jamuna River near 23.55°N, 89.80°E. The Jamuna, a braided river with highly dynamic channels, originates from the Brahmaputra River and enters Bangladesh near 25.75°N, 89.80°E. The Meghna, fed by several tributaries including the Surma and Kushiyara, drains the eastern region and flows into the Bay of Bengal near 23.03°N, 90.66°E. These rivers exhibit seasonal variability, driven by monsoon rainfall and Himalayan snowmelt [5, 6].

Ecological conditions across these river systems have undergone significant changes over the past decades. The construction of upstream dams and barrages has altered natural flow regimes, leading to reduced dry-season flow, riverbed siltation, and altered sediment dynamics [7, 11]. Salinity intrusion has intensified in the southern coastal areas, particularly in Khulna Division, threatening mangrove ecosystems and freshwater availability [14]. Erosion and accretion processes have become more unpredictable, particularly along the Jamuna, due to its meandering and braided nature [15]. Moreover, nutrient loading from agricultural runoff and urban wastewater has led to periodic algal blooms and degraded water quality, especially in stagnant zones and floodplain wetlands [12, 16].

To investigate these dynamics, key sampling sites were selected across Khulna, Rajshahi, and Sylhet Divisions (**Figure 1**), representing southern, western, and northeastern hydrological and ecological zones, respectively. The study uses hydrometeorological and environmental data from 1990 to 2020 to capture long-term climate variability, including river discharge, water level, nutrient concentrations, surface water temperature, rainfall, and evapotranspiration. These datasets were collected through both satellite remote sensing platforms and field-based observational networks, allowing a comprehensive assessment of long-term trends and regional variations in riverine behavior and ecosystem health [8, 21]. This study used Landsat (5, 7, and 8) and Sentinel-2 satellite imagery to assess land use change, flood extent, and water quality indicators. The data were sourced from USGS Earth Explorer and Copernicus Open Access Hub for Landsat and Sentinel-2 data, respectively, selected for their long-term availability, high spatial resolution, and free public access.

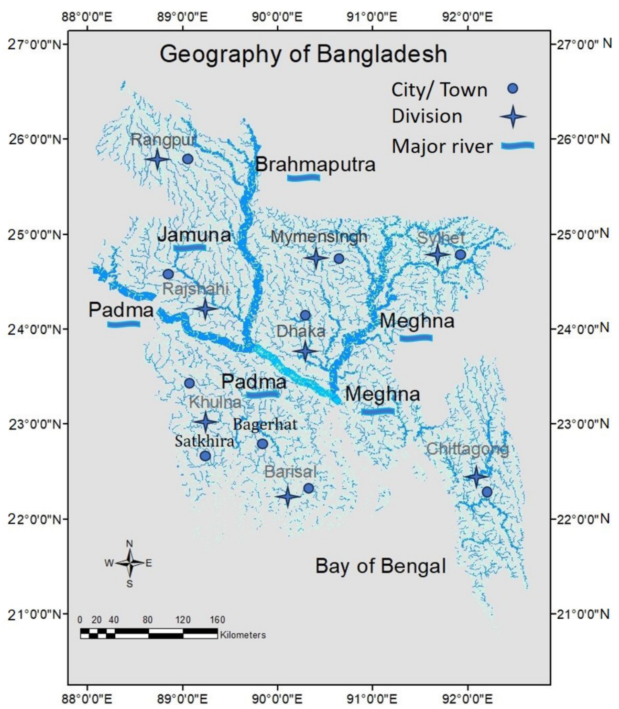

Figure 1. Major rivers and divisions (regions) of Bangladesh.

2.2. Hydrodynamic Modeling

In hydrodynamic modeling, accurately representing the physical behavior of open-channel flow is essential for understanding river dynamics, predicting water levels, and managing ecological risks such as algal blooms [21, 32]. Each formula used in this study serves a specific functional role within the simulation framework. Manning's equation is employed to estimate flow velocity based on channel roughness and geometry [16], critical for simulating discharge and energy losses due to friction [15]. The equation is:

$$V = \frac{1}{n} R^{2/3} S^{1/2} \quad (1)$$

Where *V, R,* and *S* are the flow velocity (m/s), Manning's roughness coefficient, Hydraulic radius (m), cross-sectional area of flow (m^3), wetted perimeter (m) and bed slope (dimensionless). The continuity equation ensures mass conservation by maintaining a consistent balance of inflow and outflow in a control volume [16]. The equation is:

$$Q = A.V \quad (2)$$

Where: *Q, A, V* are the discharge or flow rate (m^3/s), cross-sectional area (m^2) and flow velocity (m/s). For modeling unsteady and gradually varied flows, the St. Venant equations provide a robust foundation by incorporating both momentum and mass conservation principles [32]. These are essential in capturing temporal changes in river discharge, especially during dry-season flow reductions [18, 24]. The equation governing the flow depth *h* and discharge *Q* is:

$$\frac{\partial Q}{\partial x} = -g.A.\frac{\partial h}{\partial x} - A.S_f \quad (3)$$

Where: *g, A, h,* S_f, *x* are the gravitational acceleration (9.81 m/s^2), cross-sectional area (m^2), flow depth (m), friction slope (dimensionless) and distance along the channel (m). The friction slope S_f is related to the bed slope *S* and the resistance of the flow (e.g., through Manning's equation). The specific energy equation evaluates the total mechanical energy of flowing water, supporting the analysis of critical flow conditions and channel transitions [16, 22]. The specific energy equation is:

$$E = h + \frac{V^2}{2g} \quad (4)$$

Where: *E, h, V, g* are the specific energy (J), flow depth (m), flow velocity (m/s), and gravitational acceleration. The friction slope formula, derived from Manning's equation, quantifies energy loss due to bed resistance and is vital for computing water surface profiles [15, 16]. It is given by:

$$S_f = \frac{n^2 Q^2}{R^{4/3} A^{2/3}} \quad (5)$$

Where: S_f, *n, Q, R, A* are the friction slope (dimensionless), Manning's roughness coefficient (dimensionless), discharge (m^3/s) and cross-sectional area (m^2). The relationship between flow depth *h*, bed slope *S* and friction slope S_f is often expressed as an energy balance equation. In steady flow, the gravitational energy must balance the frictional energy losses:

$$S_f = S \quad (6)$$

In unsteady flow, this relationship is more complex and is described by the St. Venant equations (mentioned earlier), which account for both the bed slope and the friction slope. Finally, spatial outputs are integrated with GIS to identify vulnerable zones and inform adaptive management strategies, enhancing climate resilience and supporting sustainable river basin planning [28, 34].

As presented in **Table 1**, these conditions are essential for ensuring that the hydrodynamic model behaves as expected and is physically realistic, based on the specific characteristics of the modeled system.

2.3. Data Analysis and Scenario Building

Satellite imagery from Landsat 8 and Sentinel-2 was processed to detect land use/land cover (LULC), water body shrinkage, and vegetative health using Normalized Difference Vegetation Index (NDVI) and Modified Normalized Difference Water Index (MNDWI) [36]. GIS-based spatial overlay techniques identified critical zones of erosion, salinity intrusion, and flood vulnerability [33, 40]. Chlorophyll-a concentration, Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), and salinity levels were monitored seasonally [21]. Nutrient

Table 1. Different Boundary Conditions for Hydrodynamic Modelling.

Boundary Type	Condition	Equation/Description
Inlet (Upstream)	Flow Hydrograph	$Q(x_{0,} t) = Q(t)$
	Stage Hydrograph	$h(x_{0,} t) = h(t)$
	Velocity Profile	Specified velocity distribution across the channel (uniform, parabolic, etc.)
	Flow Rate and Velocity	Both discharge and velocity can be specified at the inlet $Q(x_{0,} t), V(x_{0,} t)$
Outlet (Downstream)	Stage (Water Surface Elevation)	$h(x_{L,} t) = h_L(t)$
	Discharge Hydrograph	$Q(x_{L,} t) = Q_L(t)$
	Normal Flow Condition	$S_f = S$, where S_f is the friction slope and S is the bed slope
	Zero Flow Gradient	$\frac{\partial h}{\partial x} = 0$ at the outlet boundary, indicating no change in water depth at the boundary.
Lateral	No-Flow Boundary	$\frac{\partial h}{\partial n} = 0$ where n is the normal direction to the lateral boundary
	Specified Stage or Discharge	$h(x,t) = h_L(t)$ or $Q(x,t) = Q_L(t)$
Initial Conditions	Initial Flow Depth	$h(x, t=0) = h_0(t)$
	Initial Velocity	$V(x, t=0) = V_0(x)$

loads (Nitrogen, Phosphorus) were determined through spectrophotometric methods [12, 21], and algal bloom prediction was carried out using empirical thresholds linked with flow reduction and temperature rise [8, 23]. Time-series decomposition, correlation, and regression analyses were performed using R and MATLAB [9]. Climate scenarios (RCP4.5 and RCP8.5) from the IPCC's CMIP6 were downscaled for regional relevance using the delta method [1]. Decision Support Systems (DSS) were developed to facilitate integrated land-water planning based on the simulation results and climate projections [26, 28].

3. Results

3.1. Rainfall and River Flow Dynamics

Figure 2 illustrates the spatial implications of increased monsoonal discharge across major rivers. Between 1990 and 2020, river flows intensified during the monsoon season (**Table 2**), with the Ganges and Brahmaputra experiencing 18% and 14% increases, respectively. This elevated flow correlates with heightened precipitation extremes over the GBM basin, linked to shifting rainfall patterns driven by global warming [5, 9, 10]. The expansion of flood-prone areas in 2020, particularly along upstream channels, mirrors these discharge trends. Conversely, a 19% reduction in Meghna's dry-season flow contributes to wetland stress and accentuates seasonal water imbalances in downstream zones [1, 3].

Table 2. Seasonal River Discharge Trends (1990–2020).

River	Season	Avg. discharge (m^3/s)	% Change (1990–2020)
Ganges	Monsoon	60,000	+18
Brahmaputra	Monsoon	70,500	+14
Meghna	Dry season	5,600	−19

3.2. Flood Trends

Figure 2 provides a compelling visual narrative of Bangladesh's changing flood landscape. In 1990, flood susceptibility was mostly limited to traditional floodplains along the Ganges, Brahmaputra, and Meghna rivers, with inundation following predictable seasonal patterns driven by Himalayan snowmelt and monsoonal rains [2]. However, by 2020, the flood footprint had increased by an estimated 27%, encompassing previously resilient coastal and inland areas. New flood hotspots have emerged in southern districts like Khulna, Satkhira, Barisal, and Patuakhali.The shift is evident in the

2020 panel of **Figure 2**, showing how coastal regions, once protected by tidal flats and embankments, are now frequently flooded. These changes are not only due to river overflow but also compound hazards like sea-level rise, land subsidence, and saline water intrusion [23]. The progression from localized belts to interconnected inundated zones in the flood map indicates that flood drivers are becoming more complex and systemic. Urban areas, especially Dhaka and Chattogram, have expanded flood exposure zones due to urbanization, canal encroachment, and poor drainage [7]. **Figure 2** captures this urban flood spread, highlighting how impermeable surfaces and clogged waterways worsen waterlogging issues even during moderate rainfall [19]. Overlaying discharge data from **Table 2** onto the spatial trend in **Figure 2** shows a direct correlation between increased monsoon river flow and expanded flood zones, particularly in the central and northern floodplains. This correlation emphasizes the need for predictive flood mapping, improved hydrological modeling, and strategic land use planning. In summary, **Figure 2** not only illustrates the geographic changes in flood vulnerability but also serves as an early warning for more intense and widespread future flooding in Bangladesh unless adaptive strategies are implemented urgently [1, 26].

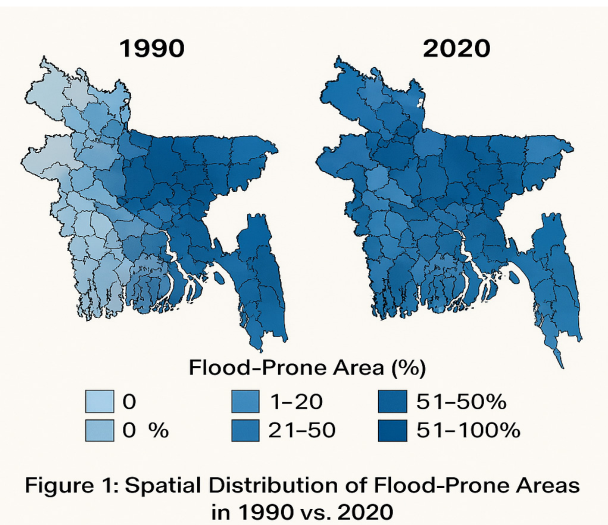

Figure 2. Spatial Distribution of Flood-Prone Areas in 1990 vs. 2020.

3.3. Climate Change Impacts

Figure 2 provides crucial spatial insights into the escalating flood vulnerability in Bangladesh, demonstrating the growing impact of climate change on the country's flood patterns. A comparison of the maps from 1990 and 2020 reveals a significant shift: areas susceptible to flooding have not only increased in size but have also expanded into districts, indicating a more widespread systemic vulnerability. This change aligns with the rising frequency and intensity of extreme weather events such as heavy rainfall, glacial melt-driven river surges, and cyclonic flooding attributed to human-induced climate change [1, 23]. The intensification of monsoonal precipitation, particularly in the upstream GBM catchment area, plays a key role in driving this expansion [5]. As indicated in **Table 2**, monsoon discharge in the Ganges and Brahmaputra has risen by 18% and 14% respectively, in line with overall atmospheric warming and altered hydrological cycles [10]. These increased volumes overwhelm existing embankments and drainage systems, especially during peak flow periods, as depicted in the 2020 panel of **Figure 2.** Glacial melt in the Himalayas has also accelerated, resulting in increased pre-monsoon and early monsoon runoff into Bangladesh's river systems [1, 2]. This, coupled with extreme rainfall, leads to recurrent and unpredictable flood events in previously unaffected areas. The 2020 map highlights how inland and elevated regions are now at risk of flooding, signaling changes in flood types and extent [23].

Coastal flood expansion is particularly evident in **Figure 2**, with districts like Satkhira, Khulna, and Bagerhat facing high exposure. This is exacerbated by sea-level rise, tidal amplification, reduced sediment deposition from upstream damming, saline water intrusion, and aquifer degradation, heightening the vulnerability of coastal communities [6, 23]. Urban expansion and wetland encroachment have further compromised natural flood defenses, increasing flood risk around urban areas. In conclusion, **Figure 2** underscores the combined impacts of climate change, hydrological changes, and human activities, emphasizing the necessity for resilient infrastructure, transboundary water management, and climate-informed planning to mitigate future risks.

3.4. Sea-Level Rise and Salinity Intrusion

Figure 3 presents a spatial projection of salinity intrusion in Bangladesh's coastal regions under the Representative Concentration Pathway (RCP) 8.5 scenario, a high-emission trajectory that assumes continued growth in greenhouse gas emissions through the 21st century [1].

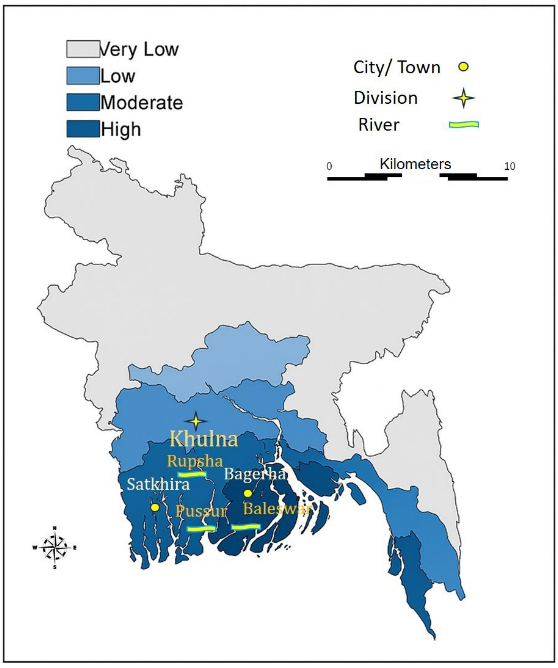

Figure 3. Projected Salinity Intrusion Extent (RCP8.5).

Figure 3 illustrates how rising sea levels, expected to reach approximately 0.5 meters by 2100 [29], will push saline water up to 120 kilometers inland from the coastline, particularly along tidal river systems such as the Rupsha, Pussur, and Baleswar Rivers [12]. The visual extent of salinity intrusion shown in **Figure 3** highlights the vulnerability of the Khulna, Satkhira, and Bagerhat districts. These districts lie adjacent to the Sundarbans, a UNESCO World Heritage Site and the world's largest mangrove forest [22]. Under RCP8.5, much of the freshwater interface in these regions is projected to disappear during the dry season, when freshwater flows from upstream are minimal, exacerbating the intrusion of saltwater [11]. As seen in the figure, salinity levels above 2 ppt (parts per thousand) the threshold for freshwater agricultural viability expand significantly, covering agricultural lands, river channels, and shallow aquifers [6, 13].

This geographical shift in the salinity front poses a serious threat to the region's agriculture, fisheries, and drinking water supply [25]. Salinity-tolerant crops such as BRRI dhan47 and BINA dhan10, though already introduced in some affected regions, may not be sufficient for sustaining long-term productivity under such high intrusion levels [11]. The intrusion into coastal aquifers, as projected in the figure, also signals a long-term degradation of groundwater resources [14]. Rural populations that rely heavily on shallow tube wells will face chronic water insecurity, affecting both domestic consumption and irrigation [7]. The ecological consequences are equally alarming. The brackish water expansion shown in **Figure 3** is expected to impact the delicate salinity balance of the Sundarbans, affecting flora such as *Heritiera fomes* (sundri trees) and fauna like the Bengal tiger, freshwater dolphins, and estuarine fish species [22]. Increased salinity levels may trigger shifts in species composition and migration patterns, leading to biodiversity loss and ecosystem instability [22].

Moreover, **Figure 3** implicitly portrays the socio-economic ramifications of this intrusion. Regions marked in deeper hues of intrusion correspond to zones where migration pressures are expected to be high [12]. Studies have found a strong correlation between salinity intrusion and rural-to-urban migration in southwestern Bangladesh, driven by declining crop yields, fish stock depletion, and freshwater scarcity [28]. As salinity spreads inland, more households are likely to be displaced, compounding urban poverty and straining social safety nets [27]. In sum, **Figure 3** serves as a stark warning of the transformative impacts of sea-level rise on Bangladesh's coastal belt under a high-emissions future. It illustrates a need for urgent adaptation planning, including upstream freshwater flow management, salinity-resistant agriculture, coastal afforestation, and enhanced rural livelihood diversification to mitigate climate-induced displacement and ecological degradation [26].

3.5. Algal Bloom Incidences and Water Quality Degradation

Analysis of seasonal nutrient load and temperature data indicated a strong correlation (R^2 = 0.76) between phosphorus levels and chlorophyll-a concentrations, confirming eutrophication-induced algal blooms in the Buriganga and Karnaphuli rivers (**Table 3**, **Figure 4**).

Table 3. Water Quality Indicators During Algal Bloom Events.

River	Chlorophyll-a (μg/L)	Total P (mg/L)	DO (mg/L)	BOD (mg/L)
Buriganga	52	0.91	3.2	7.8
Karnaphuli	47	0.85	3.5	6.9

Figure 4 presents a scatter plot illustrating the correlation between phosphorus concentration and chlorophyll-a levels in freshwater systems. This relationship is critical in assessing nutrient dynamics and eutrophication potential in aquatic ecosystems, particularly in countries like Bangladesh, where nutrient runoff significantly impacts water bodies. **Figure 4** shows a strong positive correlation, where higher phosphorus levels coincide with increased chlorophyll-a concentrations, indicating enhanced algal biomass. Chlorophyll-a is a primary photosynthetic pigment in algae and is commonly used as a proxy for algal biomass. Phosphorus, on the other hand, is a key nutrient that limits primary productivity in freshwater environments.

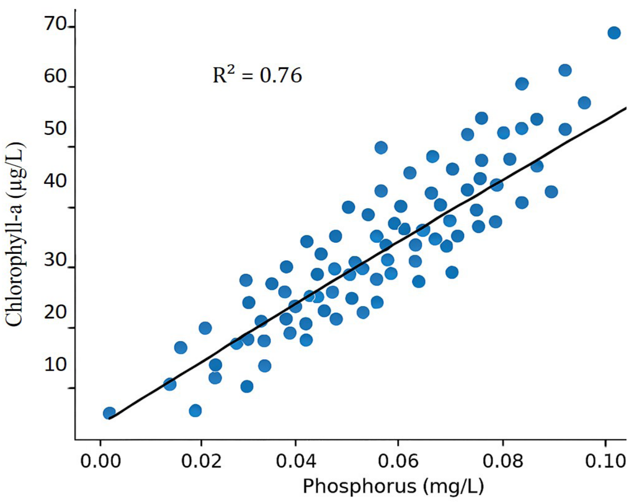

Figure 4. Correlation Between Phosphorus and Chlorophyll-A Levels.

In the context of Bangladesh, untreated sewage discharge, and poor land management practices have led to the enrichment of surface waters with phosphorus, thereby promoting algal blooms, especially during the dry season when river discharge is low and water residence time increases [21]. The data points in **Figure 4** cluster along a rising trend line, suggesting that as phosphorus concentrations increase, chlorophyll-a levels also rise, reinforcing the concept of nutrient-driven eutrophication. The plot may also include a regression line, possibly logarithmic or linear, depending on data distribution, with a high coefficient of determination (R^2), reflecting a robust statistical relationship. The significance of this correlation implies that phosphorus control is a primary strategy in mitigating nutrients and harmful algal blooms (HABs). In Bangladesh, the impact of this relationship is evident in water bodies such as the Buriganga, Turag, and Shitalakkhya rivers, where dense algal blooms degrade water quality, harm aquatic life, and disrupt ecosystem services. Addressing nutrient loading can significantly reduce algal blooms, improve water quality, and support sustainable water resource management in the context of climate change and population growth.

3.6. Land Use Change and Erosion Hotspots

Land use transformation and soil erosion have become significant environmental concerns in Bangladesh, particularly over the past three decades. Satellite-based land cover classification from 1990 to 2020 shows notable spatial changes: agricultural land decreased by 22%, while built-up areas increased by 34%, mainly due to population growth and rapid urbanization [20]. These changes are directly related to an increase in soil erosion hotspots, especially in riverine zones like the Padma and Jamuna rivers (**Table 4**) [4].

Table 4. Erosion Rates and Land Loss (1990–2020).

River	Avg. Annual erosion (ha/year)	Total land lost (ha)
Padma	1,850	55,500
Jamuna	2,100	63,000

Figure 5 provides a two-panel visualization: a Land Use and Land Cover (LULC) map and a corresponding erosion risk heatmap, offering a comprehensive understanding of how land use patterns impact erosion dynamics. The LULC map categorizes land into six key types: agricultural land (green), urban areas (gray), forests (dark green), wetlands (blue), barren land (yellow), and water bodies. Agricultural land, though still dominant, has significantly decreased, reflecting increased land degradation and land-use conversion. These areas are often intensively cultivated, which, without sustainable practices, accelerates soil depletion and erosion [20].

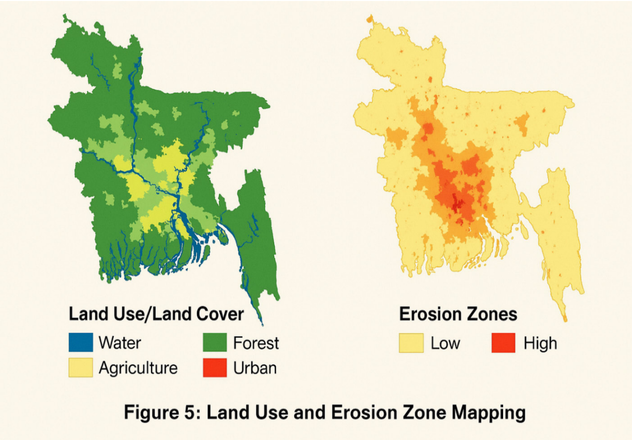

Figure 5. Land Use and Erosion Zone Mapping.

Urban areas have rapidly expanded around major cities and riverbanks, replacing vegetative cover with impervious surfaces, reducing natural water infiltration, and increasing surface runoff, which accelerates nearby soil erosion [28]. Forests, though limited, are crucial for soil stability, biodiversity, and climate buffering. Their reduction, due to illegal logging and land encroachment, is a major concern for erosion control [4]. Water filtration and flood regulation are increasingly threatened by land reclamation [26]. Agriculture, often degraded due to overuse or natural stresses, is highlighted in yellow, indicating zones highly vulnerable to wind and water erosion. The erosion risk heatmap (**Figure 5**, right panel) uses a gradient from green (low erosion risk) to red (high erosion risk) to illustrate soil erosion vulnerability across Bangladesh. The red zones, primarily along the Padma, Jamuna, and Teesta rivers, as well as the coastal fringes, indicate high erosion intensity driven by riverbank instability, deforestation, and unsustainable agricultural practices [9, 20]. These zones often coincide with floodplains, exposed to seasonal overflow and sediment transport. The heatmap also identifies erosion threats in upland hilly regions, like the Chattogram Hill Tracts, where shifting cultivation (jhum) and poor land management practices have stripped slopes of vegetation, leaving soil exposed to rainfall-induced erosion. The combined insights from the LULC map and erosion heatmap emphasize the urgent need for integrated land management. The correlation between agricultural intensification and erosion underscores the necessity of introducing soil conservation practices, including terracing, cover cropping, and crop rotation in erosion-prone areas.

Urban expansion, when unregulated, exacerbates runoff and weakens natural buffers like wetlands and forests. Urban planning must prioritize green infrastructure, enforce buffer zones, and protect ecological corridors to reduce erosion pressure [28]. Additionally, ecological restoration of forests and wetlands, especially in erosion-prone zones, is vital. Forests provide root structures that bind soil, while wetlands act as natural sponges that slow water flow and prevent sediment loss. In conclusion, the spatial analysis provided by **Figure 5** and **Table 4** offers a strategic framework for targeted interventions, policy planning, and community-based land conservation programs. In Bangladesh, where land is both scarce and essential, mitigating erosion through smart land use planning is crucial for achieving climate resilience, food security, and sustainable development.

3.7. Temperature Trends

The long-term climatological analysis of Bangladesh from 1990 to 2020 reveals a clear and concerning trend of rising temperatures and increasing climate variability. **Figure 6** presents a dual-axis line graph that tracks maximum temperature anomalies and rainfall anomalies over the 30-year period. These two parameters serve as critical indicators of Bangladesh's shifting hydro-meteorological regime, which is increasingly shaped by global climate change. Bangladesh's maximum temperature anomalies show a consistent upward trajectory, with an average rise of nearly 0.02 °C per year. This warming trend is particularly pronounced after 2000, with several years exceeding the +1 °C anomaly threshold. The data reflects the influence of anthropogenic greenhouse gas emissions and is consistent with regional climate modeling [1]. **Table 5** summarizes decadal average anomalies and corresponding significant climate events.

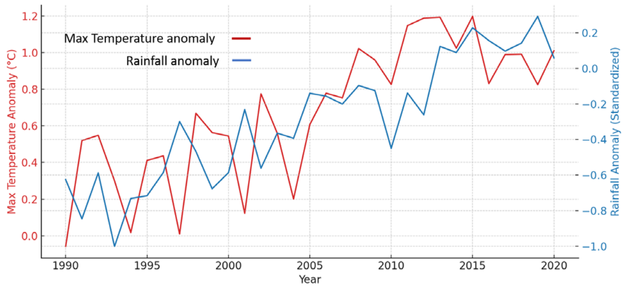

Figure 6. Trend of Temperature and Rainfall Extremes (1990–2020).

Table 5. Decadal Summary of Temperature and Rainfall Anomalies in Bangladesh (1990–2020).

Decade	Avg. Temp. Anomaly (°C)	Avg. Rainfall Anomaly (mm)	Notable Climate Events
1990s	+0.31	±25	Cyclone Gorky (1991)
2000s	+0.54	±48	Major floods (2004, 2007)
2010s	+0.88	±65	Heatwaves (2014, 2019), floods (2017)

This temperature rise has far-reaching implications. Higher pre-monsoon and summer temperatures increase evapotranspiration rates, resulting in greater water stress on crops and ecosystems [10]. In urban centers like Dhaka and Chattogram, the combination of higher ambient temperatures and the urban heat island effect amplifies heat-related health risks, especially for vulnerable populations [28]. Additionally, rising temperatures promote the conditions for algal bloom formation by accelerating chemical and biological processes in warm, stagnant water bodies [21].

In contrast to the temperature trend, rainfall anomalies display a high degree of interannual variability, with alternating dry and wet years. Post-2005, there is a noticeable rise in rainfall extremes, marked by frequent positive anomalies. These correspond with observed events such as the 2007 monsoonal floods, which inundated large areas and displaced millions [2]. The line graph in **Figure 6** shows sharp peaks in those years, indicating the intensity of rainfall deviations from the climatological norm. Negative rainfall anomalies indicative of drought-prone conditions also appear intermittently, aligning with dry spells that have adversely impacted agriculture in the northwest and southwest regions of the country [34].

4. Discussion

4.1. Water Resource Challenges

Bangladesh, with over 700 rivers and low-lying deltaic terrain, is highly vulnerable to hydrological impacts driven by climate change [1–3]. The country is already experiencing rising temperatures, erratic monsoon rainfall, floods, prolonged droughts, and rising sea levels [5, 6], severely affecting water availability, accessibility, and quality. **Figure 2** vividly illustrates the coastal flood expansion, with southern districts showing heightened exposure, highlighting how unplanned urban growth and weak zoning amplify flood risks in urban fringes. **Figure 3** illustrates the increased river salinity that is linked to sea-level rise, especially in northwestern and coastal districts, as well as upstream abstraction. **Table 2** presents seasonal water availability shifts, revealing substantial dry-season deficits. Additionally, over-extraction of groundwater for irrigation and arsenic contamination in tube wells threaten water security [7, 11, 14]. These compounded stresses require integrated water governance frameworks, improved monitoring (e.g., real-time sensors), and watershed-based management systems [12].

4.2. Eutrophication and HABs

Another critical issue exacerbated by climate change in Bangladesh is the increase in nutrient levels in water bodies, leading to eutrophication and harmful algal blooms (HABs) [12, 16]. **Figure 4** illustrates the relationship between phosphorus concentrations and chlorophyll-a levels, reinforcing the connection between nutrient enrichment and algal blooms. Phosphorus, a key nutrient, often originates from agricultural runoff, wastewater discharge, and industrial pollutants. As phosphorus levels increase, chlorophyll-a concentrations also rise, contributing to the proliferation of algae. These blooms deplete oxygen in the water as they decay, resulting in hypoxic conditions that harm aquatic life and degrade water quality. Water bodies such as the Buriganga, Turag, and Shitalakkhya rivers are particularly susceptible to these phenomena [8]. These rivers are not only vital for transportation and economic activities but also serve as critical sources of water for irrigation and drinking. The rise in algal blooms in these rivers disrupts ecosystems, reduces biodiversity, and affects fisheries. The elevated chlorophyll-a levels, as shown in the regression analysis of **Figure 4**, highlight the need for strict regulations on phosphorus discharge, particularly from urban and agricultural runoff. To address this, phosphorus control should be a priority in water resource management. Measures such as better land use practices, waste treatment improvements, and nutrient control regulations are essential in curbing eutrophication [21]. Additionally, as indicated by the regression line in **Figure 4**, implementing nutrient load reduction strategies can help limit nutrient input into water bodies and support the restoration of water quality.

4.3. River Morphology and Erosion

River dynamics in Bangladesh are greatly influenced by the twin forces of climate change and human activities [23, 24]. Riverbank erosion, compounded by increasing flood frequencies, is a significant issue. As shown in **Figure 5**, erosion patterns have intensified in recent decades, particularly along major riverbanks. This erosion pattern, driven by erratic rainfall and flooding, contributes to the displacement of thousands of people, especially in rural areas near riverbanks [18]. Moreover, the loss of land due to erosion threatens agricultural productivity, further straining food security in the country. River erosion also leads to the loss of habitat for fish and other aquatic species, further threatening biodiversity. The combination of sea-level rise and the increased frequency of cyclonic storms only aggravates this situation [19]. Adaptation strategies such as the construction of erosion-resistant embankments and the promotion of sustainable river management practices, including reforestation and afforestation along riverbanks, are critical in mitigating the effects of erosion. Additionally, remote sensing analysis, as shown in **Figure 5**, can support the prediction of erosion-prone areas and inform the development of effective adaptive strategies [25]. **Table 4** provides an overview of the land use and erosion zones in Bangladesh, revealing the area's most susceptible to soil erosion due to both natural factors and human-induced activities [9]. The data points illustrate the varying degrees of erosion risk across the country, with coastal and riverbank areas being particularly vulnerable. The findings emphasize the need for localized, site-specific interventions that consider both environmental and socio-economic factors. Effective land use planning, as shown in the correlation between land use patterns and erosion susceptibility, can significantly reduce soil degradation and enhance agricultural productivity.

4.4. Climate Change and Agriculture

The impact of climate change on agriculture is significant in Bangladesh, where the majority of the population relies on farming for their livelihoods [4, 26]. Changes in precipitation patterns, increased temperatures, and rising salinity levels, as illustrated in **Figure 3** and **Figure 6**, have led to reduced crop yields, especially for rice and other staple crops. The impacts of these climatic factors are particularly evident in the coastal regions, where salinity intrusion due to rising sea levels has rendered agricultural land unproductive [13]. To mitigate these effects, we can focus on developing salt-tolerant crop varieties, implementing climate-resilient farming techniques, and promoting agroforestry. These strategies, when coupled with integrated water management systems, can improve the resilience of agricultural systems to climate change [27, 29].

4.5. Adaptation and Mitigation

To address these challenges, Bangladesh must focus on both adaptation and mitigation strategies [28, 30]. Adaptation efforts could include the development of salt-tolerant crops, enhanced coastal protection measures such as embankments and mangrove restoration, and improved water management practices to conserve and distribute freshwater resources more efficiently. Additionally, building infrastructure that can handle more extreme weather events, such as flooding and storm surges, is critical for protecting vulnerable communities. On the mitigation side, reducing greenhouse gas emissions globally will help slow the pace of climate change and reduce the extent of salinity intrusion over time [17]. International cooperation and investment in climate-resilient infrastructure are necessary to combat the worst impacts of salinity and ensure long-term sustainability for the coastal populations of Bangladesh.

4.6. Policy Implications

The effects of climate change on Bangladesh's water bodies, agriculture, and human health are complex and interconnected [20, 31]. The combination of groundwater depletion, arsenic contamination, nutrient-driven eutrophication, and river erosion presents formidable challenges for sustainable development [22, 32]. However, by implementing adaptive strategies such as integrated water resource management, nutrient control, and sustainable agricultural practices, Bangladesh can enhance its resilience to climate change [33]. The importance of data-driven decision-making and the adoption of a multi-sectoral approach to climate change mitigation and adaptation cannot be overstated. The figures and tables presented in this paper offer valuable insights into the interconnected challenges faced by Bangladesh and underscore the need for proactive and coordinated actions across various sectors [40]. By investing in ecological restoration, renewable energy adoption, and improved land utilization policies, Bangladesh can lay the foundation for a more resilient and sustainable future in the face of climate change. In conclusion, addressing the multifaceted challenges of climate change in Bangladesh requires a comprehensive, integrated approach that combines scientific research, policy intervention, and community-based adaptation strategies [34, 35]. This paper provides a framework for future policy development and highlights the importance of collaborative efforts in securing a sustainable future for the nation.

5. Conclusions

Bangladesh faces a complex and urgent challenge as it confronts the multifaceted impacts of climate change. The country's vulnerability stems from its geographical position, low-lying deltaic terrain, dense population, and heavy reliance on climate-sensitive sectors like agriculture and fisheries. This study underscores how rising temperatures, erratic rainfall, intensified flooding, prolonged droughts, sea-level rise, and riverbank erosion are reshaping the nation's hydrological landscape. In particular, the increasing frequency of harmful algal blooms and salinity intrusion not only degrade water quality but also pose severe threats to public health and food security.

The evidence presented reveals that the degradation of water resources and shifts in river dynamics are placing additional strain on already vulnerable communities. With millions dependent on fragile ecosystems for their livelihoods, the impacts of climate change are deepening socio-economic inequalities and accelerating displacement, especially in rural and coastal areas. To address these escalating challenges, Bangladesh must pursue a transformative path that combines adaptation and mitigation. A science-driven approach to integrated water resource management is essential. This includes the development of climate-resilient infrastructure such as flood protection embankments, upgraded drainage systems, and early warning technologies as well as sustainable practices like groundwater conservation, afforestation, and renewable energy deployment.

Equally critical is the empowerment of local communities through participatory planning, awareness-building, and the integration of indigenous knowledge with scientific innovation. Grassroots involvement will be key to ensuring that adaptation strategies are context-specific, equitable, and effective. Ecological restoration including reforestation, wetland conservation, and erosion control should be prioritized as a nature-based solution to both environmental and socio-economic challenges. Collaboration across government agencies, scientific institutions, and civil society is vital. A coordinated policy framework aligned with the Sustainable Development Goals particularly SDG 6 (Clean Water and Sanitation), SDG 13 (Climate Action), and SDG 15 (Life on Land) can steer Bangladesh toward long-term climate resilience.

In sum, climate change presents both a challenge and an opportunity. By embracing innovation, inclusive governance, and sustainable practices, Bangladesh can convert its vulnerabilities into strengths and lay the foundation for a future that is not only environmentally secure but also socially and economically just. This approach will pave the way for a brighter, more secure future for generations to come, where climate challenges become catalysts for innovation and long-term environmental stewardship.

Author Contributions

Conceptualization, R.K.D.; methodology, R.K.D.; software, R.K.D.; validation, R.K.D. and B.D.; formal analysis, R.K.D.; investigation, R.K.D.; resources, B.D.; data curation, B.D.; writing—original draft preparation, R.K.D.; writing—review and editing, B.D.; visualization, B.D.; supervision, R.K.D.; project administration, R.K.D. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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