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Research Article

Assessing Climate Vulnerability in the Haor Wetland Region of Bangladesh: Policy and Governance Implications for Livelihood Resilience and Ecosystem-Based Adaptation

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Abstract

The Haor wetland region of Bangladesh faces growing climate vulnerability due to its unique geomorphology and hydrological complexity. This study assesses climate-induced hazards and their impacts on agriculture, ecosystems, and livelihoods using a nine-step methodology guided by the Climate Risk Vulnerability Assessment (CRVA) framework. Data were collected through household surveys, FGDs, and KIIs. Historical climate trends and future projections were analyzed using downscaled CMIP6 data under the SSP1-2.6 and SSP5-8.5 scenarios. Findings indicate that by the 2030s and 2050s, the Haor region will experience increased temperatures and precipitation, by the 2030s, maximum winter temperatures are projected to rise by 0.87-0.9 ℃ and under SSP5-8.5, winter rainfall may decrease by about 10%, while monsoon rainfall is expected to increase by 1.7-2% under SSP1-2.6, situation will be further aggravated by 2050; exacerbating risks such as floods, erosion, habitat degradation, and biodiversity loss. Agricultural systems are particularly susceptible to early flash floods, droughts, irrigation shortfalls, and labor shortages, all of which heighten the risk of crop failure and threaten food security. The vulnerability projections and mapping reveal more dynamic and location-specific trends. Under SSP1-2.6, Golapganj upazila's vulnerability rises from *low* to *moderate* by the 2030s, with most other upazilas—except Kulaura—experiencing further deterioration by the 2050s. Under SSP5-8.5, Juri upazila enters a *high vulnerability* zone by the 2030s, while Kulaura shifts to *moderate* vulnerability during the same period but reverts to *low* vulnerability by the 2050s. Vulnerability is disproportionately borne by marginalized groups, including the poor, women, children, the elderly, and persons with disabilities. A logit regression model was used to identify determinants influencing agricultural vulnerability in the Haor region. It was found that household savings, access to credit, use of quality inputs, crop diversification, knowledge of climate-smart agriculture (CSA), land area affected by disasters, and access to irrigation and larger landholdings were significantly affecting agricultural vulnerability in the region. The findings underscore the need for improved extension services, access to climate-resilient inputs, farmer education, and infrastructural investments to enhance resilience in the Haor agricultural systems., The study also assessed sector-specific risks and adaptive responses. It identified existing indigenous coping strategies and proposed ecosystem-based adaptation (EbA) approaches to strengthen long-term resilience. The findings offer critical policy insights and governance recommendations to support climate-resilient development and equitable adaptation in one of Bangladesh's most ecologically sensitive regions.

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1. Introduction

The Haor wetland region of Bangladesh is a distinct ecological zone characterized by its bowl-shaped depressions, seasonal flooding, and complex hydrological and geological features. These low-lying floodplains support a mosaic of aquatic and terrestrial ecosystems, providing critical habitats for diverse flora and fauna, including migratory birds, and sustaining rich fisheries that are vital for local livelihoods [2]. Despite its ecological richness, the region remains highly vulnerable to the impacts of climate change and various natural and anthropogenic hazards.

Frequent flash floods, erratic rainfall, hailstorms, riverbank erosion, tornadoes, and occasional landslides cause widespread disruption to livelihoods, agriculture, infrastructure, and the environment. According to the National Adaptation Plan approximately 4.02 million people inhabit the Haor and flash-flood-prone areas spanning 19,662 square kilometers, with their lives and livelihoods increasingly threatened by extreme weather events and environmental stressors [36].

The flash flood of 2022 exemplifies the scale of vulnerability in the region, affecting 7.2 million people across nine northeastern districts. It damaged over 113,000 hectares of croplands—including Aman paddy, seedbeds, maize, vegetables, and cash crops—alongside 44,254 fish ponds and nearly 50,000 sanitation facilities. Agriculture remains the dominant livelihood source, with the Haor region accounting for approximately 710,000 hectares of cultivable land—about 16% of the country's total rice-growing area [3]. Nearly 20 million people depend directly or indirectly on agricultural and fisheries-based activities in this region [37]. Given such dependence, any disruption to ecological functions or climate variability significantly threatens food security, income stability, and overall community resilience A growing body of literature has examined the intersection of climate vulnerability, socio-economic resilience, and adaptation strategies in this region. A study found that climate variability in Tanguar Haor disproportionately affects poor and marginalized groups, with crop diversification, homestead gardening [38], and cage aquaculture emerging as key local adaptations. Another study, using the IPCC framework, identified Sunamganj as the most vulnerable among three Haor districts due to low adaptive capacity and high flood exposure, calling for targeted policy support, used remote sensing to track climate impacts on Hakaluki Haor, revealing land use shifts, habitat degradation, and the growing threat of anthropogenic pressures to wetland ecosystems [8]. This is alo supported by other studies [17, 21, 23, 24].

Collectively, these studies point to a convergence of climate risks—flash floods, erratic rainfall, siltation, and temperature rise—that threaten both ecological integrity and livelihood sustainability in the Haor region. They also reveal a critical need for ecosystem-based adaptation (EbA) approaches that integrate indigenous knowledge, nature-based solutions, and inclusive governance mechanisms. Despite growing empirical evidence, gaps remain in longitudinal data, gender-disaggregated vulnerability analysis, and the integration of EbA into formal policy frameworks. This study builds on existing literature by applying a CRVA framework and downscaled CMIP6 projections to generate actionable insights for policy and governance reform.

Together, these studies highlight converging climate risks—flash floods, erratic rainfall, siltation, and rising temperatures—that threaten the Haor region's ecology and livelihoods. They underscore the need for ecosystem-based adaptation (EbA) rooted in indigenous knowledge, nature-based solutions, and inclusive governance. Despite growing evidence, gaps persist in longitudinal data, gender-disaggregated vulnerability analysis, and policy integration of EbA. This study advances the literature by applying a Climate Risk Vulnerability Assessment (CRVA) framework and downscaled CMIP6 projections to inform targeted policy and governance responses.

To address climate risks, the Government of Bangladesh has adopted strategic frameworks such as the Bangladesh Delta Plan 2100 and the National Adaptation Plan (2023-2050). Both identify the Haor region as a climate-vulnerable hotspot and promote a mix of "hard" interventions (e.g., embankments, drainage systems) and "soft" measures like disaster preparedness, early warning systems, and livelihood diversification [11, 45, 40].

This study assesses climate vulnerability in the Haor region using an integrated, participatory framework. Its objectives are to: (i) identify climate-induced hazards and project future scenarios; (ii) evaluate impacts on agriculture, ecosystems, settlements, and food security,—particularly under shifting rainfall patterns; (iii) analyze physical and socio-economic vulnerabilities; and (iv) propose ecosystem-based adaptation strategies to enhance livelihood resilience and environmental governance.

Limitations of the Study: While this assessment offers a robust CRVA-informed analysis of climate vulnerability across the Haor wetland region, a few methodological and data-related limitations should be acknowledged:

1) The socioeconomic survey employed is cross-sectional, which restricts the ability to infer causality or track longitudinal shifts in household adaptation strategies, income diversification, or resilience trajectories over time.
2) Although the CRVA integrates ecological indicators and field-based observations, it does not incorporate dynamic ecosystem models (e.g., sediment transport, fish population dynamics). This omission limits the capacity to generate scenario-based projections of habitat degradation or fisheries decline under varying climate and hydrological stressors.

2. Methodology

Review of Theoretical foundation for vulnerability assessment

Vulnerability assessment in climate impact studies is grounded in the IPCC conceptualization that vulnerability is a function of exposure, sensitivity, and adaptive capacity [65, 66]. In operational terms: exposure denotes the degree of climatic hazard occurrence, sensitivity reflects system susceptibility, and adaptive capacity determines the ability to cope, recover, or transform [61, 62, 72].

Two widely used approaches build on this foundation:

1). Indicator-based approaches, which develop composite indices by aggregating indicators of exposure, sensitivity, and adaptive capacity [62, 63, 78, 76].

2) Process-based or impact-chain approaches, which model causal linkages between hazards, ecosystem processes, and socio-economic outcomes, facilitating the integration of ecosystem services into vulnerability assessment [66, 70, 78].

Mixed-method applications combining statistical analysis, participatory tools, and climate projections have proven particularly effective in contexts with high social-ecological complexity [54, 60].

Comparative lessons from international EbA case studies

International EbA case studies highlight common success factors:

1) Ecosystem restoration (e.g., mangrove rehabilitation in Vietnam) reduces hazard exposure and sustains livelihoods [68, 69, 72].
2) Community-based governance improves compliance and sustainability [64, 67].
3) Integration with complementary measures, such as early-warning systems and market access, amplifies livelihood benefits [59].
4) Monitoring and adaptive management ensure scalability [74].

These findings emphasize that EbA must be implemented as integrated portfolios, combining ecological restoration, institutional strengthening, and livelihood diversification.

Gaps in gender-disaggregated analysis

Despite increasing attention, several gaps persist: lack of sex-disaggregated data, insufficient capture of gendered roles and power dynamics, and limited monitoring of equitable benefit-sharing [55-57]. Ignoring these dimensions risks maladaptation and perpetuates inequality [58].

Best practices include embedding gender-sensitive indicators in vulnerability assessments [73, 77, 75], adopting participatory gender analysis methods [71], and mainstreaming women's representation in co-management and decision-making processes [75].

2.1. Overview of Approach

The study adopted a mixed-methods approach combining both primary and secondary data sources to comprehensively assess climate vulnerability and impacts in the Haor region of Bangladesh. Secondary data were collected from credible national and international sources to establish baseline conditions, environmental trends, and sectoral indicators.

Primary data were obtained using a combination of qualitative and quantitative tools. Structured household surveys were conducted to collect socio-economic and climate-related data from affected communities. Focus Group Discussions (FGDs) were held with key stakeholder groups, including farmers, fishers, and women, while Key Informant Interviews (KIIs) were undertaken with local experts, government officials, and NGO representatives to gain contextual insights. Region-specific case studies were also carried out to capture localized vulnerabilities across different ecosystems. The integrated dataset allowed for triangulation and robust vulnerability assessment.

2.2. Historical Climate Analysis and Future Climate Scenario Modeling

A comprehensive analysis of historical and future climate patterns was undertaken for the Haor and Barind regions. Historical temperature and rainfall data were analyzed to identify long-term trends and the frequency of extreme climate events. This analysis formed the foundation for understanding past climate variability and its implications on the study regions.

Future climate scenarios were developed using statistically downscaled outputs from global climate models (GCMs), providing upazila-level projections. Two Shared Socioeconomic Pathways (SSPs) were considered—SSP1-2.6 (low emissions) and SSP5-8.5 (high emissions)—to evaluate the projected impacts of climate change under contrasting global development trajectories. These projections facilitated scenario-based assessments of future climate risks in agriculture, ecosystems, and community livelihoods.

2.3. Development of CRVA Framework and Impact Chain Analysis

A Climate Risk Vulnerability Assessment (CRVA) framework was developed based on the IPCC AR5 conceptual model and the GIZ *Vulnerability Sourcebook* [6, 7]. The framework was also aligned with the draft Nationwide Climate Vulnerability Assessment [9]

Sector-specific impact chains were developed to analyze causal links between climate hazards and sectoral vulnerabilities, focusing on five thematic areas:

1) Ecosystems and Biodiversity
2) Agriculture
3) Fisheries
4) Water & Disaster
5) Socio-Economic Dimensions

Each impact chain outlined how climate hazards (e.g., floods, droughts, erosion) interact with sector-specific exposure, sensitivity, and adaptive capacity components. This process guided the selection of indicators and informed the design of vulnerability and risk assessments (illustrated in Figure 1).

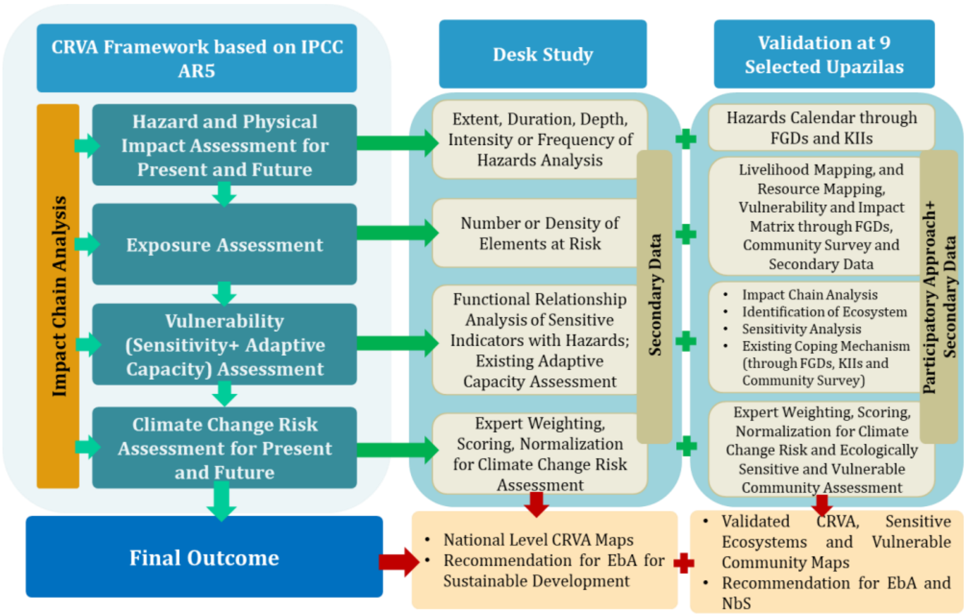

Figure 1. *Overall Methodological Framework for Climate Change Vulnerability, Impact and Risk Assessment.*

2.4. Selection of Indicators and Desk-Based CRVA

Indicators representing exposure, sensitivity, and adaptive capacity were selected based on relevance, data availability, and expert input. Table 1 presents the finalized set of indicators, which span environmental, socio-economic, infrastructure, and institutional dimensions.

Examples of indicators include:

1) *Temperature rise*: Number of extreme heat days
2) *Flood risk*: Inundation depth and extent
3) *Livelihood dependency*: Share of households engaged in agriculture or fisheries
4) *Socio-economic vulnerability*: Per capita income, incidence of poverty
5) *Adaptive capacity*: Access to credit, early warning systems, education levels

The indicators were used to assess vulnerability levels across both current and projected future scenarios.

Table 1. *Selected Indicators for the CRVA.*

Elements	Indicators (Unit)	Elements	Indicators (Unit)
Temperature Rise	Extreme temperature days (no. of days)	Fish Migration	Fish Net Migration Rate (%)
Rainfall Variability	Change in Total Seasonal rainfall (percent)	Occupation pattern	People having Primary occupation (%)
Flood	Inundation depth, extents and flood levels (m)		People having Secondary occupation (%)
Flash Floods	Timing of flash floods and extents (sq. km.)	Income	Per capita or household Income in a year (Tk.)

Elements	**Indicators (Unit)**	**Elements**	**Indicators (Unit)**
Erosion	Erosion rate (ha or acres/year)	Incidence of poverty	% of poor and hardcore poor households
Drought	Successive non rain days (no. of days)	Habitat	Number/Density of habitats
Thunderstorm	Frequency of injuries (no. of person injured/ died)	Fish Sanctuaries	Number of Sanctuaries
Water quality	Concentration of selected parameters	Beel Nursery	Number and Area of Beel Nursery
Habitat Potentiality	Productivity (kg/ha)	Communication & technology	Density of Road (km^2)
Crop Production	MT		Use of paved Road (%)
Crop Yield	MT/ha		Use of Kutcha Road (%)
Fish production & yield	Production (MT), Fish Yield (MT/ha)		Use of Mobile phone (%)
Human asset			
Education	Education of head of household (School years)	Labour productivity	%
	Literacy rate (%)	Population density	No. per sq. km
Family size	Average family size (No)	Dependent population	No. below 5 year and No. above 60 year per sq. km
Family labour/HH, Employment rate	Average no, Employment, rate (%)	Victims of disasters	No. per sq. km
Occupation		Coping capacity indicators	
Occupation in agriculture (Crop, livestock and fishery)	No. and percentage (%)	Access to physical capital	Land holding (ha/hh), income (Tk/hh) and access to credit (% of HH), remittance (Tk/HH)
Occupation in non-agriculture	No, and Percentage (%)	Access to social capital	Participation in CBOs, linkage with extension agencies, NGOs
Instability of production	Incidence of crop failure due to natural calamities		
Access to living condition			
Brick-Built (Pucca) house	Percentage (%)	Early Warning System	Knowledge on early warning (%)
Semi-Pucca house	Percentage (%)		Medium (i.e. Radio/television/Social media) of Early Warning (%)
Tin Shed (Katcha) house	Percentage (%)		Availability of hazard early warning information
E-commerce/SME	Involvement in e commerce (%)	Capacity Building	Training on hazard resilient crops
	Support and training on E-commerce/SME		Training on mechanization of agriculture (and support for such actions)
Capacity Building	Training on alternate livelihood activities (and support for such actions)		Training on integrated farming, fisheries and afforestation (and support for such actions)

2.5. Validation and Uncertainty Treatment of Downscaled CMIP6 Projections

Downscaled CMIP6 outputs were validated against long-term observational records from the Bangladesh Meteorological Department (BMD) to assess reliability for the Haor wetland region. Statistical metrics including Mean Bias Error (MBE), Root Mean Square Error (RMSE), Nash-Sutcliffe Efficiency (NSE), and the coefficient of determination (R^2) were employed to quantify model performance. Multi-model ensemble means were compared with observed climatology, while inter-model spread was used to capture variability.

Bias correction was applied using quantile mapping (QM), selected for its ability to address non-linear biases and improve the representation of precipitation extremes critical to hydrological systems in the Haor. This enhanced the accuracy of rainfall distributions and temperature extremes relative to observed baselines.

Uncertainty was addressed along three dimensions: (i) scenario uncertainty, captured through SSP1-2.6 (low emissions) and SSP5-8.5 (high emissions); (ii) model uncertainty, reflected in ensemble statistics such as interquartile ranges and standard deviations; and (iii) internal climate variability, considered particularly important for near-term projections (2030s). Confidence levels were reported following IPCC AR6 guidance: high confidence for temperature projections (±0.5-1.2 ℃ by the 2030s), medium confidence for precipitation changes (±8-20%), and low to medium confidence for hydrological extremes such as flash floods.

This validation framework ensures that climate risk and vulnerability assessments for the Haor region are grounded in robust, bias-corrected projections, while explicitly accounting for uncertainty ranges and confidence levels.

2.6. CRVA Mapping Using Geo-Spatial Techniques

To produce detailed vulnerability and risk maps, a geo-spatial analysis was conducted using ArcGIS. The process followed four main steps:

Step 1: Weighting, Scoring, and Normalization

Indicator weights were derived through a participatory Budget Allocation Process , incorporating expert judgment and stakeholder input [79]. In order to conduct CRVA through geo-spatial techniques, collected and processed data of indicators were used following a weighted arithmetic aggregation. The first step encompassed weighting, scoring, and normalization of various indicators, using the Budget Allocation Approach in collaboration with stakeholders. Expert judgment was applied to ensure consistency in scores and weights, with equal weights assigned to indicators lacking complete sets. Where data gaps existed, equal weights were applied. Indicator values were normalized using a min-max scaling formula:

$$X_{i,\,0\,to1} = (Xi - XMin)/(XMax - Xmin)$$

Where,

X_i represents the individual data point to be transformed,

X_{Min} the lowest value for that indicator,

X_{Max} the highest value for that indicator, and

$X_{i,\,0\,to\,1}$ the new value to be calculated, i.e. the normalized data point within the range of 0 to 1.

Step 2: Aggregation of Indicator Scores

Normalized indicator scores were aggregated using a weighted arithmetic approach, following guidelines from the GIZ *Vulnerability Sourcebook* [5]. The aggregated risk was calculated as [79]:

$$Risk = \frac{(\text{Hazard}*W_H) + (\text{Hazard}*W_V) + (\text{Hazard}*W_E)}{W_H + W_v + W_E}$$

Where: H = Hazard, E = Exposure, V = Vulnerability and W = Corresponding weights

Step 3: Risk Classification

Normalized risk scores were classified into five categories as shown in (Table 2)

Table 2. *Classification of risk level.*

Vulnerability/Risk Level	Normalized Score Range	Color Code
Very Low	0.00 - 0.20	
Low	0.21 - 0.40	
Moderate	0.41 - 0.70	
High	0.71 - 0.85	
Very High	0.86 - 1.00	

Step 4: GIS-Based Mapping

Final CRVA maps were produced in ArcGIS, showing spatial distributions of current and future vulnerability levels under SSP1-2.6 and SSP5-8.5 scenarios. These maps were specifically developed for the agricultural sector in the Haor region and provide critical input for planning climate-resilient interventions.

2.7. Modeling of the Determinants of Agricultural Vulnerability

To identify the key factors influencing agricultural vulnerability in the Haor region, an ordered logistic regression model was estimated. This model, appropriate for ordinal dependent variables, allowed for assessing the probability of a household experiencing low, medium, or high levels of vulnerability based on a set of explanatory variables [30, 7, 9].

The dependent variable was categorized into three ordinal levels of agricultural vulnerability:

Low (0)
Medium (1)
High (2)
The general form of the model is represented as:

$$\Pr(Yi \le r) = ln \frac{pr(Y \le j)|x}{1 - pr(Y \le j)|x} = \alpha j + \beta 1X1 + \beta 2X2 + \cdots + \beta nXn$$

Where:

Where, Y = Agricultural vulnerability to climate induced disasters for each household of the study site (which is categorized into 2: low = 0, and high = 2); α = threshold; ß1-ßn = estimated parameters; X_i are the sub-indicators of adaptive capacity.

Data for the model were derived from household-level surveys conducted in the Haor region. The explanatory variables (presented in Table 2) were grouped under three major components: Exposure, Sensitivity, and Adaptive Capacity. Each sub-indicator was hypothesized to have either a direct or inverse relationship with agricultural vulnerability.

Development of the Agricultural Vulnerability Index (AVI)

In addition to the regression analysis, a composite Agricultural Vulnerability Index (AVI) was developed to quantify the overall vulnerability of the study sites. The AVI integrates three key dimensions—exposure (E), sensitivity (S), and adaptive capacity (AC)—using the following equations:

Step 1: Compute Indicator Scores

$$DO_i = \sum_{k=1}^{n} (SIS)k \,/k \qquad (1)$$

Where DO_i is the indicator-scores (exposure, sensitivity, and adaptive capacity) of vulnerability index 'i', which is the average of all sub-indicators within each indicator (here SISk is the score of each sub-indicator within the concerned indictor and k is the total number of sub-indicators within the concerned indicator that have been indicated in Table 3). After the calculation of the "Exposure", "Sensitivity" and "Adaptive Capacity" scores, Equation (2) has been used to calculate the agricultural vulnerability index as like as [32]

Step 2: Compute the Overall Agricultural Vulnerability Index

Equation (2) has been used to calculate the agricultural vulnerability index as like as [28].

$$AV_i = [E + S + (1 - AC)]/3 \qquad (2)$$

Where AVI_i, E, S and AC represent the agricultural vulnerability index, exposure, sensitivity and adaptive capacity of each study site, respectively. The analysis has been conducted by using Statistical Package for Social Sciences (SPSS 20.0) and Microsoft Excel (Version 2013). Where higher values of E and S, and lower values of AC, contribute to higher vulnerability. For estimating above model, we used household data collected from the sample households of Haor area through questionnaire survey. The computations were carried out using SPSS (version 20.0) and Microsoft Excel (2013), enabling both statistical analysis and cross-indicator comparison across study sites.

Table 3. *Vulnerability Indicators and Sub-Indicators for Haor Households.*

Component	Sub-indicators	Unit of Measurement	Expected Relationship
Exposure	Position of agricultural land from river	Dummy (1 = near, 0 = far)	Higher value reflects higher exposure. Higher exposure = Higher vulnerability
	Std. deviation of annual rainfall	Number (15-year average)	
	Std. deviation of annual temperature	Number (15-year average)	
	Occurrence of river erosion	Dummy (1 = yes, 0 = no)	
Sensitivity	Frequency of higher intensity of floods	Dummy (1 = yes, 0 = no)	Higher value reflects higher sensitivity. Higher sensitivity = Higher vulnerability
	Irrigation water availability reduced	Dummy (1 = yes, 0 = no)	
	Loss of cultivable land	Dummy (1 = yes, 0 = no)	
	Loss of agricultural assets	Dummy (1 = yes, 0 = no)	
	Decreasing trend in production	Dummy (1 = yes, 0 = no)	
	Income loss from agriculture	Dummy (1 = yes, 0 = no)	
	Perceived food insecurity	Dummy (1 = yes, 0 = no)	
	High experience of the head of the households	Dummy (1 = yes, 0 = no)	
Adaptive Capacity	Education level of household head	Years of schooling	Higher Adaptive Capacity = Lower vulnerability
	Female-headed household	Dummy (1 = yes, 0 = no)	

Component	Sub-indicators	Unit of Measurement	Expected Relationship
	Secondary income source	Dummy (1 = yes, 0 = no)	
	Annual household savings	Dummy (1 = yes, 0 = no)	
	Use of quality agricultural inputs	Dummy (1 = yes, 0 = no)	
	Access to irrigation	Dummy (1 = yes, 0 = no)	
	Rainwater harvesting	Dummy (1 = yes, 0 = no)	
	Adoption of Alternating wetting or drying (AWD) practices	Dummy (1 = yes, 0 = no)	
	Use of stress-tolerant crop varieties	Dummy (1 = yes, 0 = no)	
	Knowledge on climate-smart agriculture practices	Dummy (1 = yes, 0 = no)	
	Improved crop diversification	Dummy (1 = yes, 0 = no)	
	Access to large farm size	Dummy (1 = yes, 0 = no)	
	Access to farm credit	Dummy (1 = yes, 0 = no)	
	NGO/CBO membership	Dummy (1 = yes, 0 = no)	
	Presence of embankments or dams	Dummy (1 = yes, 0 = no)	

2.7. Formulation of Ecosystem-Based Adaptation (EbA) and Nature-Based Solutions (NbS)

As part of the vulnerability assessment, a tailored Ecosystem-Based Adaptation (EbA) and Nature-Based Solutions (NbS) strategy was formulated for the Haor wetland region. This process integrated site-specific analyses of ecological integrity, socio-economic conditions, and climate risks.

Data for formulating EbA/NbS actions were collected through expert consultations, community-level surveys, FGDs, and KIIs. These participatory approaches ensured that proposed adaptation measures were grounded in local knowledge, gender inclusivity, and culturally appropriate practices. Key emphasis was placed on restoring ecosystem services, enhancing biodiversity, promoting indigenous farming systems, and empowering marginalized groups—particularly women and youth—to foster community resilience in alignment with national development priorities and the SDGs.

2.8. Data Sources

Data collection combined both primary and secondary sources to ensure reliability and comprehensiveness.

Collection of primary data: study area and sampling strategy

Five upazilas were purposively selected based on their high exposure to flooding and vulnerability within the Haor region: Kulaura, Juri, and Barlekha in Moulvibazar District, and Fenchuganj and Golapganj in Sylhet District.

The optimum sample size of 250 households was calculated using the standard formula for estimating a proportion:

$$n_0 = Z^2(1-P)/e^2,$$

where n_0 = Required sample size

Z = z-score for the 95% confidence level = 1.96;

p = expected proportion = 0.5

e = desired margin of error = .062

Substituting these values yields $n_0 \approx 250$, corresponding to a precision of ±6.2% at the 95% confidence level. Primary data were collected through a household survey, with 50 households randomly selected from each upazila (total = 250). In addition, qualitative data were obtained through 20 Key Informant Interviews (KIIs) with local upazilla officials, NGO representatives, and community leaders. and 10 Focus Group Discussions (FGDs) held across upazilas to capture community-level perceptions and gendered insights. to complement and triangulate the household-level findings.

Collection of secondary data: Secondary data were collected from national institutions and agencies, including:

(i) Bangladesh Meteorological Department (BMD), (ii) Bangladesh Water Development Board (BWDB), (iii) Bangladesh Bureau of Statistics (BBS), (iv) Department of Fisheries (DoF), (v) Department of Agricultural Extension (DAE), (vi) SPARRSO, WARPO, SRDI, DoE, GED, BARC, CDMP, CEGIS, IWM, and (vii) National Water Resources Database (NWRD)

Primary data were collected through structured household surveys, KIIs, and FGDs across selected sites. In cases where data were unavailable, expert elicitation and rational assumptions based on proxy indicators were used to ensure continuity and consistency in the analysis. All spatial and statistical analyses were conducted using ArcGIS, SPSS, and Microsoft Excel to support indicator mapping and future scenario modeling for the 2050s and 2080s.

3. Results and Discussion

3.1. Hydrological System of the Haor Region

3.1.1. Surface Water System

The surface water system of the Haor region is primarily sustained by major rivers such as the Surma, Kushiyara, Juri, Manu, and Sonai-Bordal, along with numerous tributaries, distributaries, and perennial Haors. Additionally, the area features seasonal *beels* that serve as temporary water bodies during monsoon and post-monsoon periods. These interconnected hydrological networks play a vital role in shaping the region's ecosystem and agricultural practices.

3.1.2. Surface and Groundwater Quality Status

A total of 12 surface water samples were collected from distinct locations across the study area. The quality assessment revealed spatial variations in water characteristics. Most physico-chemical parameters—including pH, Total Dissolved Solids (TDS), and Electrical Conductivity (EC)—were within acceptable limits, supporting fisheries and aquatic biodiversity. However, water temperature often exceeded the optimal range, and Total Suspended Solids (TSS) were frequently elevated. Dissolved Oxygen (DO) levels were generally low, posing risks to aquatic life. While Biological Oxygen Demand (BOD) was mostly within safe limits, Chemical Oxygen Demand (COD) levels frequently surpassed acceptable thresholds, indicating organic pollution and potential ecological stress.

Similarly, groundwater samples (n=12) indicated that temperature, pH, TDS, and hardness levels were mostly within standard limits. However, isolated sites exhibited elevated TDS and COD levels, possibly due to geological mineral content and contamination from organic sources.

3.2. Major Ecosystems and Ecosystem Services

The Haor region is recognized as a unique floodplain wetland ecosystem located in northeastern Bangladesh, covering parts of Sylhet, Sunamganj, Habiganj, and Moulvibazar districts. It hosts a rich diversity of flora and fauna, contributing significantly to the region’s economic, ecological, and social fabric.

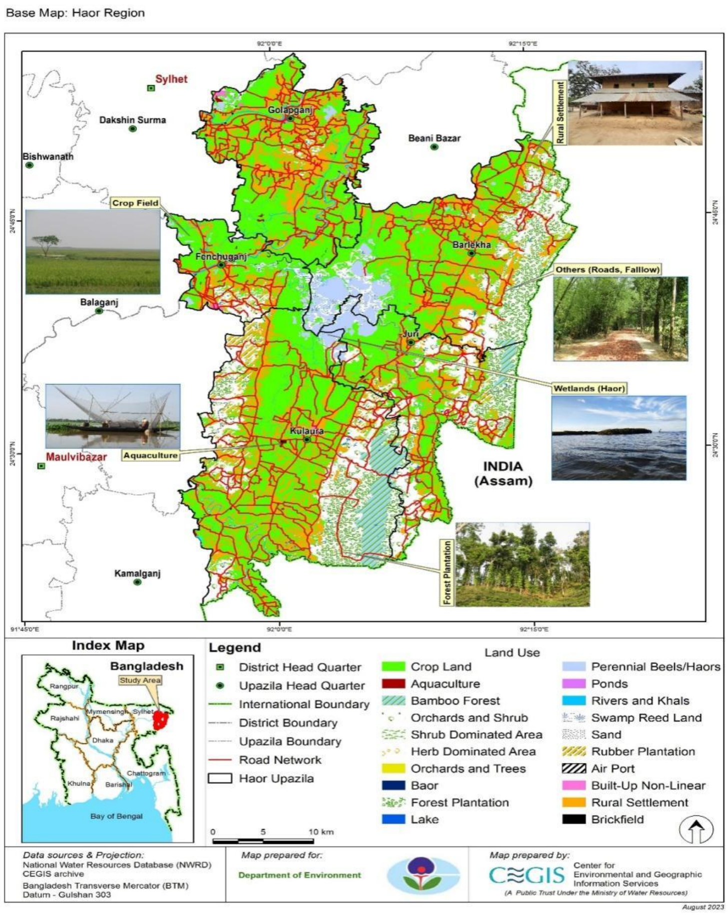

Figure 2. *Major Ecosystems of the study area according to land use.*

The ecosystems in the study area are broadly categorized into:

1) Terrestrial ecosystems, including agricultural land, homesteads, and forests.
2) Aquatic ecosystems, comprising rivers, haors, beels, and wetlands.

These ecosystems deliver vital provisioning, regulating, and supporting services, such as crop and fish production, flood regulation, groundwater recharge, and biodiversity conservation. Ecosystem delineation was carried out using land use maps derived from satellite imagery and field observations, as illustrated in Figure 2

3.3. Land Use Patterns in the Haor Region

Land use and land cover classification of the study area was conducted using KOMPSAT-2 and KOMPSAT-3 satellite imagery for 2019/20. The total gross area was estimated at 153,801 hectares (Table 4 and Figure 3), of which:

1) Net Cultivated Area (NCA) covers 69,621 ha (45.27%)
2) Forest Land spans 41,012 ha (26.67%)
3) Settlements occupy 34,514 ha (22.44%)
4) Other categories include wetlands, grasslands, aquaculture zones, orchards, and miscellaneous land uses.

This classification highlights the dominance of agricultural and forest land uses, with significant portions also allocated to human settlements and natural wetlands.

Table 4. *Land Use/Land Cover in the Haor Region.*

Land Use	Area (ha)	% of Gross Area
Net Cultivated Area (NCA)	69,621	45.27%
Aquaculture	234	0.15%
Forest Land	41,012	26.67%
Grassland	779	0.50%
Orchard and Other Plantation (Trees)	61	0.04%
Settlements	34,514	22.44%
Wetlands	7,306	4.75%
Other Lands	274	0.18%
Total	153,801	100%

Source: KOMPSAT-2,3 Satellite Imagery, 2019/20

Livelihoods

Agriculture remains the dominant livelihood in the Haor region, employing approximately 66.6% of the population. Another 23.3% are engaged in the service sector and 10.5% are engaed in industrial work. Due to seasonal inundation of the region for extended periods each year, residents primarily rely on agriculture and fishing as major sources of income. Figure 4 presents the occupational distribution in the Haor region. Alarmingly, 22.6% of the population is unemployed. In terms of specific agricultural roles, about 35% of the population are directly involved in crop production, 29% in Fishery while 12% work as agricultural day laborers

3.4. Climate-Induced Hazards: Historical Trends and Future Projections

Historical Climate Trends

Analysis of BMD weather station data shows a rising trend in average temperature across the Haor region, with Sylhet exhibiting the highest increase. Maximum temperatures are gradually rising at all stations, while minimum temperatures remain mostly unchanged.Rainfall trends in Sylhet and Sreemangal show substantial increases, especially in the pre-monsoon period, suggesting a heightened risk of early flash floods.

Flash Flood Trends

The northeastern Haor areas are particularly vulnerable to flash floods, which pose serious threats to Boro rice cultivation—the only major crop in the region. Boro rice covers about 80% of the area during the dry season (January to May) and contributes approximately 18% of national rice production [2].

Major flash floods occurred in 2006, 2007, 2009, 2010, 2017, and 2022. The 2017 flood was especially devastating, destroying premature crops worth $1.49 billion. The 2022 flood affected 7.2 million people across nine districts, damaged 1,133 sq. km of cropland, 44,254 water bodies, and over 49,000 sanitation facilities, causing livestock losses of $27.84 million. Additionally, 3,600 schools suspended classes and 480,000 people were displaced (UN RC Bangladesh, 2022).

These flash floods are not only increasing in frequency but are also occurring earlier in the season, further reducing the harvest window for Boro rice.

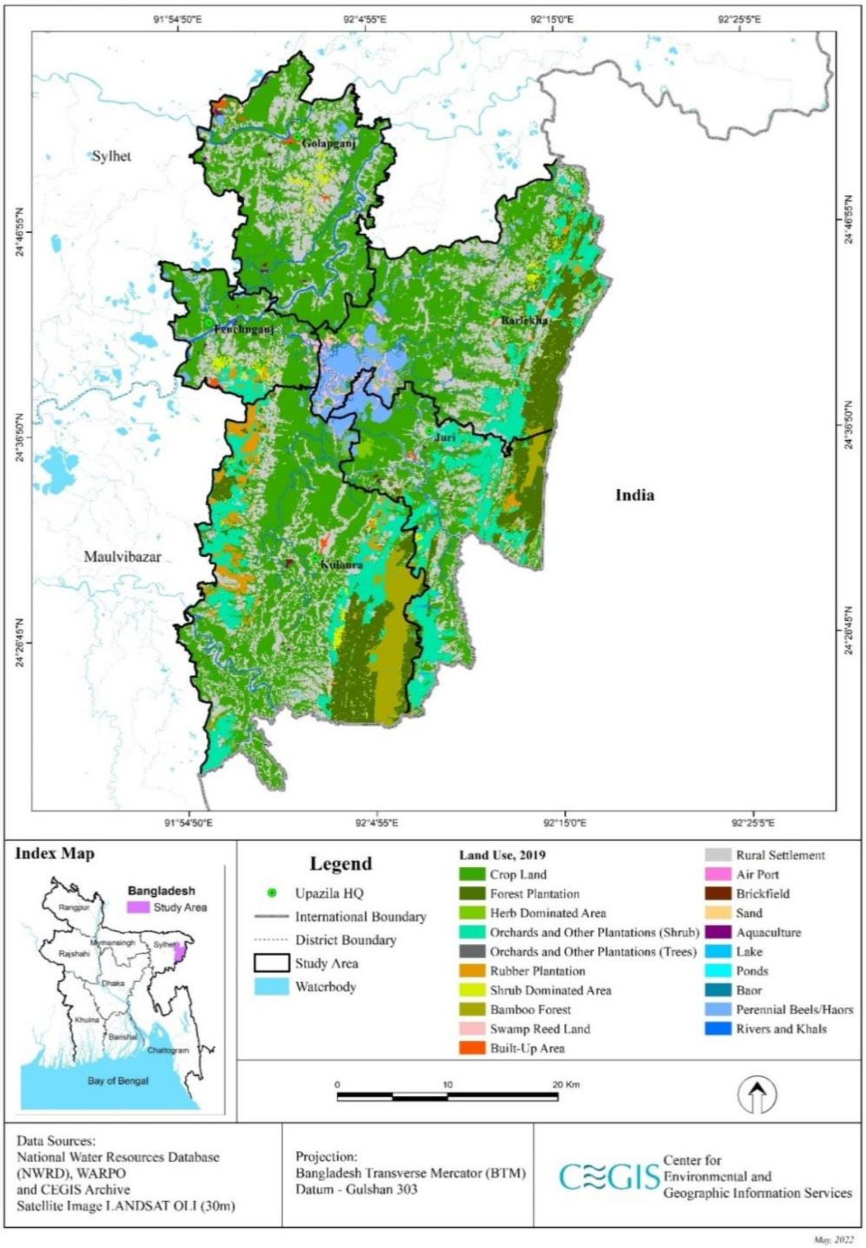

Figure 3. *Land use Map of the Haor Region.*

Climate Projections for the Haor Area by 2030 and 2050

Future climate projections under different emission scenarios (SSP1-2.6 and SSP5-8.5) show significant variations (Figure 4):

Temperature:

By the 2030s, maximum winter temperatures are projected to rise by 0.87-0.9 ℃, while in other seasons, the increase will range from 0.62-0.76 ℃. Barlekha and Juri are expected to experience the highest increases.

Rainfall:

Average rainfall will rise, especially in Golabganj, Fenchuganj, and Barlekha. Under SSP5-8.5, winter rainfall may decrease by about 10%, while monsoon rainfall is expected to increase by 1.7-2% under SSP1-2.6.

By the 2050s:

1) Winter rainfall could decline by 3.5-7%.
2) Pre-monsoon rainfall might fall slightly under SSP1-2.6 but increase under SSP5-8.5.

3) Monsoon rainfall will likely increase further, with the most significant rise under SSP5-8.5.

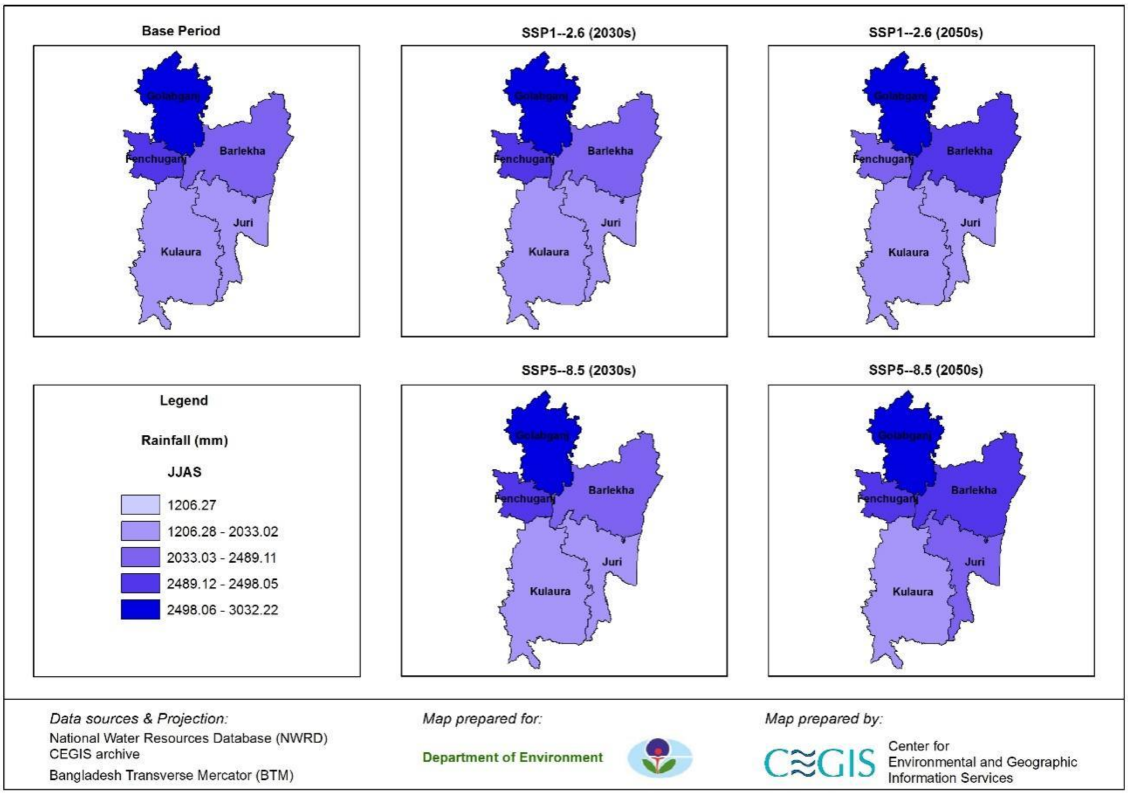

Figure 4. *Projected Changes in Monsoon Rainfall in the Haor Region by 2030 and 2050.*

Exposure and Sensitivity to Climate Hazards

Community consultations through FGDs identified key environmental hazards: seasonal flooding, flash floods, hailstorms, excessive rainfall, drought, riverbank erosion, waterlogging, lightning, temperature rise, and tornadoes.

Among these, flash floods, regular floods, and wave actions known as *Afal* are especially destructive to crops. Waterlogging exacerbates land degradation, while rising temperatures and water scarcity hinder irrigation and crop growth. Hailstorms also damage both crops and natural habitats, accelerating ecosystem fragmentation and reducing biodiversity and forest resources.

Barlekha, Kulaura, and Fenchuganj experience seasonal flooding due to siltation. Erosion along the Kushiyara River affects Fenchuganj and parts of Golapganj. Lightning strikes have caused fatalities, such as the 2019 incident in Dhupri Haor. Prolonged dry spells further deplete water resources, affecting both agriculture and biodiversity.

Agricultural Landscape: Mapping Exposure and Sensitivity

The Haor region's agricultural landscape is both ecologically sensitive and socioeconomically significant. The area relies heavily on Boro rice cultivation, which increases its exposure and sensitivity to climate-related hazards.

Key observations:

Cropping Patterns:

The dominance of rice, particularly HYV Boro, Aman, and Aus, indicates a lack of diversification, increasing vulnerability to crop-specific threats.

Cropping Intensity:

Varies between 151% to 186%, suggesting dependence on multiple crop cycles that are vulnerable to seasonal disruptions.

Fallow Land:

Fallow periods leave land exposed to erosion and fertility loss, particularly during erratic rainfall.

Cropping Distribution:

Upazilas like Barlekha and Fenchuganj show a higher proportion of single-cropped areas, making them more susceptible to climate shocks.

3.5. Key Stressors Affecting Agricultural Productivity

Field visits identified the following critical stressors in the Haor region's agricultural sector (Figure 5):

1) Early Flash Floods and Crop Susceptibility: Early monsoon floods, often triggered by upstream rainfall, severely damage Boro crops. In Hakaluki Haor, early flash floods leave little time for harvest, leading to near-total crop losses.

2) Inadequate Irrigation: Despite prolonged waterlogging, Boro rice suffers from water shortages during key growth stages. Only 19-20% of Boro land in Hakaluki Haor is irrigated, deterring investment and reducing yields [18, 19, 20, 27, 33].
3) Pest and Disease Outbreaks: BRRI dhan-28, a common short-duration variety, has become susceptible to Rice Blast disease due to overuse, leading to frequent yield losses [29].
4) Labor Shortages: Farmers face tight planting and harvesting windows, yet mechanization remains limited. Dependence on seasonal migrant labor from nearby districts causes delays and inefficiencies.

Figure 5. *Key Stressors Impacting the Agricultural Sector in the Haor Region.*

Flash floods are a recurring hazard in the Haor wetlands and have devastating impacts on agriculture-based livelihoods [17, 27]. According to [41] the 2017 flash floods affected nearly 1 million households, causing an estimated US$450 million in damage to rice crops alone. The study [42] further reported that the premature floods destroyed almost all ready-to-harvest rice crops, severely affecting household incomes and food security. Agricultural communities in the Haor, highly dependent on a single annual rice harvest, are particularly vulnerable. Loss of crops due to unexpected flooding has pushed many into income insecurity, deepened poverty, and heightened vulnerability across the region.

Key Stressors Affecting Livestock Production in the Haor Region

Livestock production in the Haor wetlands of Bangladesh faces a range of biophysical and institutional challenges, exacerbated by seasonal flooding and climate variability. Based on recent literature and field-based assessments, the following stressors are most critical [3, 4, 25]:

1) Seasonal Flooding and Flash Floods: The Haor basin remains submerged for nearly half the year, typically from June to November, due to monsoon rains and upstream runoff. Flash floods cause displacement, drowning, and distress sales of livestock, severely disrupting production cycles.

2) Scarcity of Feed and Fodder: Flooding submerges grazing lands and homestead vegetation, leading to acute shortages of green fodder. Farmers often rely on costly or inadequate alternatives, resulting in undernourished animals and reduced productivity.

3) Limited Access to Clean Water: Contaminated floodwaters and stagnant pools pose serious health risks. Lack of clean drinking water contributes to disease outbreaks and poor weight gain, especially in cattle and goats.

4) Inadequate Shelter and Housing: Traditional livestock shelters are not flood-resilient. Without elevated or reinforced housing, animals are exposed to stress, injury, and increased mortality during inundation periods.

5) Disease Outbreaks and Poor Veterinary Access: Wet conditions and overcrowding heighten the risk of infectious diseases such as foot-and-mouth disease and parasitic infections. Veterinary services are limited in remote Haor areas, and emergency response capacity is often inadequate.

6) Market Disruption and Economic Losses

Floods disrupt transportation and market access, leading to reduced demand, lower prices, and spoilage of animal products. Farmers face liquidity constraints and are often forced to sell livestock prematurely at depressed prices.

Governance and Institutional Gaps: There is a lack of coordinated livestock management policies tailored to Haor conditions. Limited integration of indigenous knowledge and community-based adaptation strategies further weakens resilience.

Key Stressors Affecting Fishery Production in the Haor Region

Based on recent literature and field-based assessments, the following stressors are most critical affecting fishery production [1, 22, 35]:

1) Hydrological Extremes and Flash Floods: Sudden flash floods during pre-monsoon months (March-April) damage breeding grounds and disrupt spawning cycles. Early inundation of *beels* (seasonal water bodies) leads to premature escape of juvenile fish, reducing catch volumes and recruitment rates.
2) Destructive Fishing Practices: Use of harmful gear such as fine-mesh nets, poison fishing, and dewatering of beels during dry seasons has led to indiscriminate harvesting of brood fish and juveniles. These practices undermine natural regeneration and long-term sus-

tainability of fish stocks.

3) Siltation and Habitat Degradation: (i) Sediment accumulation from upstream erosion and poor watershed management reduces water depth and connectivity between beels and rivers.(ii) Loss of swamp forests and aquatic vegetation further degrades critical habitats for spawning and feeding.
4) Water Quality Decline: (i) Pollution from agricultural runoff, domestic waste, and low dissolved oxygen (DO) levels during dry months negatively affect fish health and diversity. (ii) Key water parameters such as temperature, pH, nitrate, and phosphate have shown seasonal fluctuations that correlate with declining fish abundance.
5) Obstruction of Fish Migration: (i) Embankments, sluice gates, and road infrastructure impede natural fish migration between rivers and floodplains.(ii) This fragmentation of aquatic connectivity restricts access to breeding and feeding habitats, especially for migratory species.
6) Overexploitation and Lack of Regulation: High fishing pressure during peak seasons, coupled with weak enforcement of fisheries regulations, contributes to stock depletion. (ii) Absence of effective co-management or sanctuary systems in many Haor areas exacerbates the problem.
7) Climate Change Impacts: (i)Rising temperatures and erratic rainfall patterns alter hydrological regimes, affecting fish breeding cycles and productivity. (ii) Increased frequency of extreme weather events (e.g., droughts, floods) adds uncertainty to fishery planning and harvest outcomes.

Socio-Economic Profile of Farm Households

The socio-economic characteristics of the surveyed households across five Upazilas are summarized in Table 5. The average age of respondents is 46.1 years, with slight variations by location. The average education level is 4.01 years, with Golapganj having the highest (5.02 years) and Kulaura the lowest (3.07 years).

Average farm size is 101.53 decimals, with the largest in Juri (128.00 decimals) and smallest in Kulaura (67.38 decimals). The average monthly income from farming is Tk 7,324, highest in Golapganj (Tk 9,100). Off-farm income averages Tk 5,629, ranging from Tk 6,158 in Fenchuganj to Tk 5,171 in Barlekha.

Table 5. *Socio-Economic Profile of Respondent Households.*

Indicator	Kulaura	Barlekha	Fenchuganj	Golapganj	Juri	Average
Age (Years)	49.07	42.90	43.22	47.28	48.15	46.10
Education (School Years)	3.07	4.00	4.02	5.02	3.87	4.01
Farm Size (Decimal)	67.38	107.57	72.04	126.58	128.00	101.53
Income (Farming, Tk)	6,377.78	7,540.00	6,640.00	9,100.00	6,909.09	7,324.00
Income (Off-Farm, Tk)	5,772	5,171	6,158	5,567	5,500	5,629

3.6. Logit Regression Results on Agricultural Vulnerability Factors

A logit regression model was used to identify determinants influencing agricultural vulnerability in the Haor region. Eight variables were found to be statistically significant ($p < 0.01$ to $p < 0.05$): household savings, access to credit, use of quality inputs, crop diversification, knowledge of climate-smart agriculture (CSA), land area affected by disasters, and access to irrigation and larger landholdings (Table 6).

These factors reflect the adaptive capacity of households and their ability to withstand climate-induced agricultural shocks and vulnerability. Variables such as use of stress-tolerant varieties, water harvesting, participation in farmers' organizations, and benefit-sharing from embankment schemes also showed potential in reducing vulnerability, although not statistically significant.

These findings align with previous studies [10, 12-16, 26, 31, 30, 34, 39], reinforcing that diversified income sources, improved seed access, irrigation, and institutional support play critical roles in reducing vulnerability

Access to off-farm income is a vital coping mechanism post-disaster [15], but remains limited in the study area. Use of high-yield, stress-tolerant crop varieties is shown to reduce vulnerability significantly [13, 25]. Our results similarly show that the absence of such varieties, combined with poor irrigation access, contributes to low adaptive capacity.

Furthermore, institutional weaknesses—like limited access to credit and lack of research—exacerbate vulnerability. Female-headed households were found to be more vulnerable, consistent with [78]

Female-headed households in Nigeria experience heightened agricultural vulnerability—a finding that aligns with the results of our own study [78]. Furthermore, improved application of farming technologies, such as the use of high-quality inputs and efficient fertilizer practices, has been associated with significant average productivity gains per hectare in dryland agro-ecological systems [78]. In contrast, our research in the Haor wetland ecosystem reveals that access to and use of quality agricultural inputs contributes to a reduction in agricultural vulnerability.

Similarly, membership in community-based organizations and education were identified as factors exacerbating vulnerability in Ethiopia's lowland agro-ecological systems [78, 31]. Our findings corroborate this pattern in the Haor region, where farmers' educational attainment and participation in farmers' organizations appear to be linked with increased agricultural vulnerability in wetland contexts. The findings underscore the need for improved extension services, access to climate-resilient inputs, farmer education, and infrastructural investments to enhance resilience in the Haor agricultural systems.

Table 6. *Results of logit regression model explaining the determinants of agricultural vulnerability of the households of Haor area.*

Independent Variable X	Regression Coefficient b(i)	Standard Error Sb(i)	Wald Z-Value H0: β=0	Wald P-Value	Odds Ratio Exp(b(i))
Intercept	-0.24718	0.54833	-0.451	0.65214	0.78100
Total value of asset	0.00000	0.00000	1.149	0.25066	1.00000
Education	0.07788	0.07720	1.009	0.31305	1.08100
Regular contact with GOB extension department	0.70529	1.00065	0.705	0.48091	2.02444
Stress tolerant variety	-0.43371	0.86275	-0.503	0.61517	0.64810
Savings	-1.24550**	0.46961	-2.652	0.00800	0.28780
Access to credit	-1.35133**	0.43254	-3.124	0.00178	0.25890
Use good inputs	-1.41606**	0.68140	-2.078	0.03770	0.24267
Practice crop diversification	-2.22893**	0.91786	-2.428	0.01517	9.28989
Knowledge of climate smart agriculture	-2.19298**	1.02863	-2.132	0.03301	0.11158
Have water harvest	-0.28428	0.79732	-0.357	0.72144	0.75256
Have Membership of farmer's organization	-0.12905	0.65087	-0.198	0.84283	0.87893
Female head	0.14472	0.61312	0.236	0.81340	1.15572
Second occupation	0.19253	0.46340	0.415	0.67780	1.21231
Benefit sharing embankment	-0.98855	1.20619	-0.820	0.41246	0.37211
Use AWD	9.93337	195.37365	0.051	0.95945	10000+
Land Area Damaged	4.24517**	0.80204	5.293	0.00000	69.76761
Access to irrigation	-1.48607**	0.57412	-2.588	0.00964	4.41970
Access to large land holding	-0.86212*	0.55180	-1.562	0.11820	0.42226

Note: The fitness of the model is good as judged by -2 Log likelihood ratio of 170.948** and Nagelkerke R Square 0.669

3.7. Identification of Agricultural Vulnerable Zones

The Climate Risk and Vulnerability Assessment (CRVA) framework was employed to map agricultural risk and vulnerability in the Haor region across three time horizons: (i) the current baseline period, (ii) the 2030s, and (iii) the 2050s. Figure 6 illustrates these spatial variations. For the purpose of zoning, five Upazilas—Kulaura, Barlekha, Fenchuganj, Golapganj, and Juri—were selected. Risk levels were categorized into five classes: Very Low, Low, Moderate, High, and Very High.

Under the baseline scenario, agricultural risk was found to be low in Kulaura, moderate in Fenchuganj, Barlekha, and Juri, and high in Golapganj. CRVA projections under both SSP1-2.6 and SSP5-8.5 scenarios suggest that the overall risk profile of the Upazilas is expected to remain largely unchanged through the 2030s and continue into the 2050s, primarily due to the slow-onset nature of some climate risks and existing adaptation responses.

Figure 7 presents the vulnerability mapping, revealing more dynamic trends. Under SSP1-2.6, Golapganj's vulnerability increases from low to moderate by the 2030s, with conditions worsening in all Upazilas—except Kulaura—by the 2050s. Under SSP5-8.5, Juri shifts to a high vulnerability zone by the 2030s, while Kulaura transitions to moderate vulnerability in the same period, but returns to low vulnerability by the 2050s—reflecting the potential impact of climate-smart technology adoption and adaptive capacity improvements.

In both climate scenarios, Fenchuganj is projected to experience moderate agricultural vulnerability by the 2050s. The rate of vulnerability increase is expected to be more rapid in the 2030s, but will likely decelerate in the 2050s, largely due to technological advancements, improved infrastructure, and targeted adaptation interventions.

3.8. Ecosystem-based Adaptation (EbA) Solutions of the Haor Region

The Haor region's Ecosystem-based Adaptation (EbA) portfolio encompasses a set of integrated interventions across four critical sectors: agriculture, livestock, fisheries and aquaculture, and ecosystem and biodiversity conservation. These interventions are designed to enhance the region's resilience to climate change through nature-based solutions (NbS), while simultaneously improving livelihoods and preserving ecological integrity.

For the environmental sector, key short-, medium-, and long-term priorities include community-based reforestation, creation of buffer zones to protect water bodies, and restoration of degraded wetlands. These efforts are expected to be led by the Ministry of Environment, Forests and Climate Change (MoEFCC) and the Department of Environment (DoE).

In the agriculture sector, adaptive interventions should focus on scaling up climate-resilient technologies such as stress-tolerant crop varieties, alternate wetting and drying (AWD) irrigation techniques, floating bed cultivation, and diversified cropping patterns. These measures will require medium- to long-term implementation by the Department of Agricultural Extension (DAE) and the Bangladesh Agricultural Research Council (BARC).

For socioeconomic resilience, short- to medium-term actions are necessary to strengthen adaptive capacities, particularly among vulnerable communities. Priorities include promotion of alternative livelihoods, development of climate-resilient infrastructure, and expansion of eco-tourism. These will be facilitated by the Local Government Engineering Department (LGED) in coordination with relevant agencies.

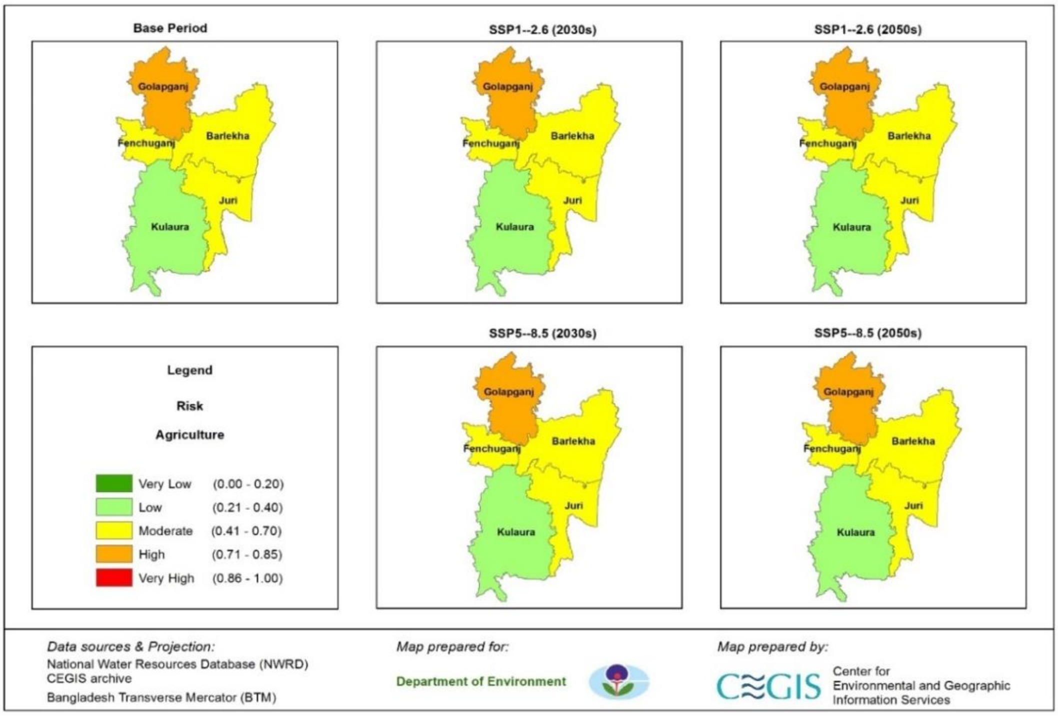

Figure 6. *Haor Risk Map- Agriculture Sector.*

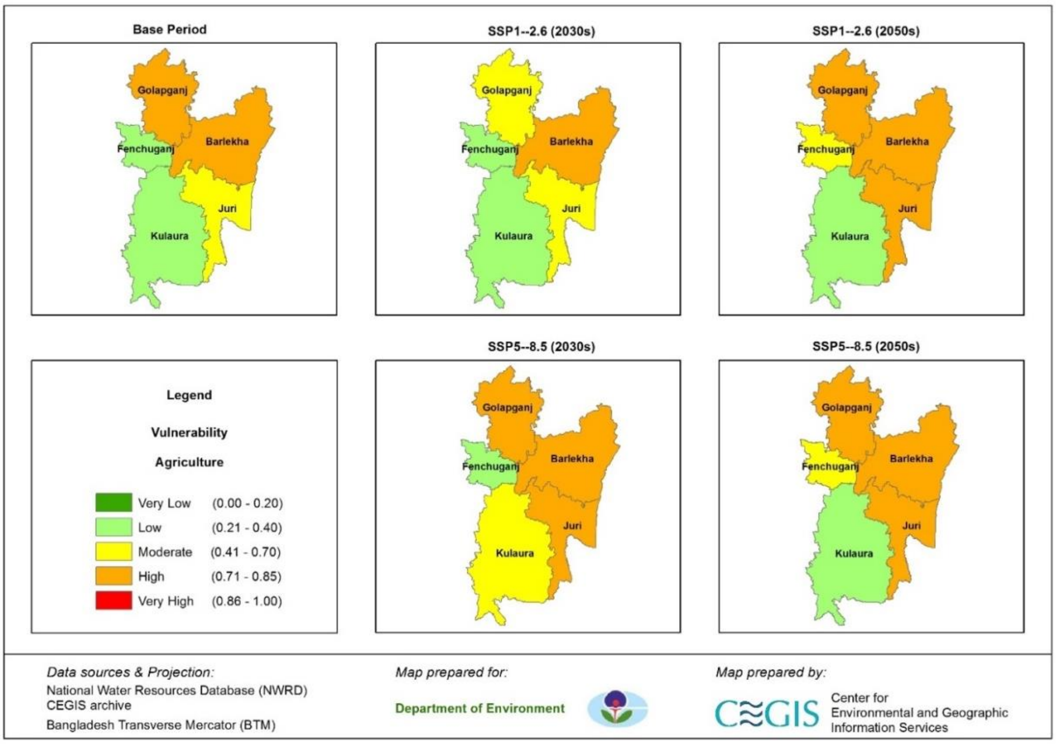

Figure 7. *Haor Vulnerability Map- Agriculture Sector.*

Considering target risk and existing adaptation capacity we have proposed ecosystem-based adaptation (EbA) solutions of the Haor Region in Table 7.

Table 7. *Proposed ecosystem-based adaptation (EbA) solutions of the Haor Region.*

A. Agriculture

Targeted Risk	Existing Adaptation Capacity	Proposed Nature-based Solutions (NbS)
1. Decline in upland irrigation water & increased flash floods	• Surface water irrigation from canals	• Rainwater harvesting systems • Canal excavation for water retention • Expansion of AWD irrigation
2. Flash flood damage to Boro rice & income loss	• Early harvesting & seedbed preparation • Short-duration and HYV varieties	• Floating bed agriculture • Bag gardening • Combine harvesters for rapid harvesting • Homestead and fallow land nutrition gardens
3. Soil nutrient depletion	• Imbalanced fertilizer usage	• Organic fertilizers (e.g., vermicompost, tricho-compost) • Biochar application for soil health • Improved input supply systems
4. Pest and disease outbreak	• Increased pesticide use • Limited IPM	• Scale-up IPM practices (pheromone traps, yellow sticky traps, bio-pesticides) • Promote biological control methods (e.g., parching)
5. Rising temperatures & erratic rainfall affecting crop growth	• Adjusted sowing times and crop diversification	• Disseminate stress-tolerant crop varieties (heat, flood, drought-resilient) • Promote mulching techniques in vegetable production
6. High household vulnerability due to low adaptive	• Limited institutional and livelihood support	• Training and capacity building • Women empowerment and group formation

Targeted Risk	Existing Adaptation Capacity	Proposed Nature-based Solutions (NbS)
capacity		• Market access, savings, credit access, and resilient infrastructure

B. Livestock Sector

Targeted Risk	Existing Adaptation Capacity	Proposed Nature-based Solutions (NbS)
Seasonal flooding and flash flood displacement	Use of elevated bamboo platforms and temporary shelters during peak inundation	Establish community-managed flood-resilient livestock shelters with raised earthen plinths and vet support
Scarcity of fodder during monsoon	Reliance on stored straw, rice bran, and market-purchased feed	Promote flood-tolerant fodder crops (e.g., Napier grass, water hyacinth composting) and floating fodder beds
Waterborne diseases and poor sanitation	Basic knowledge of disease symptoms and occasional access to para-vets	Develop wetland-integrated livestock corridors with natural filtration ponds and constructed wetlands for clean water access
Limited veterinary access in remote areas	Occasional NGO-supported mobile clinics	Establish community animal health hubs integrated with wetland biodiversity zones for shared services
Nutrient runoff and waste accumulation	Manual waste disposal and limited composting	Introduce biogas units and compost pits using livestock waste, integrated with wetland restoration zones
Loss of grazing land due to siltation	Seasonal migration of livestock to higher ground	Restore degraded grazing wetlands through sediment dredging, native grass replanting, and buffer zone creation

C. Fisheries and Aquaculture

Targeted Risk	Existing Adaptation Capacity	Proposed Nature-based Solutions (NbS)
1. Siltation of rivers and beels	No significant adaptive practices	• Restore wetlands by re-excavating silted rivers and beels, especially seasonal waterbodies
2. Disruption of fish breeding/spawning	Use of brush piles (kathas) in perennial beels	• Plant water-tolerant native trees like *Hijol* (Barringtonia acutangula) and *Koroch* (Pongamia pinnata)• Conserve core wetland zones and restore connectivity between waterbodies
3. Outbreak of fish diseases	No significant adaptive practices	• Regulate the use of agrochemicals in adjacent agricultural fields • Raise awareness on responsible chemical fertilizer application • Control disposal of household, animal, and latrine waste into open fields and waterbodies
4. Decline in fish species diversity	Established fish sanctuaries and beel nursery programs	• Expand fish sanctuaries and protect core wetland areas • Release fry of commercially and ecologically important fish species • Enforce sustainable fishing practices (ban on destructive gear, dewatering, and poison fishing)
5. Impediments to fishing activity (e.g., strong wave action)	No significant adaptive practices	• Plant wave-buffering species (e.g., *Hijol, Koroch*) in wetland perimeters • Conduct awareness campaigns for fisher communities on climate-resilient practices
6. Flooding of aquaculture ponds	• Raising pond dykes • Premature harvesting of fish	• Plant wave-breaking trees (e.g., Coconut, Palm, Date) and grasses along pond dykes to reduce erosion and structural damage

D. Ecosystem and Biodiversity

Targeted Risk	Existing Adaptation Capacity	Proposed Nature-based Solutions (NbS)
1. Habitat destruction due to flash floods	Conservation nurseries and wild animal habitat protection by CNRS in Juri, Kulaura, Barlekha	• Promote community-based afforestation and reforestation initiatives • Strengthen forest and biodiversity management systems to conserve both terrestrial and aquatic habitats
2. Pollution and wetland siltation damaging faunal feeding grounds	Use of tree branches in beels for water retention	• Establish buffer zones with native vegetation along canals and waterbodies to reduce sedimentation and pollution • Restore fish migration routes • Construct artificial nesting platforms for species like migratory birds and turtles
3. Increased faunal mortality due to rising temperatures	Bird habitat (Pakhi Bari) development in Juri Upazila, supported by eco-tourism	• Develop green spaces and urban forestry to reduce heat island effects • Plant shade trees and promote rooftop greenery • Engage local communities in awareness and conservation programs targeting temperature-sensitive species
4. Spread of invasive alien species (e.g., *Ipomoea* spp., *Eichhornia crassipes*)	Community-led use of invasive species for fencing and erosion control	• Restore native plant habitats to compete with invasives • Conduct invasive plant removal campaigns • Educate communities on the ecological risks and promote ecologically sound landscaping practices
5. Disease outbreak among faunal species	No significant adaptive practices	• Enhance biodiversity to reduce disease risk through ecosystem balancing • Improve land and water management to increase ecosystem resilience • Reduce habitat fragmentation and pollution that facilitate disease spread

3.9. Comparison with Regional Studies

Shared patterns and convergent findings: Studies across Southeast and South Asia reveal consistent observations that align with the Haor assessment:

1) Increasing hydrological variability and extreme events. Research from Cambodia's Tonle Sap system and Vietnam's Mekong floodplains shows rising variability in precipitation and floods, echoing Haor's flash-flood dynamics [42, 47]. South Asian floodplain studies, including India's Brahmaputra and the Sundarbans, similarly highlight intensified flood hazards linked to climate variability [44].
2) Acute vulnerability of mono-cropping systems. Evidence from Cambodia and the Mekong basin demonstrates that dependence on single-season rice amplifies food-security risks from unseasonal flooding [45, 49]. This is consistent with Haor's Boro rice vulnerability.
3) Fisheries decline linked to habitat degradation. Tonle Sap case studies show fisheries declines due to siltation, blocked connectivity, and land-use change [46]. Mekong delta studies report similar losses, paralleling Haor's beel (lake) siltation and declining spawning grounds [43].
4) Marginalized groups at highest risk. Studies across Cambodia and Vietnam note that landless fishers, women, and smallholders face disproportionate climate impacts [48, 52], reinforcing Haor findings on unequal vulnerability.

Contrasts and context-specific dynamics: While convergent patterns exist, regional contrasts highlight lessons for Haor:

1) Hydrological regime and upstream drivers. Cambodia's Tonle Sap is shaped by Mekong flood pulses and upstream dams, unlike Haor's localized pre-monsoon flash floods [42].
2) Institutional capacity. Vietnam's large-scale mangrove EbA programs, supported by PES schemes and state extension services [50], contrast with weaker institutional support in Bangladesh and Cambodia.
3) Land-tenure regimes. Cambodia's community fisheries (CFis) benefit from legal recognition of user rights [51], whereas Haor's tenure complexities could constrain similar co-management schemes.

Lessons from EbA implementations: Regional EbA experiences offer pragmatic lessons:

1) Combine NbS with livelihood programs. Vietnam's

mangrove restoration projects integrated aquaculture and PES incentives, ensuring uptake [53].

2) Community co-management. Cambodia's CFis improved stewardship through local rule-making and government backing [51].
3) Phased restoration. Mekong pilots demonstrated ecological and economic returns from phased wetland re-excavation and connectivity restoration [43].
4) Gender mainstreaming. Projects in Cambodia and Vietnam show that explicit gender-sensitive design (training, microfinance, representation) improves outcomes [71].

Gender and equity implications: Regional studies confirm that without gender-disaggregated approaches, EbA risks excluding women from decision-making and benefits [48]. Evidence from Cambodia shows that women's inclusion in CFis enhances equity and adaptive capacity [71]. These insights reinforce the need for Haor adaptation to embed gendered diagnostics, women's representation in governance, and targeted livelihood supports.

4. Conclusions and Recommendations

The Haor region, characterized by its unique hydro-ecological system and high vulnerability to climate variability, faces a complex set of interlinked environmental, agricultural, and socioeconomic challenges. The analysis presented in this Ecosystem-based Adaptation (EbA) portfolio demonstrates that nature-based solutions (NbS), when integrated across sectors, offer a viable and cost-effective pathway to building resilience and sustaining livelihoods in the face of climate change.

Key Conclusions:

1) Multisectoral vulnerability requires integrated response: The risks posed by flash floods, erratic rainfall, soil degradation, fishery decline, and biodiversity loss cannot be addressed through siloed approaches. Coordinated, ecosystem-based actions are essential.
2) Limited existing adaptive capacity: Most current adaptation practices are fragmented and reactive, with significant gaps in local capacity, infrastructure, and awareness. Many risks, especially in fisheries and ecosystem conservation, remain unaddressed.
3) Nature-based solutions offer multiple co-benefits: Proposed NbS—such as wetland restoration, community-based afforestation, floating agriculture, stress-tolerant crops, and sustainable aquaculture practices—not only address climate risks but also improve biodiversity, enhance soil and water health, and diversify livelihoods.
4) Institutional support is critical: Effective implementation will require active engagement and coordination among key actors including the Department of Agricultural Extension, Department of Fisheries, Department of Environment, LGED, BARC, and local government institutions.

Strategic Recommendations:

1) Mainstream Ecosystem-based Adaptation (EbA) into regional planning: EbA principles should be integrated into the Haor Master Plan, district-level development strategies, and national climate policies.
2) Invest in community-led interventions and capacity building: Strengthen local institutions and empower communities through training, access to finance, and market linkages to ensure ownership and sustainability of EbA practices.
3) Scale up proven climate-smart technologies: Expand successful interventions such as AWD irrigation, floating bed cultivation, fish sanctuaries, stress-tolerant crop varieties, and vermicomposting to improve adaptive capacity at scale.
4) Restore and conserve critical wetland ecosystems: Prioritize re-excavation of silted beels and rivers, protection of core habitats, regulation of agrochemical use, and control of invasive species to maintain ecological integrity.
5) Elevated and Flood-Resilient Livestock Shelters: (i) Raised platforms using bamboo, concrete, or earthen plinths to protect animals during seasonal flooding. (ii) Proven effective in reducing livestock mortality and stress during flash floods.
6) Flood-Tolerant Fodder Systems: (i) Cultivation of Napier grass, para grass, and floating fodder beds using water hyacinth compost. (ii)Ensures year-round feed availability and reduces reliance on external feed markets.
7) Mobile Veterinary Clinics and Tele-Vet Platforms: (i) Mobile units equipped with basic diagnostics and treatment kits. (2) Supported by digital platforms for remote consultation and disease surveillance in remote Haor areas.
8) Climate-Resilient Breeds and Improved Genetics: (i) Promotion of crossbred cattle and goats with higher tolerance to heat and disease. (ii) Enhances productivity and resilience under erratic climate conditions
9) Foster cross-sectoral coordination: Establish a multi-stakeholder platform to align actions across agriculture, livestock, fisheries, environment, and rural development sectors for synergy in EbA implementation.
10) Enhance climate and ecological monitoring systems: Invest in data systems and local observation networks to support timely risk assessment, early warning, and adaptive management of interventions.

By adopting these ecosystem-based strategies, the Haor region can build long-term resilience, secure food and water resources, protect biodiversity, and ensure sustainable development for its vulnerable communities.

Abbreviations

NAP	National Adaptation Plan
Eba	Ecosystem-based adaptation
CRVA	Climate Risk Vulnerability Assessment
CMIP6	Coupled Model Intercomparison Project, Phase 6
GCMs	Global climate models
SSPs	Shared Socioeconomic Pathways
BMD	Bangladesh Meteorological Department
MBE	Mean Bias Error
RMSE	Root Mean Square Error
QM	Quantile mapping
IPCC	Intergovernmental Panel on Climate Change
AVI	Agricultural Vulnerability Index
NBS	Nature based solutions
FGDs	Focus Group Discussion
KIIs	Key Informant Interviews
SDGs	Sustainable Development Goals
BMD	Bangladesh Meteorological Department
BWDB	Bangladesh Water Development Board
BBS	Bangladesh Bureau of Statistics
DOF	Department of Fisheries
DAE	Department of Agricultural Extension
SPARRSO	Bangladesh Space Research and Remote Sensing Organization
WARPO	Water Resources Planning Organization
SRDI	Soil Resource Development Institute
DoE	Deartment of Envioronment
GED	General Economics Division
BARC	Bangladesh Agricultural Reserch Council
CDMP	Certified Data Management Professional
CEGIS	Center of Environment and Geographic Information Suystem
IWM	Irrigation and Water Management
NWRD	National Water Resources Database
SPSS	Statistical Package for Social Science
TDS	Total Dissolved Solids
EC	Electrical Conductivity
TSS	Total Suspended Solids
DO	Dissolved Oxygen
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
NCA	Net Cultivated Area
BRRI	Bangladesh Rice Research Institute
CSA	Climate-Smart Agriculture

Author Contributions

Sheikh Mohammad Fakhrul Islam: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing

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Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

Sheikh Mohammad Fakhrul Islam is a retired professor at Bangabandhu Sheikh Mujibur Rahman Agricultural University, Bangladesh, Department of Agricultural Economics. He completed his PhD in Agricultural Economics from University of Philippines in 1995 and post Ph. D in natural resource and Environmental Economics from Aristotle University of Thessaloniki in 1998, and his Master of Agricultural Economics in Agricultural Marketing from Bangladesh Agricultural University in 1987. He has sound experience of working as a think tank, teaching at universities, working as researcher and development professional at various international organizations such as World Bank, FAO, WFP, UNDP, ADB, EU, USAID, DFID, IRRI, ILRI, IFPRI, etc. He has participated in multiple international research collaboration projects in recent years. He served as Team Leader for the Vulnerability Impact Assessment study of the Haor and Barind regions of Bangladesh, implemented under the CEGIS-UNEP and Department of Environment initiative. He also led the IRGDSL-World Bank Cool Chain Project for Livestock in Dhaka, Bangladesh, overseeing strategic planning and implementation. He has numerous publications and has been invited as a Keynote Speaker, Technical Committee Member, Session Chair, and Judge at national and international conferences.

Laila Sanjida is an experienced specialist in Nature-based Resource Management at CEGIS. She provides input to assess and manage climate-induced disaster risks and vulnerabilities through the application of Ecosystem-based Adaptation Approaches. Sanjida has over 14 years of practical experience in project management for national and international planning projects. She has worked extensively on conducting various studies such as EIA, SIA, SEA, EbA, and Feasibility studies under different projects. Additionally, she has provided Environmental Management Plans (EMP) and Disaster Risk Reduction (DRR) Plans, including adaptation and monitoring plans. Ms. Laila has worked on a variety of significant projects, sometimes as a project leader, task leader, or member of the study team. She has extensive experience collaborating with various international organizations, including the World Bank, FAO, ADB, UNDP, EU, GIZ, UNEP, USAID, and many others. In most projects, she worked as an Ecosystem Management and NbS Specialist. Her responsibilities included collecting and analyzing environmental, ecological, and climatic disaster-related data to assess the risk and vulnerability of the study areas. She interpreted the results to prepare sustainable development plans and management frameworks that introduced Nature-based Solutions (NbSs). Ms. Laila also plays a pivotal role in analyzing biodiversity and habitat data using ecological models (InVEST) and preparing maps using GIS-RS technology.

Mohammad Hasan Sabit is a Research Consultant at the Center for Environmental and Geographic Information Services (CEGIS). He specialized in sustainable agriculture, soil health, and nutrient recycling. He holds a Master of Science in Agroforestry and Environmental Science from Sher-e-Bangla Agricultural University in 2021 following a Bachelor of Science in Agricultural Science at Khulna University in 2018. For his master's thesis, he investigated the effects of coal mining on surrounding soil properties, laying the foundation for his ongoing research interests in soil remediation and biochar. In recognition of his academic promise, he was awarded the National Science and Technology (NST) Fellowship in 2019. At CEGIS, In his current role, Hasan conducts vulnerability assessments of agricultural resources with a focus on climate change impacts in regions like Barind and Haor. His responsibilities include managing field research teams, conducting data analysis using SPSS and R, and formulating environmental management plans. His work also involves reviewing national agricultural policies and collaborating with government departments. He is an active member of the Krishibid Institute Bangladesh (KIB) and the Khulna University Alumni Association.

Bhuiya Mohammad Tamim Al Hossain is a climate change specialist currently serving at the Center for Environmental and Geographic Information Services (CEGIS), Bangladesh. He holds a Master’s degree in Flood Risk Management from UNESCO-IHE, The Netherlands (2013), and brings over 15 years of robust experience in climate change, water resources, and disaster risk management. Mr. Hossain has led and contributed to numerous climate-focused projects funded by both national and international agencies, collaborating with esteemed research institutions. His core expertise lies in analyzing climatic parameters and projecting their future variability to assess sectoral vulnerabilities—particularly in hydrology, agriculture, natural resources, public health, and disaster events such as floods. He is proficient in simulating regional climate models to develop high-resolution climate scenarios for Bangladesh. His technical contributions have been instrumental in shaping key national policy documents, including the National Adaptation Plan (NAP), Nationally Determined Contributions (NDCs) 2021, Second and Third National Communications, Biennial Transparency Report (BTR1), and the Bangladesh Delta Plan 2100 (BDP2100). Mr. Hossain’s portfolio includes comprehensive impact assessments and vulnerability analyses across critical sectors such as water resources, agriculture, fisheries, livestock, and health. He has also conducted hydrological assessments for major infrastructure projects, ensuring climate-resilient design and implementation. His research on sea level rise and its regional variations along the Bangladesh coast under changing climate conditions further underscores his commitment to advancing climate resilience through evidence-based policy and planning.

Research Field

Sheikh Mohammad Fakhrul Islam: Agricultural Economics, Natural resource management, Climate change and environment, Climate smart agriculture, Agricultural Value Chain, Consumer's perceptions on demand for chilled meat and milk, Investment in cool chain, Food quality and safety, Impact assessment

Laila Sanjida: Ecosystem Management, Assessing risk and vulnerability, Sustainable development, Analyzing biodiversity and habitat data using ecological models, Ecology

Mohammad Hasan Sabit: Sustainable Agriculture, Climate Smart Agriculture, Soil Remediation, Soil Health and Plant Nutrition, Biochar and Nutrient Recycling

Bhuiya Mohammad Tamim Al Hossain: Climate change, Climate vulnerability analysis, Hydrology, Ecosystem-Based Adaptation