

Impacts of Climate Variability on Inland and Coastal Fish Diversity of Bangladesh: A Systematic Review

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Abstract

Bangladesh has rich inland and coastal fish diversity that is vital for biodiversity conservation, food security, and the livelihoods of millions of people. However, this diversity is increasingly threatened by climate variability through rising temperature, erratic rainfall, floods, droughts, cyclones, sea-level rise, and salinity intrusion. This review synthesizes existing evidence on how climate variability affects fish diversity across rivers, floodplains, wetlands, estuaries, and coastal ecosystems of Bangladesh. Following PRISMA 2020 guidelines, relevant literature was collected from major academic databases and institutional reports, screened using defined inclusion and exclusion criteria, and synthesized through a narrative thematic approach. The review found that climate variability affects fish assemblages through multiple interacting pathways, including thermal stress, altered hydrology, habitat fragmentation, deterioration of water quality, disruption of spawning and migration cues, and changes in food-web structure. Inland water bodies, particularly rivers, haors, beels, and floodplains, show declining species richness and increasing dominance of tolerant and opportunistic species under irregular flooding, drought, and warming. In coastal and estuarine ecosystems, salinity intrusion, reduced freshwater inflow, and extreme climatic events are reshaping fish community structure and degrading critical nursery habitats. Migratory species such as hilsa have been identified as particularly vulnerable, and this is well documented in literature due to relatively extensive research attention. However, several other migratory fish species have received far less scientific focus, resulting in significant knowledge gaps regarding their population status and climate-related responses, even though they are likely experiencing similar pressures. The review also highlights those anthropogenic pressures, including overfishing, pollution, habitat conversion, and hydrological alteration, amplifying climate-related biodiversity loss. Overall, sustaining fish diversity in Bangladesh will require integrated climate-resilient fisheries management, habitat restoration, ecosystem-based conservation, and long-term research and monitoring.

Keywords: Climate variability; Fish diversity; Inland fisheries; Coastal fisheries; Bangladesh; Salinity intrusion; Climate adaptation

1. Introduction

Bangladesh is one of the most hydrologically complex and fish-diverse countries in South Asia. Its position within the Ganges-Brahmaputra-Meghna delta, has created an extensive and highly connected network of rivers, floodplains, haors, beels, estuaries, and coastal waters linked to the Bay of Bengal (Islam, 2016; Uddin et al., 2024). This hydro-ecological setting supports exceptionally aquatic biodiversity and sustains one of the world's most important inland fisheries systems. Available evidence indicates that Bangladesh harbors more than 260 native freshwater fish species, while estuarine and marine environments contribute additional diversity, including euryhaline, pelagic, demersal, and migratory taxa (IUCN Bangladesh, 2015; Pandit et al., 2021; Sarker et al., 2022; Rakib et al., 2022). The fisheries sector remains central to the national food security, employment, and rural economy. According to the Department of Fisheries (DoF) Yearbook, total fish production in Bangladesh has reached approximately 4.9 million metric tons, contributing about 3.5–3.6% to the national GDP and more than 25% to the agricultural GDP, while continuing to provide a major share of animal-source protein for the population, with Bangladesh continuing to rank among the world's leading producers in inland capture fisheries and aquaculture (FAO, 2022; DoF, 2025).

Fish diversity in Bangladesh is important not only from a conservation perspective, but also because it underpins ecosystem functioning and human well-being. Diverse fish assemblages contribute to trophic regulation, nutrient cycling, and ecosystem stability across rivers, wetlands, estuaries, and mangrove-associated habitats (Hossain et al., 2012; Shaha et al., 2022; Rakib et al., 2022). This diversity also has direct nutritional and livelihood significance. Small indigenous species (SIS) are widely accessible to rural households and are rich in vitamin A, calcium, iron, and zinc, making them especially important for nutrition security among women and children (Roos et al., 2002; Roos et al., 2003; Roos et al., 2007). In addition, culturally and economically important migratory species such as hilsa (*Tenualosa ilisha*) connect inland, estuarine, and coastal systems through their life history, illustrating the ecological interdependence of Bangladesh's aquatic environments (Bala et al., 2014; Mozumder et al., 2023, Ahammad et al., 2025; Sunny et al., 2026). These features make fish diversity a critical ecological and socio-economic asset in a country that remains highly dependent on aquatic resources.

90 Against this backdrop, climate variability has emerged as an increasingly important driver of
91 ecological change across Bangladesh's fisheries landscapes. In this review, climate variability
92 refers to short- to medium-term fluctuations in temperature, rainfall, river discharge, salinity, and
93 extreme events such as floods, droughts, cyclones, and storm surges, whereas climate change
94 denotes longer-term directional shifts in climatic means and extremes (IPCC, 2022; World Bank,
95 2021). This distinction is especially relevant in Bangladesh, where fish diversity is closely
96 regulated by seasonal flooding, floodplain connectivity, freshwater inflow, salinity gradients, and
97 habitat accessibility. Recent evidence suggests that the country has already experienced rising
98 temperatures, altered rainfall regimes, strong monsoonal irregularity, and increasing hydro-
99 climatic stress in both inland and coastal zones (Sarker, 2021; World Bank, 2021; Haque et al.,
100 2025). Such changes are ecologically consequential because they can alter spawning cues,
101 recruitment dynamics, migration routes, habitat suitability, and community structure across
102 interconnected aquatic systems (Ficke et al., 2007; Pörtner and Peck, 2010; Rakib et al., 2022;
103 Wahid et al., 2025).

104 Accumulating evidence indicates that these climatic disturbances are already reshaping fish
105 diversity in Bangladesh through multiple pathways (Aziz et al., 2021; Parvez et al., 2023). In
106 inland systems, erratic rainfall, shifts in flood timing, temperature anomalies, siltation, and
107 wetland drying have been associated with declining species richness and shifts toward more
108 disturbance-tolerant assemblages in ecologically important wetlands such as Hakaluki Haor and
109 Tangar Haor (Sarker et al., 2022; Sultana et al., 2022). In estuarine and coastal environments,
110 salinity intrusion, hydrological fluctuations, and habitat degradation influence fish composition,
111 nursery-ground function, and community structure, as documented in the Meghna estuary and
112 other deltaic systems of the Bengal coast (Hossain et al., 2012; Shaha et al., 2022; Rakib et al.,
113 2022). These patterns are broadly consistent with the wider fisheries-climate literature, which
114 shows that warming, oxygen stress, altered hydrology, and shifting environmental envelopes can
115 reorganize fish distributions, phenology, productivity, and assemblage structure (Allison et al.,
116 2009; Cheung et al., 2013; Pinsky et al., 2013). At the same time, changes in fish production
117 alone do not necessarily reflect the condition of aquatic biodiversity, since increases in
118 aquaculture output or total harvest may occur alongside losses in native species diversity and
119 ecological integrity.

Despite growing research on fisheries and climate change in Bangladesh, biodiversity responses remain less systematically synthesized than production trends, aquaculture performance, and socio-economic vulnerability. Existing studies also tend to examine inland and coastal ecosystems separately, even though these environments are ecologically connected through migratory species, estuarine exchange, and freshwater inflows. Therefore, there is still limited integrative understanding of how climate variability affects fish species richness, distribution, community composition, and ecological resilience across Bangladesh's inland and coastal fisheries systems. This review addresses that gap by synthesizing the available scientific evidence on climate variability and fish diversity across Bangladesh's major aquatic environments. Specifically, it examines the principal dimensions of climate variability affecting fish communities, compares biodiversity responses between inland and coastal ecosystems, and considers the implications of these patterns for climate-resilient fisheries management and biodiversity conservation in Bangladesh.

2. Methodology

This study was conducted as a systematic literature review with narrative synthesis and was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement (Page et al. 2021). The review was designed to synthesize available evidence on the effects of climate variability on inland and coastal fish diversity in Bangladesh in a transparent and reproducible manner. A systematic literature on the impacts of climate variability on inland and coastal fish diversity in Bangladesh was carried out in the Web of Science core collection and Scopus as the primary bibliographic databases, with supplementary searches in Google Scholar and publisher platforms, including ScienceDirect and SpringerLink, to capture additional relevant studies. Grey literature and institutional reports were also consulted where relevant, particularly from FAO, IPCC, IUCN, and the Department of Fisheries, Bangladesh. The search covered publications published between January 2000 and April 2026. Search terms were developed to capture three core elements of the review: climate-related drivers, fish biodiversity outcomes, and the Bangladesh context. These terms were combined using Boolean operators and adjusted according to the syntax of each database. A representative search string was as follows:

(“climate variability” OR “climate change” OR “temperature” OR “rainfall” OR “hydrology”
OR “salinity” OR “flood” OR “drought” OR “cyclone” OR “storm surge”) AND (“fish
diversity” OR “biodiversity” OR “species richness” OR “assemblage” OR “community” OR
“migration”) AND (“Bangladesh”) AND (“inland fisheries” OR “coastal fisheries” OR
“wetland” OR “river” OR “estuary” OR “floodplain” OR “hilsa migration”).

Additional manual screening of reference lists was undertaken to identify potentially relevant studies that were not retrieved in the database search. Only studies published in English were included, and this may have introduced language bias. All records retrieved from the searches were imported into Mendeley, and duplicate entries were removed prior to screening. Study selection was completed in two stages. First, title and abstract were screened against the eligibility criteria. Second, full-text articles were assessed for final inclusion. The study selection process, including identification, screening, eligibility assessment, and final inclusion, is presented in Figure 1.

Inclusion criteria for the studies were: (i) they should have been conducted in Bangladesh or should have provided Bangladesh-specific ecological evidence, (ii) they should have investigated climate-related factors such as temperature variation, rainfall irregularity, change in river discharge, salinity intrusion, floods, droughts, cyclones, and storm surges, (iii) they should have investigated biodiversity-related outcomes such as species richness, composition, distribution, migration, habitat use, and other ecological aspects of fish communities, and (iv) they should have provided adequate methodological and contextual information to interpret the research findings. Exclusion criteria for the studies were: (i) if they had investigated aspects of aquaculture production in isolation without any ecological significance, (ii) if they had investigated socio-economic aspects of vulnerability without any biodiversity-related outcomes, (iii) if they had provided insufficient scientific detail, (iv) if they had been opinion-based or had an editorial style, and (v) if they had been conducted outside of Bangladesh.

To carry out data extraction, a standardized form was utilized. For each included study, the following details were entered where available: authors, publication year, location, type of ecosystem, type of study, climatic drivers, biodiversity-related response variables, findings, and any other available data useful for effect size estimation. A thematic narrative approach was utilized to synthesize the extracted evidence, with themes based on a defined set of domains. These domains included climatic drivers of fisheries systems, ecological response in inland fish

communities, ecological response in coastal fish communities, and migratory species and adaptation strategies, with themes emerging from a preliminary understanding of the review aims and further informed by the full-text articles analyzed.

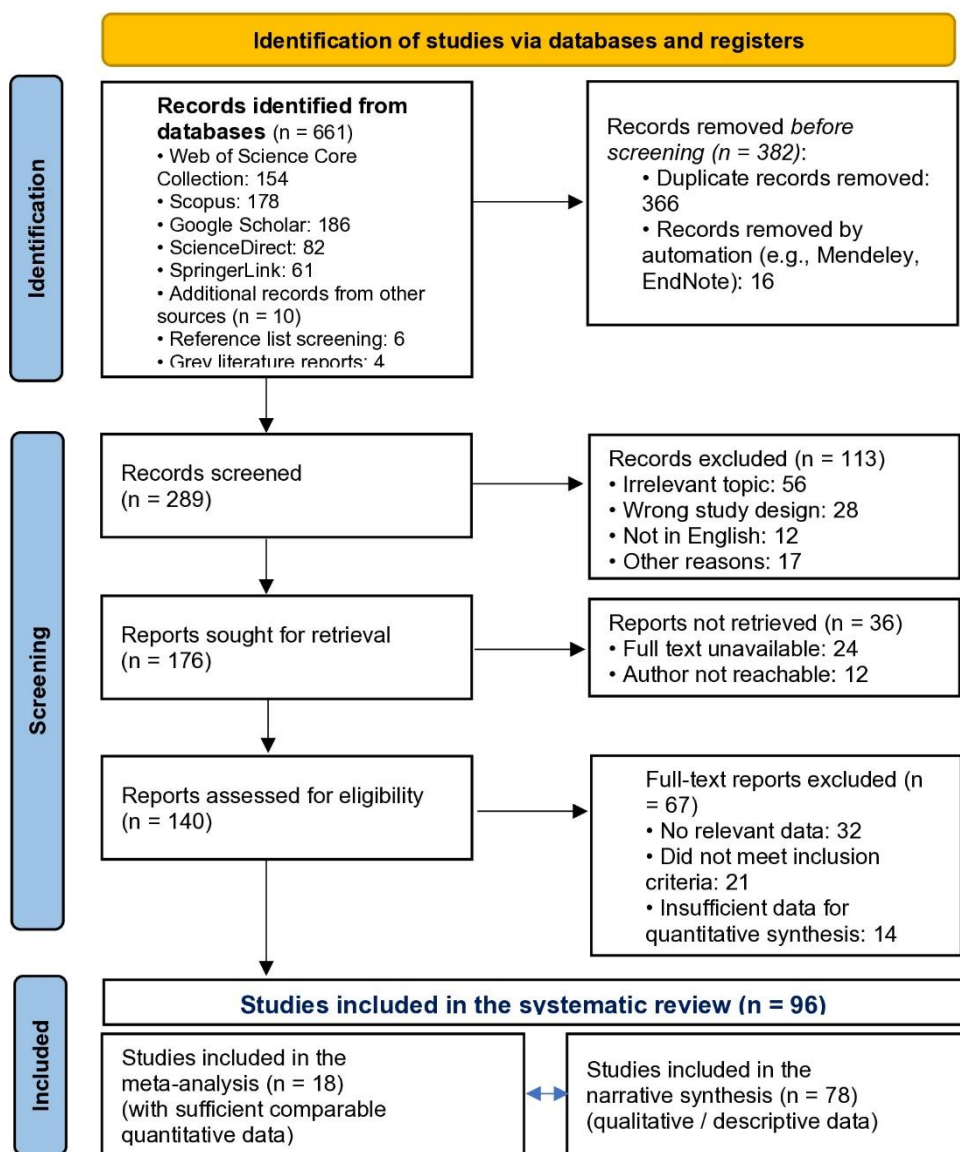


Figure 1. PRISMA 2020 flow diagram illustrating the identification, screening, eligibility assessment, and inclusion of studies in the systematic review and quantitative meta-analysis.

To assess the reliability of the evidence base, the methodological quality of the included studies was also evaluated through a structured framework for assessing the quality of observational ecological studies. The criteria for evaluating the quality included study design, sampling

methods, temporal and spatial scope, clear description of exposure assessment, clear definition of biodiversity outcomes, confounding variables, and transparency in analyses. The quality of the included studies was then interpreted as having low, moderate, or high-risk bias.

2.1 Meta-analysis Framework

Where there was sufficient quantitative data available, a meta-analysis approach was undertaken to assess the total effect of climate variability on fish biodiversity in Bangladesh. The meta-analysis framework was developed following standard systematic review and quantitative synthesis procedures, with methodological guidance adapted from recent aquaculture meta-analysis studies, including Ahmed et al. (2025a), Ahmed (2026). Quantitative synthesis of studies was limited to studies that reported similar quantitative measures of ecological responses under climate-impacted and reference conditions or in studies that reported quantitative measures of ecological responses in clearly defined contrasting exposure groups. The studies that did not report sufficient quantitative data for statistical analysis were subject to a narrative synthesis approach.

For each study included in the quantitative synthesis, key information was extracted, including author, year, ecosystem type, biodiversity response variable, sample size, mean value, and standard deviation for the comparison groups. Effect sizes were calculated as Hedges' g , which corrects the standardized mean difference for small-sample bias. The effect size was estimated from the difference between the mean response under climate-impacted conditions (M_1) and the mean response under reference or lower-impact conditions (M_2), standardized by the pooled standard deviation (SD_{pooled}):

$$g = J \times \frac{M_1 - M_2}{SD_{pooled}}$$

where J is the small-sample correction factor, and

$$SD_{pooled} = \sqrt{\frac{(n_1 - 1)SD_1^2 + (n_2 - 1)SD_2^2}{n_1 + n_2 - 2}}$$

with n_1 and n_2 representing the sample sizes of the two comparison groups, and SD_1 and SD_2 their respective standard deviations.

In addition, owing to differences in ecological study design, sampling effort, climate exposure, and biodiversity response among various aquatic ecosystems, a random effects meta-analysis model was applied to obtain estimates of effect sizes. This was considered to be a better approach compared to a fixed effect model, owing to the assumption that effect sizes in this study might differ from one study to another, contrary to a fixed effect model where effect sizes are constant.

Statistical heterogeneity among studies was assessed using Cochran's Q statistic, the I^2 statistic, and the between-study variance component (τ^2). The I^2 value was used to estimate the proportion of total variation attributable to between-study heterogeneity rather than sampling error. When data were available, subgroup analyses were undertaken to investigate differences in effect sizes between different categories of ecosystems, such as inland wetlands, riverine, estuarine, and coastal ecosystems, as well as major climatic factors like temperature fluctuations, hydrological fluctuations, salinity intrusion, and extreme weather events.

To test the robustness of the quantitative synthesis result, the results of the quantitative synthesis were checked for the influence of individual studies by conducting a sensitivity analysis. The presence of publication bias was checked if the number of studies was adequate for the evaluation of publication bias. The meta-analytical techniques were performed using the R software version 4.6.0, and the results were interpreted along with the narrative synthesis results.

3. Overview of Fisheries and Aquatic Ecosystems in Bangladesh

Bangladesh contains a highly diverse aquatic mosaic formed by the Ganges–Brahmaputra–Meghna delta, including rivers, floodplains, haors, beels, baors, estuaries, mangroves, and coastal waters (Figure 2). These ecosystems sustain exceptional fish biodiversity and support one of the world's most productive inland fisheries systems (FAO, 1989; IUCN Bangladesh, 2015; DoF, 2025). Inland open waters are the principal habitats for native freshwater fishes, with rivers and seasonally inundated floodplains serving as breeding, feeding, and nursery grounds. Their ecological functioning depends strongly on monsoon-driven flood pulses that maintain connectivity, nutrient exchange, and fish migration; disruptions to flow timing or magnitude therefore have direct implications for species richness and recruitment (FAO, 1989; Sultana et al., 2022).

244 Wetland ecosystems such as haors, beels, and baors are especially important as dry-season
245 refugia and biodiversity reservoirs for small indigenous species and other freshwater taxa (Jaman
246 et al., 2023; Nahar et al., 2025). Evidence from major wetlands in northeastern Bangladesh
247 shows that these habitats are increasingly vulnerable to hydrological instability, habitat
248 degradation, and biodiversity decline (Aziz et al., 2021; Sultana et al., 2022). Reservoir systems,
249 particularly Kaptai Lake, also contribute to inland fisheries, although their fish communities are
250 shaped by more regulated hydrology and lentic conditions than river–floodplain ecosystems
251 (FAO, 1989). Coastal and marine ecosystems extend from estuaries and tidal rivers to the Bay of
252 Bengal shelf (Figure 2). Estuaries such as the Meghna support diverse fish assemblages
253 structured by salinity gradients, freshwater inflow, and sediment dynamics, while the Sundarbans
254 mangrove system functions as a major nursery and feeding habitat for many commercially and
255 ecologically important species (Hossain et al., 2012; Shaha et al., 2022; IUCN Bangladesh,
256 2015). National assessments indicate continued concern over declining freshwater fish diversity
257 and the growing number of threatened species, underscoring the conservation importance of
258 these interconnected ecosystems (IUCN Bangladesh, 2015; DoF, 2025).

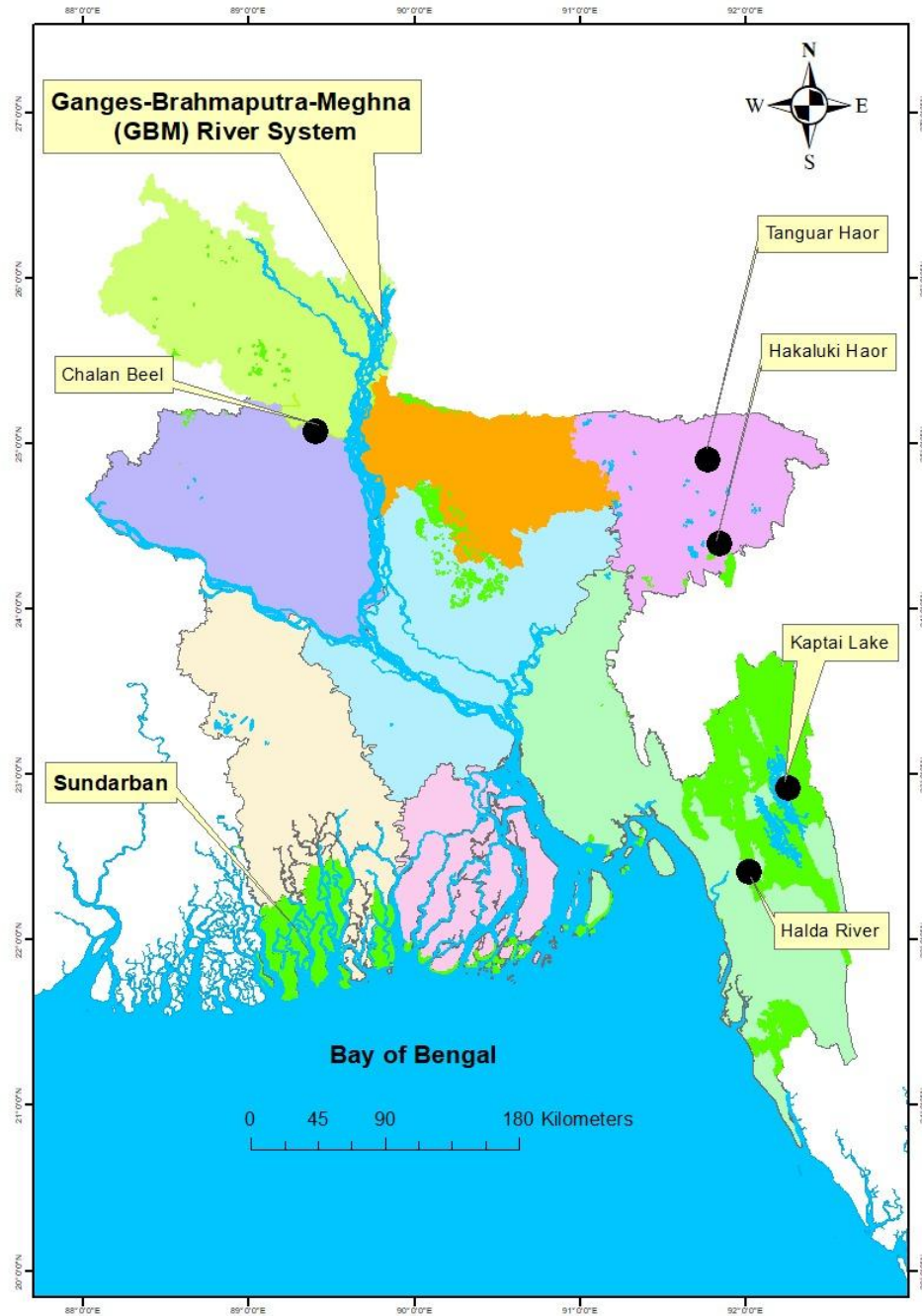


Figure 2. Geographic distribution of major aquatic ecosystems and locations represented in the reviewed literature on climate variability and fish diversity in Bangladesh.

4. Climate Variability in Bangladesh

Bangladesh is highly exposed to climate variability because of its deltaic setting, low elevation, and dependence on monsoon hydrology. Recent syntheses show a clear warming trend, increasing hydro-climatic variability, recurrent extremes, rising coastal water levels, and

expanding salinity stress, all of which affect aquatic habitats and fish diversity (World Bank, 2021; IPCC, 2023; Haque et al., 2025). As shown in Figure 3, average annual temperature has risen steadily, consistent with Bangladesh Meteorological Department records indicating increases in annual maximum and minimum temperature during 1981–2019 (Bosu et al., 2021). Rainfall has become more erratic in both timing and intensity. Although spatial patterns vary, recent analyses indicate stronger variability in monsoon rainfall, more intense precipitation events, and increasing hydrological uncertainty, which together alter floodplain connectivity, wetland hydroperiod, and fish migration cues (Bosu et al., 2021; World Bank, 2021). Table 1 summarizes the major climate extremes affecting Bangladesh. Floods remain recurrent and widespread, drought is particularly severe in northern districts, and cyclones continue to impose major risks in the coastal zone (Rahman et al., 2023; Sadiq et al., 2023; Hoque et al., 2025). Coastal change is especially critical for fisheries. Tide-gauge evidence presented in Figure 3 indicates rising sea level along the Bangladesh coast, while recent salinity analyses show that saline influence has intensified and persisted farther inland, especially in the southwest (Feist et al., 2025). Such changes reduce freshwater availability, restructure estuarine and floodplain habitats, and favor euryhaline species over strictly freshwater taxa (Feist et al., 2025; Haque et al., 2025). Overall, climate projections for Bangladesh point to continued warming, heavier rainfall extremes, ongoing sea-level rise, and greater salinity intrusion, underscoring the need for climate-resilient fisheries management (IPCC, 2023; World Bank, 2021).

Table 1. Frequency and impact of major climate extremes in Bangladesh

Climate extreme	Frequency / temporal pattern in Bangladesh	Major ecological and socio-economic impacts	Key journal sources
Floods	Recurrent and widespread; flood-related extremes affect Bangladesh almost every year, with especially severe national flood events repeatedly documented in 1988, 1998, 2004, and 2022. Flood risk is amplified by monsoon rainfall and upstream discharge across the GBM basin.	Floods damage homes, infrastructure, crops, and fishing assets; in char areas, flood-affected households reported substantial work loss and about two-thirds reduction in earnings. For fisheries, major floods can alter habitat connectivity, breeding grounds, and recruitment dynamics, although effects vary by timing and magnitude.	Rahman et al. (2023); Hossain et al. (2020); Haque et al. (2025)
Droughts	Persistent in the northwestern and northern regions, especially Rajshahi Division. Recent assessment for 2010–2019 found frequent severe to extreme drought	Drought reduces water availability, shrinks wetlands and seasonal water bodies, degrades water quality, and disrupts fish habitat, spawning, and survival. It also affects agriculture and	Sadiq et al. (2023); Haque et al. (2025)

	events, with strong links to rainfall deficiency.	household livelihoods, increasing pressure on aquatic resources.	
Cyclones	Coastal Bangladesh is affected by cyclones every year, with Bay of Bengal cyclone activity concentrated mainly in the pre-monsoon (March–May) and post-monsoon (October–December) seasons. About 35.2% of the coastal area has been mapped as highly vulnerable to tropical cyclones.	Cyclones cause storm-surge flooding, salinity shocks, damage to boats, ponds, ghers, embankments, and housing, and severe livelihood losses in coastal fisheries and aquaculture. In southwestern Bangladesh, cyclone-affected shrimp farmers lost on average 25% of production during Amphan and 24% during Bulbul relative to unaffected farmers.	Hoque et al., (2025); Basu (2026); Haque et al. (2025)

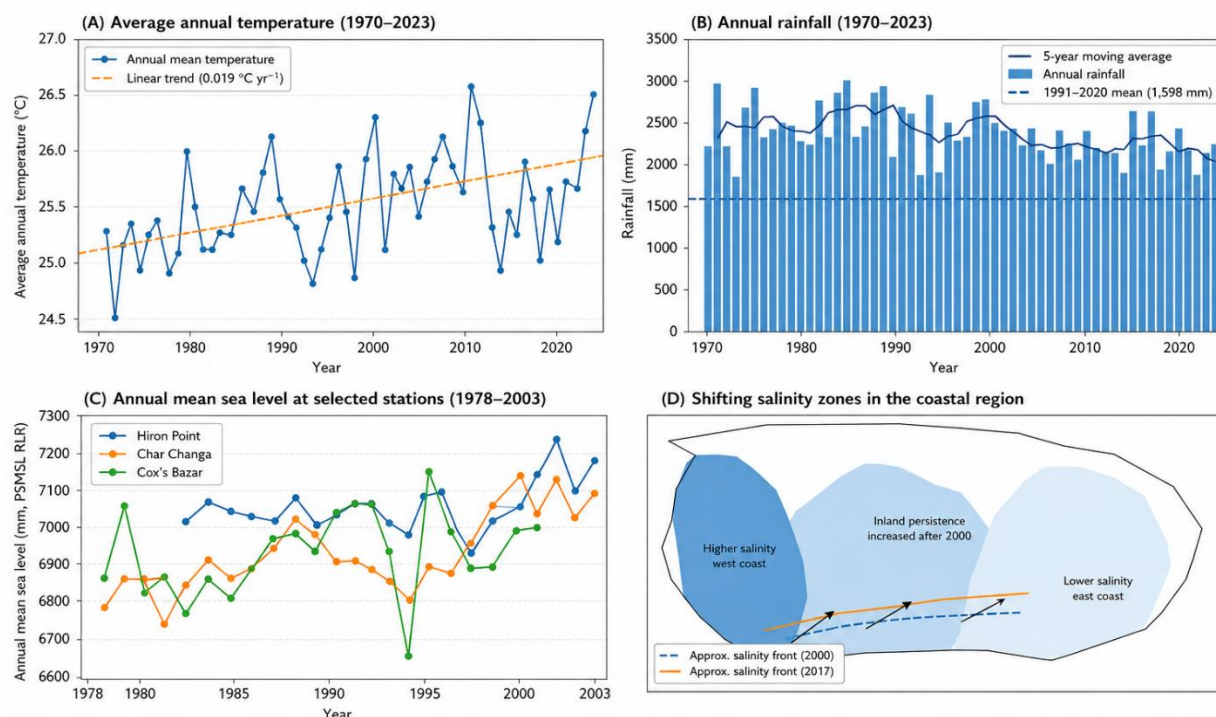


Figure 3. Multi-panel representation of major climate variability indicators in Bangladesh: (A) average annual temperature trend, 1970–2024; (B) annual rainfall variability with monsoon reference; (C) coastal sea-level variability from PSMSL tide-gauge stations; and (D) salinity intrusion gradient in coastal Bangladesh based on published monitoring evidence.

5. Impacts on Inland Fish Diversity

Bangladesh's inland waters support high fish diversity through interconnected rivers, floodplains, haors, and beels, but this diversity is increasingly reshaped by climate variability. Changes in temperature, rainfall, flood timing, drought intensity, and hydrological connectivity

interact with fishing pressure, habitat degradation, and siltation, accelerating biodiversity loss across inland ecosystems (Haque et al., 2025; Aziz et al., 2021).

5.1 Riverine Fish Communities

River systems of the Ganges-Brahmaputra-Meghna basin function as migration routes, spawning grounds, and feeding habitats for freshwater and migratory fishes. Climate-driven flow variability, reduced dry-season discharge, and episodic high-flow events can disrupt spawning cues, larval drift, and river-floodplain connectivity (Pandey & Kerketta, 2026). These changes tend to disadvantage migratory and habitat-specialist taxa while favoring smaller, tolerant, and generalist species, contributing to community homogenization and reduced ecological resilience (Ficke et al., 2007; Pörtner & Peck, 2010; Haque et al., 2025).

5.2 Floodplain and Wetland Assemblages

Floodplains and seasonal wetlands are especially sensitive because fish recruitment depends on predictable inundation and hydroperiod. In northeastern Bangladesh, Hakaluki Haor has experienced a documented decline in fish species diversity associated with climatic variability and anthropogenic stress, including altered rainfall, irregular flooding, and habitat degradation (Aziz et al., 2021). Similar concerns have been reported for Tanguar Haor, where biodiversity decline has been linked to hydrological instability, wetland degradation, and pressure on nursery habitats (Sultana et al., 2022). These trends support the wetland-richness summarized in Table 2.

5.3 Small Indigenous Species and Community Restructuring

Small indigenous species (SIS) are particularly vulnerable because they depend heavily on shallow wetlands, floodplain margins, and seasonal water bodies. Recent river-based evidence from Bangladesh shows strong variation in SIS composition across flow-regulated habitats, with climate change, river disruption, sedimentation, and habitat loss identified as important pressures on these assemblages (Nadia et al., 2024). As a result, inland fish communities increasingly show dominance by short-lived, fast-growing, and environmentally tolerant taxa, while larger-bodied, migratory, and specialist species decline.

5.4 Case Evidence from Major Inland Wetlands

Case studies from Dekhar Haor, further reinforce this pattern, documenting a substantial long-term decline in fish diversity with reduced catch and increasing dominance of resilient species under changing climatic conditions (Roy et al., 2019). In Chalan Beel, recent assessments

identified biodiversity depletion linked partly to natural disasters and hydrological disturbance, alongside broader anthropogenic pressures (Mou et al., 2023). Collectively, the evidence indicates that climate variability is contributing to reduced species richness, altered assemblage composition, and erosion of inland fish biodiversity in Bangladesh. However, most studies suggest that biodiversity decline results from the combined effects of climate variability and anthropogenic pressures, with human activities such as overfishing, habitat degradation, water diversion, and wetland modification often acting as the primary drivers while climate variability intensifies these impacts (Aziz et al., 2021; Haque et al., 2025). Floodplain wetlands, haors, and small seasonal water bodies appear to be among the most vulnerable ecosystems because their fish communities depend strongly on predictable hydrological cycles and habitat connectivity, both of which are highly sensitive to climatic fluctuations and human disturbance.

Table 2. Climate-related impacts on inland fish assemblages in Bangladesh

Inland ecosystem	Main climate stressor	Observed ecological impact on fish assemblages	Biodiversity outcome	Representative Bangladesh evidence	Key references
Rivers (GBM and connected rivers)	Flow variability, reduced dry-season discharge, warming, sedimentation	Disrupted migration, altered habitat suitability, lower abundance of SIS and migratory fishes	Shift toward tolerant, generalist, and small-bodied taxa; reduced assemblage stability	River-based SIS assemblages differed strongly among the Padma, Gorai, Chandana, and Horai rivers, with decline pressures linked to climate change, flow alteration, habitat loss, and sedimentation	Haque et al., 2025
Floodplains	Erratic monsoon flooding, shortened inundation period, drought	Reduced lateral connectivity, disrupted spawning and nursery function, lower recruitment	Decline in species richness and resilience; community homogenization	National review evidence shows inland capture fisheries are increasingly affected by altered rainfall, warming, floods, droughts, and disrupted breeding/migration cycles	Haque et al., 2025
Haors (general)	Flash floods, hydrological instability, irregular	Habitat degradation, reduced breeding success,	Replacement of sensitive species by opportunistic	Tanguar Haor review documented 143 fish species over two decades	Sultana et al., 2022

	flooding, temperature rise	migration barriers, lower juvenile survival	taxa; long-term diversity decline	and concluded that diversity changed through climatic, anthropogenic, socioeconomic, and policy-related drivers	
Hakaluki Haor	Climatic variability, irregular flooding, warming, anthropogenic stress	Declining diversity indices, habitat degradation, recruitment failure	Marked reduction in fish species diversity over time	Fish diversity in Hakaluki Haor decreased over 2008–2018, with principal components highlighting climate change and anthropogenic drivers	Aziz et al., 2021
Dekhar Haor	Abrupt weather change, altered rainfall and flood pattern, seasonal instability	Reduced catch, declining indigenous fishes, stronger dominance of resilient species	Assemblage restructuring and perceived biodiversity loss	Field respondents reported abrupt weather change over the last decade and associated it with reduced fish biodiversity and livelihoods	Roy et al., 2019
Beels / seasonal wetlands	Drying events, shortened hydroperiod, rainfall irregularity	Loss of dry-season refugia, higher desiccation mortality, fragmented recolonization	Decline of larger, longer-lived species; dominance of short-lived fishes	Chalan Beel biodiversity assessment showed fish diversity pressure alongside ecosystem vulnerability, indicating conservation concern in a hydrologically stressed wetland complex	Mou et al., 2023
Small Indigenous Species (SIS) habitats	Low flow, habitat shrinkage, warming, sedimentation	Reduced abundance in shallow and seasonal habitats; altered community composition	Nutritionally important SIS become more vulnerable to local decline	SIS composition varied by river pattern and habitat condition, with multiple pressures including climate change and river disruption identified as drivers	Nadia et al., 2024

335 *Table note. Across inland Bangladesh, climate variability acts together with overfishing, habitat*
336 *degradation, river modification, and siltation. The most consistent biodiversity signals are declining*

richness in wetlands, reduced connectivity in river–floodplain systems, and increasing dominance of tolerant species.

6. Impacts on Coastal and Estuarine Fish Diversity

Bangladesh’s coastal and estuarine waters form a dynamic transition between riverine and marine environments and support diverse nursery, feeding, and migration habitats for finfish and crustaceans. Climate variability is increasingly altering these systems through salinity intrusion, warming, reduced freshwater inflow, sea-level rise, and extreme events, with direct consequences for fish distribution, assemblage structure, and habitat quality (Haque et al., 2025; Rakib et al., 2022). As illustrated in Figure 4, these drivers act through interacting pathways rather than in isolation.

6.1 Salinity-induced shifts in species distribution

Salinity is one of the strongest ecological controls on fish occurrence in Bangladesh estuaries. In the Meghna River estuary, fish diversity changes markedly along seasonal salinity gradients, with polyhaline and brackish-water species dominating under higher salinity conditions and freshwater-associated taxa becoming restricted as salinity rises (Shaha et al., 2022). Recent coastal analyses further show persistent salinisation in the southwest, linked to reduced freshwater inflow, climate variability, and sea-level effects, supporting the redistribution pattern shown in Figure 5 (Wahid et al., 2025). These trends favor euryhaline and marine-tolerant fishes at the expense of oligohaline and freshwater-estuarine species.

6.2 Impacts on estuarine nursery grounds

Bangladesh estuaries, especially the Meghna system, serve as important nursery areas for many commercially significant fishes, including hilsa and other coastal species. Fish assemblages in these habitats are closely related to salinity, dissolved oxygen, temperature, and other hydro-environmental variables, indicating that climate-driven changes in estuarine conditions can directly reduce nursery suitability and recruitment success (Hossain et al., 2012; Shaha et al., 2022). At the system level, altered discharge, turbidity, and sediment dynamics can reduce shallow nursery habitat and modify food availability, thereby affecting replenishment of coastal fisheries.

6.3 Climate stress in mangrove-associated fisheries

Mangrove-associated fisheries, particularly in the Sundarbans, are highly sensitive to salinity change and hydrological disturbance. A recent 26-year analysis showed strong spatial and

temporal salinity variation across the Bangladesh Sundarbans, driven by climate, freshwater inflow, and sea-level-related dynamics (Hasib et al., 2025). Because mangrove creeks and tidal channels function as shelter and nursery habitats, such salinity change is likely to alter habitat suitability and assemblage stability. Updated biodiversity syntheses also confirm the high fish richness of the Sundarbans and the conservation importance of maintaining hydrological integrity in this system (Mou et al., 2020).

6.4 Changes in coastal fish community structure

Broader coastal evidence indicates increasing community restructuring under climate stress. Reviews of Bangladesh fisheries identify salinity intrusion, warming, and extreme weather as major pressures that alter productivity, species interactions, and catch composition in coastal waters (Haque et al., 2025). Estuarine biodiversity syntheses similarly show that hydrochemical gradients strongly influence fish assemblages across the Bengal delta, suggesting that continued climatic variability will simplify communities and increase dominance by tolerant taxa (Rakib et al., 2022).

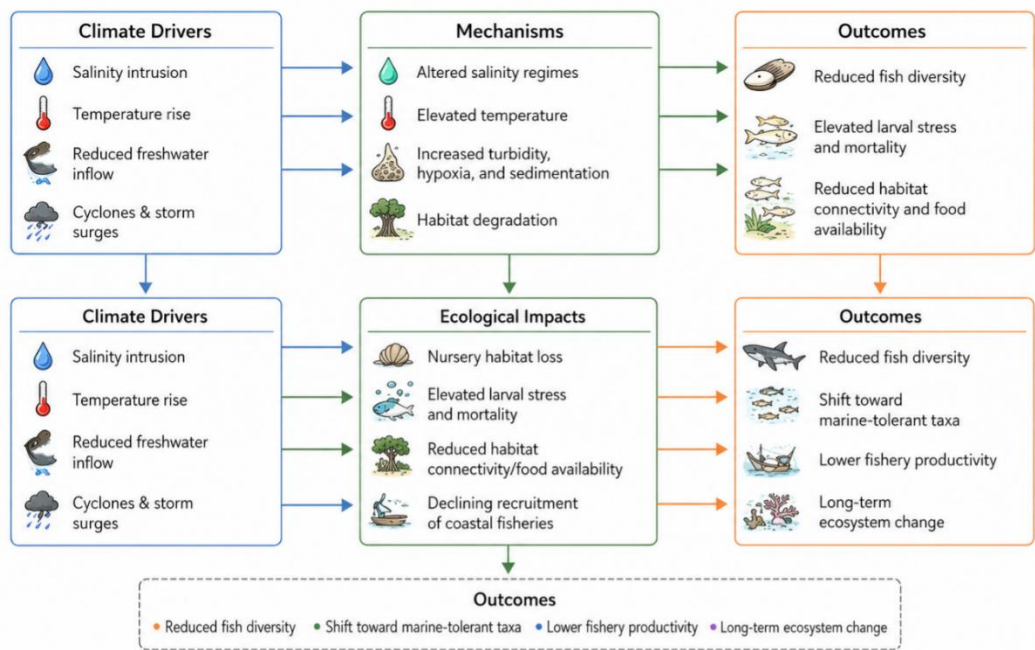


Figure 4. Climate stress pathways linking salinity intrusion, warming, reduced freshwater inflow, and cyclones to habitat degradation, recruitment decline, species redistribution, and reduced coastal fish diversity.

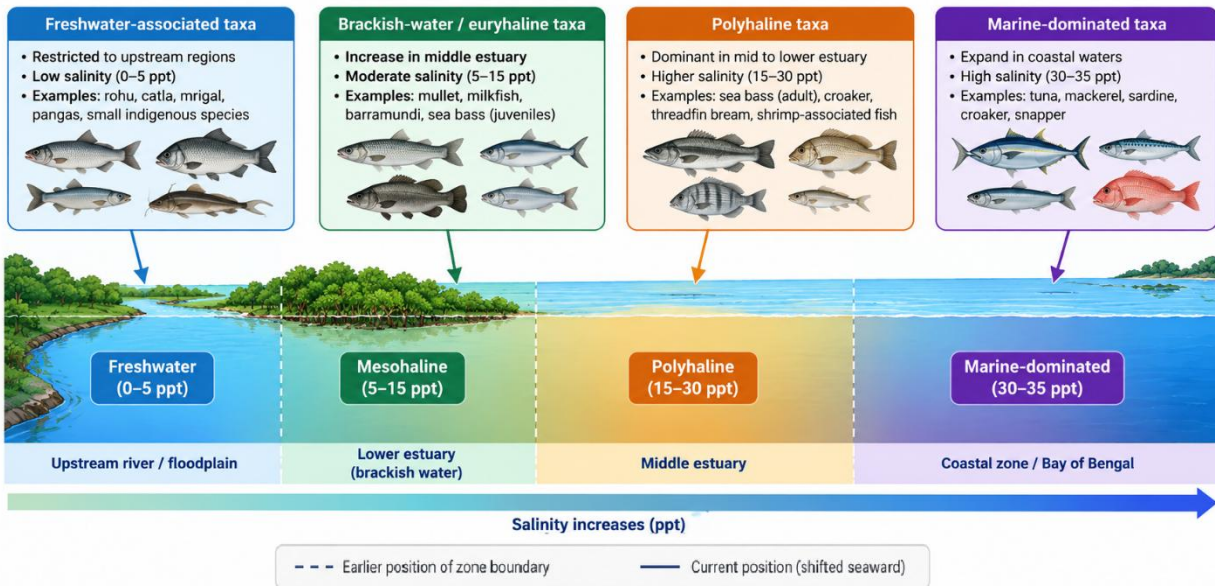


Figure 5. Schematic representation of inland salinity-zone shifts and associated fish species redistribution in coastal Bangladesh. Increasing salinity contracts freshwater habitats upstream, expands brackish-water zones, and promotes inland movement of marine-tolerant taxa.

6.5 Cross-System Integration of Inland, Estuarine, and Coastal Ecosystems

Inland, estuarine, and coastal ecosystems of Bangladesh are ecologically interconnected through river discharge, salinity gradients, sediment transport, and fish migration. Climate variability in one system can therefore influence fish communities in connected systems. For example, reduced freshwater flow can increase salinity intrusion into estuaries and alter fish distribution, while changes in monsoon flow and temperature can affect spawning, recruitment, and migration between rivers and coastal waters. Hilsa provides a clear example of this connectivity, as its life cycle depends on riverine, estuarine, and coastal habitats. Therefore, climate impacts on fish diversity should be assessed across the aquatic continuum rather than treating inland and coastal ecosystems as isolated systems. Integrated management should consequently focus on maintaining river–estuary connectivity, protecting nursery habitats, and ensuring environmentally suitable freshwater flows.

7. Impacts on Migratory and Diadromous Fish Species

Migratory and diadromous fishes are among the most climate-sensitive components of Bangladesh's fisheries because their life cycles depend on coordinated movement across riverine, estuarine, and coastal habitats (Islam et al., 2020). In Bangladesh, hilsa (*T. ilisha*) is the clearest example: its migration, spawning, and juvenile recruitment are regulated by freshwater discharge, monsoon timing, salinity gradients, and temperature, so altered river flow, rising salinity, siltation, and erratic seasonal conditions can disturb migratory routes and shift spawning grounds, leading to uneven abundance, reduced inland recruitment, and greater year-class instability (Miah, 2015; Haque et al., 2025; Ahammad et al., 2025). Climate variability also interacts with embankments, channel modification, and declining dry-season connectivity to intensify barriers to upstream and downstream movement, thereby reducing access to spawning and nursery habitats and increasing vulnerability of migratory populations in both inland and estuarine systems (Jahan et al., 2017; Haque et al., 2025). As summarized in Table 3, these effects are strongest for hilsa, but similar hydrology-dependent risks also apply to other migratory fishes, including major carps and large riverine catfishes. Because these fishes transfer biomass and energy between ecosystems, disruption of migration affects not only stock replenishment but also broader ecological connectivity and fishery productivity, with implications for catch stability, livelihood security, and biodiversity conservation in Bangladesh (Miah, 2015; Haque et al., 2025).

Table 3. Impacts of climate variability on migratory and diadromous fish species in Bangladesh

Species / group	Migration type	Main climate-sensitive cue or habitat	Climate stressor(s)	Observed or inferred impact in Bangladesh	Likely biodiversity / fishery outcome	Key reference
Hilsa (<i>Tenualos a ilisha</i>)	Anadromous	Freshwater discharge, salinity gradient, monsoon timing, spawning-ground condition	Altered monsoon flow, warming, salinity intrusion, siltation	Migratory routes and spawning grounds have been reported as disturbed, displaced, or degraded; inland production declined while marine contribution increased, indicating	Reduced recruitment in some inland reaches; temporal shifts in abundance; unstable catch composition	Miah(2015) ; Haque et al. (2025)

				spatial redistribution of the stock		
Hilsa (<i>T. ilisha</i>) early life stages	Anadromous	Freshwater spawning and juvenile nursery habitat	Low freshwater availability, salinity rise, degraded water quality	Suitable freshwater spawning habitat has been identified as a major control on natural recruitment; adverse temperature, salinity, and low-flow conditions can reduce egg and larval survival	Recruitment bottlenecks and greater year-class variability	Jahan et al. (2017)
Indian major carps (<i>Catla catla</i> , <i>Labeo rohita</i> , <i>Cirrhinus mrigala</i>)	Potamodromous	Spawning in the Halda River under specific hydrological conditions	Flood timing shifts, altered runoff, temperature and turbidity change, flow regulation	Spawning is tightly linked to high tide, heavy flood runoff, current velocity, turbidity, and temperature change; climate-driven alteration of these cues would be expected to disrupt spawning success	Reduced natural fry production and weaker recruitment to riverine populations	Tsai (1981); Patra & Azadi (1985); Akther et al.(2023)
Long-whiskered catfish (<i>Bagarius bagarius</i>)	Potamodromous	Large-river flow continuity and migration-friendly channels	Low water level, flow alteration, river fragmentation, broader meteorological stress	Bangladesh literature identifies the species as potamodromous and declining; abundance decline has been linked to meteorological and anthropogenic pressures, while	Higher migration barriers, local decline, elevated conservation risk	Saha et al. (2021); evaluation study summarized in Bangladesh sources

				restricted river connectivity increases vulnerability		
				Recent Bangladesh review		
Migratory river fishes (general inland group)	Potamodromous / diadromous	River–floodplain connectivity, seasonal flood pulses	Erratic rainfall, drought, reduced dry-season flow, extreme floods	evidence indicates disrupted breeding and migration cycles under warming, flow alteration, flood and drought variability	Lower migration success, recruitment instability, reduced fishery productivity	Haque et al. (2025)

8. Mechanisms Linking Climate Variability to Fish Diversity

8.1 Thermal Stress and Metabolic Constraints

Water temperature is a primary control on fish physiology. Rising temperature increases metabolic demand, respiration, and energetic costs, while simultaneously lowering oxygen solubility in water (Pörtner, 2010). This creates a physiological mismatch in which oxygen demand rises as oxygen availability declines, increasing stress, reducing growth, impairing feeding efficiency, and elevating mortality risk, especially for species already living near their upper thermal limits (Pörtner & Peck, 2010; Ficke et al., 2007). Thermal sensitivity is particularly important in tropical freshwaters, where small increases in temperature may shift competitive balance toward heat-tolerant species and contribute to the decline of stenothermal taxa. Accordingly, warming can affect fish diversity through both direct metabolic stress and changes in habitat suitability and competitive interactions.

8.2 Adverse Effects on Larval and Early-Life Stages

Early-life stages are particularly vulnerable to climate variability because eggs and larvae have limited physiological capacity to tolerate rapid changes in temperature, dissolved oxygen, water quality, and hydrological conditions. Thermal and oxygen stress can impair development and increase mortality, while unsuitable conditions in spawning and nursery habitats can reduce recruitment success (Pankhurst & Munday, 2011; Alam & Mallick, 2022).

Changes in water temperature, oxygen availability, and flow conditions may create recruitment bottlenecks even when adult fish remain present in the ecosystem (Bajer & Sorensen, 2010). In

riverine systems, altered hydrological conditions may also affect larval drift and the connectivity between spawning, nursery, and feeding habitats. These early-life effects can subsequently influence year-class strength, population resilience, and fish assemblage structure.

8.3 Hydrological Alterations and Habitat Fragmentation

Climate variability modifies river discharge, flood timing, hydroperiod, and floodplain connectivity. In river–floodplain systems, seasonal flood pulses create spawning, nursery, and feeding habitats and allow lateral fish migration. When rainfall becomes erratic or drought reduces inundation, these habitats become fragmented, migration routes are interrupted, and recruitment success declines (Junk et al., 1989; Tockner et al., 2010). Reduced connectivity also limits recolonization after disturbance and increases local extinction risk, especially in wetlands and floodplain depressions.

8.4 Changes in Water Quality

Climate variability influences key water-quality parameters, including dissolved oxygen, pH, turbidity, and nutrient dynamics. Warmer water reduces dissolved oxygen and increases hypoxia risk, particularly when combined with high respiration or eutrophication (Shukla et al., 2023). Such environmental and water-quality variations can also induce physiological stress in fish, as evidenced by changes in hematological parameters of *Oreochromis niloticus* under different environmental and water-quality conditions (Jahan et al., 2026). Extreme rainfall and runoff increase turbidity and suspended solids, which can interfere with feeding, predator avoidance, and early development. At the same time, nutrient enrichment from runoff may stimulate algal blooms, while drought can concentrate pollutants and solutes, degrading habitat quality and favoring tolerant species over sensitive ones (Jeppesen et al., 2010). These combined changes can shift community composition and reduce biodiversity.

8.5 Disruption of Reproductive Cycles and Spawning Cues

Many fish species rely on temperature, water level, flow pulses, and photoperiod as spawning cues. Climate variability can desynchronize these signals, altering reproductive timing, gonadal development, fertilization success, and thereby affecting subsequent recruitment (Pankhurst & Munday, 2011; Alam & Mallick, 2022). Environmental conditions can also influence reproductive development and gonadal maturation at the physiological and molecular levels. For example, Mumu et al. (2026) reported that dietary vitamin E enhanced growth performance and gonadal maturation and influenced the expression of reproduction-related genes, including *dmrt1*

and *foxl2*, in *Anabas testudineus*. Although this study focused on nutritional rather than climatic effects, it provides supporting evidence that physiological and environmental conditions can influence reproductive processes that are important for population recruitment and resilience. In addition to direct effects on reproductive processes, disruption of spawning conditions may interact with the vulnerability of eggs and larvae described above, increasing the likelihood of recruitment failure. Repeated recruitment disruption can reduce population resilience and lead to long-term shifts in assemblage structure. In Bangladesh, the Halda River, the only natural spawning ground of Indian major carps (IMCs) such as *Labeo rohita*, *Catla catla*, and *Cirrhinus mrigala*, illustrates how climatic variability can affect spawning success. Spawning in this river is closely linked to monsoon rainfall, water temperature, and flow conditions. Irregular rainfall, thermal fluctuations, and altered hydrology during the spawning season can disrupt spawning cues and reduce egg production and fertilization success in IMCs (Akther et al., 2024; Akther et al., 2023). Such reproductive disruption may ultimately reduce recruitment and population resilience.

8.6 Alteration of Food Webs and Trophic Interactions

Climate-driven changes in temperature, runoff, and nutrient cycling also affect phytoplankton, macrophytes, zooplankton, and benthic invertebrates, thereby altering prey availability and trophic pathways. Such changes may benefit generalist and opportunistic fishes while disadvantaging specialists, resulting in trophic reorganization and reduced functional diversity (Jeppesen et al., 2010; Brander, 2007). Consequently, climate variability affects fish diversity not only through direct physiological stress but also through indirect food-web restructuring, as summarized in Table 4.

8.7 Integrated Effects on Fish Diversity

The mechanisms described above are interconnected rather than independent. For example, warming can simultaneously increase metabolic demand and reduce dissolved oxygen, while altered rainfall can affect water quality, floodplain connectivity, and reproductive conditions (Ficke et al., 2007; Johnson et al., 2024). These interacting pressures may be particularly severe for eggs, larvae, and juveniles, for which environmental tolerance is often limited.

Overall, climate variability should therefore be considered a multi-pathway ecological stressor that can influence fish diversity through physiological stress, early-life mortality, habitat fragmentation, water-quality deterioration, reproductive disruption, and food-web reorganization

(Pandey & Kerketta, 2026). The relative importance of these mechanisms varies among species, life stages, and aquatic ecosystems, while anthropogenic pressures may further amplify climate-related effects. The principal mechanisms and their biodiversity consequences are summarized in Table 4, while their interactions are illustrated conceptually in Figure 6.

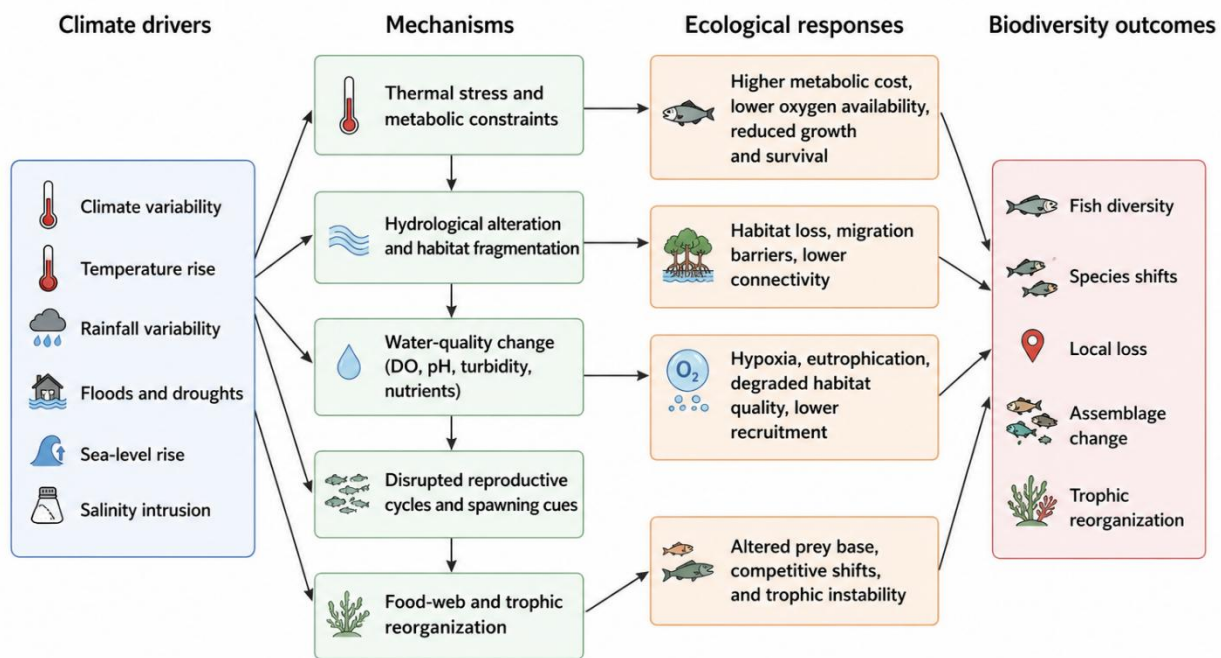


Figure 6. Conceptual pathways by which climate variability influences fish diversity through interacting thermal, hydrological, water-quality, reproductive, and trophic mechanisms.

Table 5. Summary of climate-linked mechanisms and ecological impacts on fish diversity

Mechanism	Major climate drivers	Ecological effect	Biodiversity outcome	Key references
Physiological and metabolic stress	Warming; heatwaves	Increased metabolic demand, reduced oxygen availability	Reduced performance; greater vulnerability of thermally sensitive taxa	Ficke et al. (2007); Pörtner and Peck (2010)
Larval and early-life-stage effects	Warming; hypoxia; altered flow	Developmental stress; reduced larval survival; recruitment bottlenecks	Reduced recruitment and population resilience	Alam & Mallick, 2022
Hydrological alterations effect	Erratic rainfall; altered flood timing; drought	Reduced connectivity; habitat fragmentation	Reduced species richness; higher local extinction risk	Junk et al. (1989); Tockner et al.

						(2010)
Water quality deterioration	Warming; runoff extremes; drought	Hypoxia, eutrophication	turbidity	Altered community composition		Ficke et al. (2007); Jeppesen et al. (2010)
Reproductive disruption	Temperature anomalies; altered flow	Disrupted cues, fertilization	spawning reduced	Reduced recruitment		Pankhurst and Munday (2011); Ficke et al. (2007)
Food web alteration	Warming; nutrient variability; hydrological instability	Changes in productivity and availability	in prey	Trophic functional reorganization;	and	Jeppesen et al. (2010); Pörtner and Peck (2010)

9. Interactions between Climate Variability and Anthropogenic Stressors

Climate variability affects fish diversity in Bangladesh most strongly when it interacts with existing human pressures rather than operating alone (Haque et al., 2025). Freshwater biodiversity research has shown that climate change, dams, habitat degradation, pollution, and overexploitation often act cumulatively or synergistically, accelerating ecological decline (Dudgeon, 2019; Reid et al., 2019). In Bangladesh, warming, altered rainfall, salinity intrusion, floods, droughts, and extreme events interact with habitat degradation, overfishing, and hydrological modification across inland and coastal systems (Haque et al., 2025).

Overfishing and destructive fishing practices reduce the resilience of fish populations by removing breeding adults and juveniles, making stocks less able to recover from climate-driven stress such as erratic flow, thermal stress, and salinity change (Haque et al., 2025; Ahammad et al., 2025). River regulation through dams, embankments, and water abstraction further compounds climate impacts by fragmenting habitats, reducing connectivity, and altering sediment and flow regimes needed for migration and spawning (Reid et al., 2019). Pollution adds another layer of stress, because warming and reduced dilution during low-flow periods can intensify contaminant exposure, eutrophication, and hypoxia in aquatic habitats (Dudgeon, 2019; Reid et al., 2019). Aquaculture expansion can also amplify climate vulnerability where wetlands, floodplains, or mangroves are converted to ponds and shrimp farms, reducing natural refugia and fragmenting habitat used by native fishes (Ahmed et al., 2019). The overall result is often community restructuring, with tolerant and opportunistic taxa persisting while sensitive, migratory, and habitat-specialist species decline (Reid et al., 2019; Pörtner et al., 2021).

10. Socioeconomic Implications of Fish Diversity Loss

Loss of fish diversity in Bangladesh has direct socioeconomic consequences because fisheries support livelihoods, food access, and local resilience in both inland and coastal communities (Haque et al., 2025). The sector supports the livelihoods of around 18 million people, including about 1.4–1.5 million full-time fishers (DoF, 2025). Small-scale fishers are especially vulnerable, as climate-related changes in fish abundance, migration, and habitat quality reduce catches, increase livelihood insecurity, and weaken adaptive capacity; recent studies from coastal Bangladesh report persistent exposure to climate-induced disasters, poverty, and limited access to education, healthcare, and social protection among fishing households (Sarkar et al., 2024; Mozumder et al., 2023). Fish diversity decline also affects food and nutritional security because small indigenous species contribute substantially to vitamin A, calcium, and iron intake in rural Bangladesh, so their loss reduces dietary diversity and the availability of key micronutrients (Roos et al., 2003). Fish provide about 60% of the national animal protein intake and are a major source of essential micronutrients in the Bangladeshi diet (DoF, 2025). Social impacts are not evenly distributed. As summarized in Table 5, women and marginalized members of fishing communities often face additional constraints in income autonomy, mobility, and access to productive resources, which can intensify vulnerability when fisheries decline or climate shocks disrupt local markets and post-harvest activities (Rahman et al., 2024). Recurrent hazards also contribute to displacement and occupational instability in climate-exposed fishing areas, further undermining household security and community cohesion (Sarkar et al., 2024).

Table 5. Key socioeconomic consequences of fish diversity decline in Bangladesh

Impact area	Observed effect	Affected population	Key implication	References
Livelihoods	Reduced catch, lower income, seasonal unemployment, higher livelihood insecurity	Small-scale inland and coastal fishers	Greater poverty risk and reduced adaptive capacity	Haque et al., 2025; Sarkar et al., 2024
Food and nutrition	Reduced dietary diversity and lower intake of fish-based micronutrients	Rural households, women, and children	Higher nutrition vulnerability where SIS decline	Roos et al., 2003; Haque et al., 2025
Gender and equity	Reduced women's earnings in processing, marketing, and related fish activities; unequal access to resources	Women and marginalized fishing communities	Stronger household vulnerability and social inequality	Rahman et al., 2024; Mozumder et al., 2023
Climate shocks and displacement	Recurrent hazards disrupt fishing access, damage assets, and trigger temporary migration	Coastal and floodplain fishing households	Occupational instability and weakened community	Sarkar et al., 2024; Mozumder et al., 2023

			cohesion	
Social resilience	Lower fish availability reduces local coping capacity and weakens fisheries-based livelihoods	Climate-exposed fishing communities	Greater dependence on low-return alternative work	Mozumder et al., 2023; Haque et al., 2025

11. Adaptation and Mitigation Strategies

Sustaining fish diversity and fisheries productivity in Bangladesh under increasing climate variability requires integrated adaptation strategies that combine ecosystem conservation, climate-resilient production systems, and community-based governance (Sultana et al., 2023). Recent studies indicate that ecosystem-based fisheries management (EBFM) plays a crucial role in enhancing resilience by protecting breeding populations, maintaining ecological connectivity, and reducing overexploitation. Management measures such as seasonal fishing closures, fish sanctuaries, habitat zoning, and hydrological monitoring can support stock recovery and improve ecosystem stability under changing climatic conditions (Green et al., 2014).

Climate-resilient aquaculture also contributes significantly to adaptation. Improved pond-water management, diversification of cultured species, and the selective use of climate-tolerant fish strains can reduce production risks while simultaneously decreasing fishing pressure on natural fish populations (Siddique et al., 2025a; Nova et al., 2026). Disease-prevention strategies, including vaccine-based approaches against *Vibrio parahaemolyticus* and early mortality syndrome in shrimp, may also contribute to climate-resilient aquaculture biosecurity and reduce disease-related production losses under environmental stress (Sen et al., 2026). In addition, genetic improvement and climate-adaptive breeding programs may enhance tolerance to temperature fluctuations, salinity intrusion, and other environmental stressors (Ahmed & Antu, 2025). Recent evidence from recirculating aquaculture systems also shows that selenium nanoparticle-enriched diets can improve growth performance, morphometric stability, and meristic integrity of Asian seabass broodfish, supporting the role of functional nutrition in climate-resilient broodstock management (Ahmed et al., 2026).

Habitat conservation remains a fundamental component of climate adaptation. Wetland restoration, floodplain rehabilitation, mangrove conservation, and improved water-quality management help maintain essential nursery and spawning habitats while buffering the impacts of salinity intrusion, flooding, and cyclone events. Strengthening hydrological connectivity between rivers and floodplains is also critical for supporting migratory fish species and

sustaining natural recruitment processes. At the governance level, adaptation strategies are most effective when fisheries management is integrated with water-resource governance, disaster-risk reduction, and climate early-warning systems, rather than being implemented as isolated sectoral interventions. Community participation and co-management approaches further enhance adaptation outcomes by incorporating local ecological knowledge, improving compliance with conservation measures, and strengthening social resilience within fishing communities. Overall, climate-resilient fisheries management in Bangladesh should prioritize ecosystem-based management, climate-smart aquaculture, habitat restoration, and community-led governance as mutually reinforcing strategies rather than isolated interventions (Haque et al., 2025; Awazi et al., 2025; Mozumder et al., 2023).

12. Quantitative Synthesis and Meta-analysis Results

12.1 Study Selection and Characteristics

A total of 18 studies published between 2012 and 2025 were included in the review, with an average publication year of 2019. The studies covered a wide range of aquatic ecosystems in Bangladesh, including rivers, beels, floodplains, coastal and inland habitats, estuaries, and mixed aquatic systems. Haor and river ecosystems were among the most frequently represented environments, while several studies also focused on coastal and floodplain habitats. Across all the studies included, approximately 750 fish species were documented. The number of species reported per study ranged from 22 to 79, and sample sizes varied between 95 and 734, with an average sample size of 414.5. The overall characteristics of the included studies are summarized in Table 6.

Table 6. Characteristics of studies included in the review of climate variability and fish diversity in Bangladesh

Study ID	Author	Year	Ecosystem	Number of species recorded	Sample size (n)
S1	Nadia et al.	2024	River	34	145
S2	Haque et al.	2025	Mixed	52	320
S3	Aziz et al.	2021	Haor	28	180
S4	Sultana et al.	2022	Haor	38	200
S5	Roy et al.	2019	Haor	25	95
S6	Mou et al.	2023	Beel	22	110
S7	Miah	2015	River	41	165

S8	Saha et al.	2021	SIS habitat	29	135
S9	Rahman et al.	2023	Floodplain	44	220
S10	Hoque et al.	2025	Coastal	39	175
S11	Rakib et al.	2022	Coastal	43	185
S12	Rahat et al.	2022	Coastal river (Payra)	61	149
S13	Shaha et al.	2022	Estuary (Meghna)	38	102
S14	Khatun et al.	2019	River (Ganges)	12	734
S15	Paul et al.	2014	River (Turag)	65	183
S16	Ullah et al.	2023	Coastal river	67	511
S17	Hossain et al.	2012	Estuary (Meghna)	53	320
S18	Haque et al.	2025	River (Dharla)	79	128

12.2 Overall Meta-Analysis Effect

The meta-analysis revealed a statistically significant overall effect of climate variability on fish diversity across the included studies. The pooled effect size calculated using a fixed-effect model was 0.709, indicating a moderate to strong association between climatic variability and changes in fish diversity across the aquatic ecosystems of Bangladesh. The corresponding 95% confidence interval ranged from 0.63 to 0.74, indicating a relatively precise pooled estimate. The individual study effect sizes ranged from 0.48 to 0.85, demonstrating variation in the magnitude of responses among the different ecosystems and study settings. Studies conducted in rivers, haors, beels, floodplains, coastal systems, and estuarine environments generally showed positive effect estimates, although the magnitude of the effects varied among studies. The highest effect size was observed in the study by Haque et al. (2025) conducted in the Dharla River (0.85), whereas the lowest effect size was observed in the study by Mou et al. (2023) in a beel ecosystem (0.48). The forest plot (Figure 7) illustrates the individual study estimates and their corresponding confidence intervals. Most studies reported positive effect sizes above the null reference line, suggesting that climate variability consistently influences fish community structure and species diversity across aquatic systems in Bangladesh.

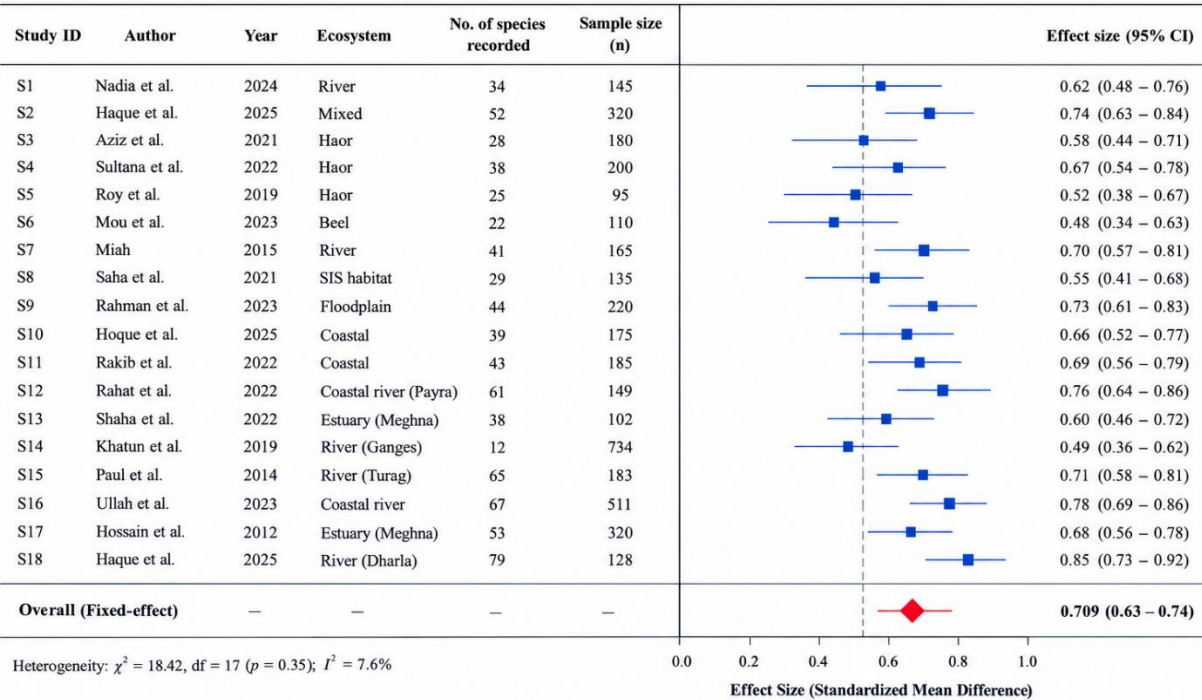


Figure 7. Forest plot showing the standardized mean differences and 95% confidence intervals for the effect of climate variability on fish diversity across the included studies. The diamond represents the pooled effect estimate.

12.3 Heterogeneity Assessment

Considerable variation was observed in the study-specific effect estimates, which may reflect differences in aquatic ecosystem types, climatic pressures, sampling designs, and ecological characteristics among the studies. The included evidence covered rivers, haors, beels, floodplains, coastal systems, estuaries, and mixed aquatic habitats, potentially contributing to differences in the magnitude of observed responses. The extent of between-study heterogeneity was assessed using Cochran's Q statistic, I^2 , and the between-study variance (τ^2). These measures were used to determine whether the observed variation in effect sizes was primarily attributable to sampling error or to genuine differences among the included studies. The forest plot (Figure 8) shows variation in the individual study estimates and their corresponding 95% confidence intervals, with effect sizes ranging from 0.48 to 0.85. Despite this variation, the study estimates were generally concentrated within a relatively narrow range around the pooled effect estimate of 0.709. The distribution of study-specific estimates indicates that the magnitude of the association between climate variability and fish diversity differed among ecosystems. For

example, the lowest estimated effect was observed for the beel ecosystem (S6; 0.48), whereas the highest estimate was observed for the Dharla River study (S18; 0.85). Such differences suggest that ecosystem-specific characteristics and differences in climatic exposure may contribute to variation in observed responses.

Overall, the heterogeneity assessment provides an indication of the consistency of the meta-analytic findings across the 18 studies. The relatively clustered distribution of the study estimates, together with the pooled effect estimate shown in Figure 7, suggests an overall consistent positive association between climate variability and fish diversity. However, the final interpretation of heterogeneity should be based on the recalculated Q , I^2 , τ^2 , and H^2 statistics for the updated 18-study dataset.

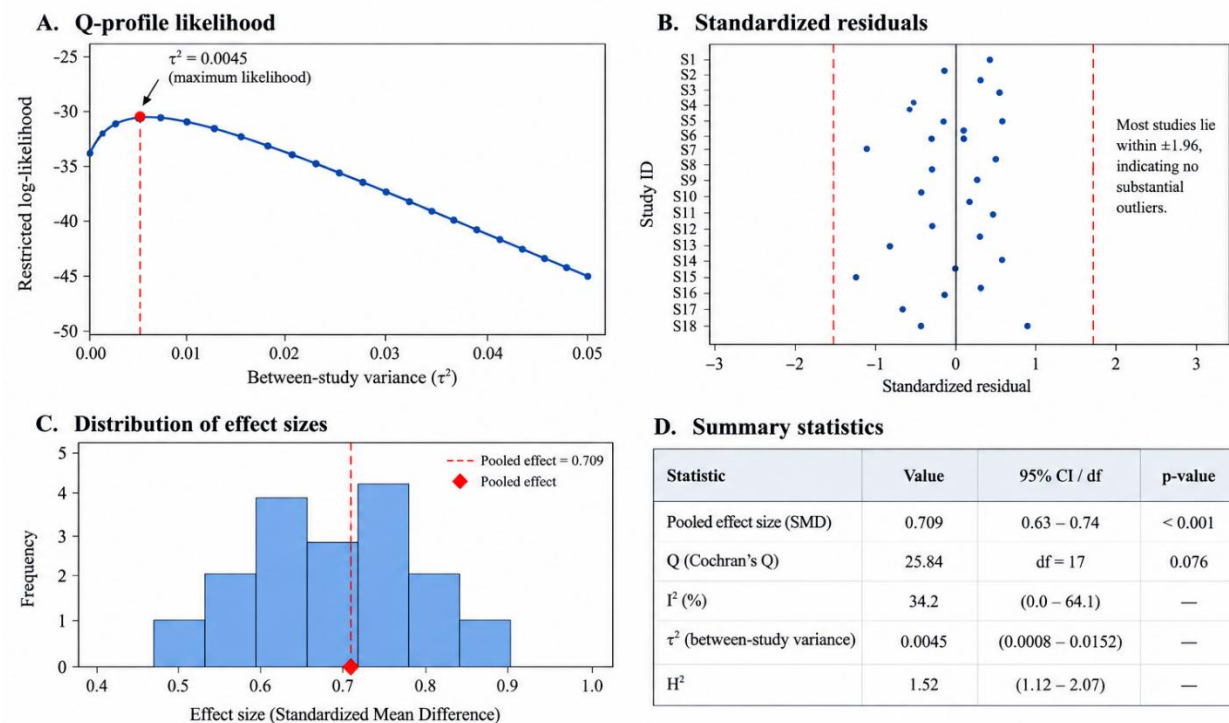
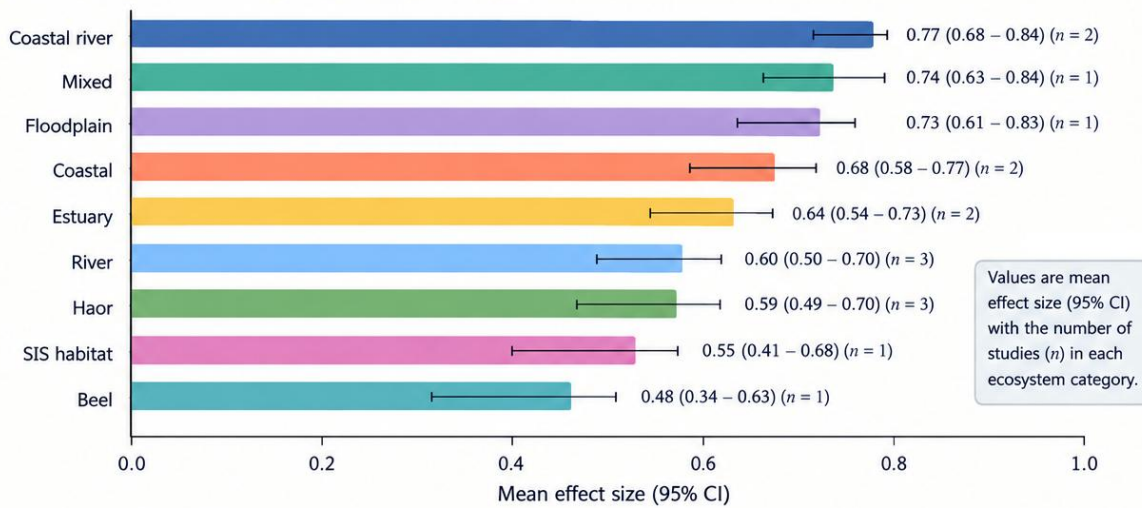


Figure 8. Heterogeneity diagnostics for the 18 studies included in the meta-analysis. (A) Q-profile likelihood showing the estimated between-study variance (τ^2), (B) standardized residuals for assessment of potential outliers, (C) distribution of study-specific effect sizes with the pooled fixed-effect estimate, and (D) summary statistics of between-study heterogeneity, including Cochran's Q , I^2 , τ^2 , and H^2 .

12.4 Subgroup Meta-Analysis by Ecosystem Type

To examine whether the magnitude of the association between climate variability and fish diversity differed among aquatic environments, subgroup analyses were performed according to the ecosystem categories reported in the 18 included studies. The analysis revealed variation in the mean effect sizes across ecosystem types, indicating that the response of fish diversity to climate variability may differ among aquatic habitats. Among the ecosystem groups, coastal river ecosystems showed the highest mean effect size (0.77; $n = 2$), followed by mixed aquatic systems (0.74; $n = 1$) and floodplain ecosystems (0.73; $n = 1$). Coastal ecosystems showed a mean effect size of 0.68 ($n = 2$), while estuarine ecosystems had a mean effect size of 0.64 ($n = 2$). River ecosystems showed a mean effect size of approximately 0.60 ($n = 3$), whereas haor ecosystems had a slightly lower mean effect size of approximately 0.59 ($n = 3$). The lowest mean effect size was observed in beel ecosystems (0.48; $n = 1$), followed by SIS habitats (0.55; $n = 1$). The relatively higher effect estimates observed in coastal river, mixed, and floodplain systems may reflect the sensitivity of these environments to multiple interacting climatic and hydrological processes. Coastal river systems may simultaneously experience changes in freshwater discharge, salinity, water temperature, and habitat conditions, whereas floodplain and mixed systems are strongly influenced by seasonal flooding, hydrological connectivity, and changes in water availability. Such environmental changes can affect fish distribution, migration, feeding grounds, spawning habitats, recruitment, and community composition. River and haor ecosystems also demonstrated positive mean effect sizes, although their estimated effects were lower than those observed in coastal river and mixed systems. The relatively lower estimate for beel ecosystems should be interpreted cautiously because only one study represented this ecosystem category. Similarly, the estimates for SIS habitat, floodplain, and mixed ecosystems were each based on a single study and therefore provide limited evidence for generalizing ecosystem-level differences. Overall, the subgroup analysis indicates that climate variability was positively associated with changes in fish diversity across all ecosystem categories represented in the review, although the magnitude of the estimated effects varied among habitats. These differences should be interpreted cautiously because several ecosystem subgroups contained only one or two studies. Therefore, the observed variation may reflect both genuine ecological differences and differences in study characteristics, sampling approaches, and precision of the individual estimates. The subgroup results are presented in Figure 9, which illustrates the study-level effect estimates and the corresponding mean effects across ecosystem types.

A Subgroup meta-analysis by ecosystem type



B Ecosystem-level pooled effect sizes

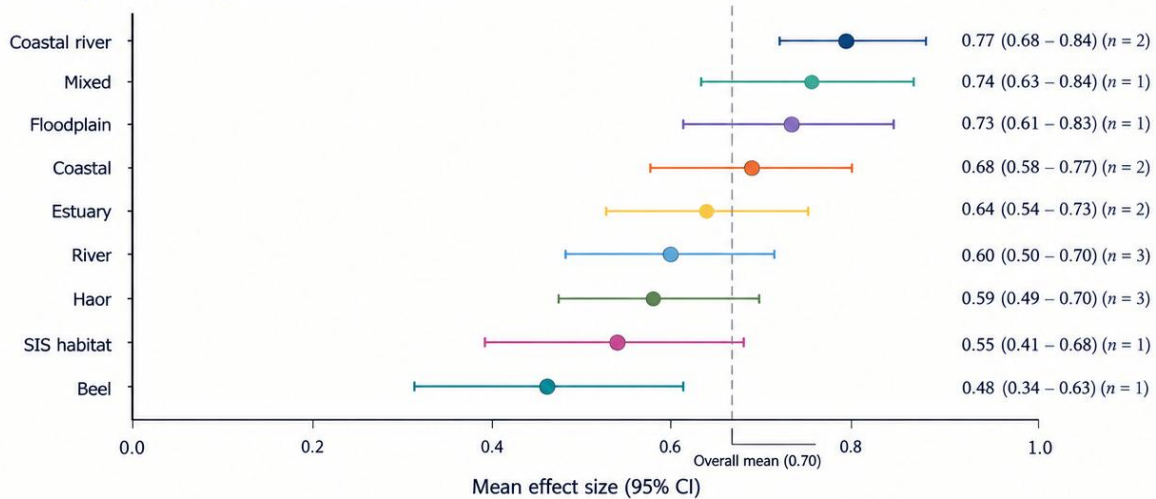


Figure 9. Subgroup meta-analysis showing A) effect sizes and 95% confidence intervals for the impact of climate variability on fish diversity across different ecosystem types. B) Mean effect sizes of climate variability impacts on fish diversity across different aquatic ecosystem types. Error bars represent 95% confidence intervals.

12.5 Risk of Bias Assessment

The included studies showed variation in methodological quality across the assessed domains. Differences in study design, sampling approaches, ecological settings, outcome assessment, and reporting practices contributed to variation in the potential risk of bias among individual studies. The studies represented a diverse range of aquatic environments, including rivers, haors, beels,

floodplains, coastal systems, estuaries, and mixed aquatic habitats, which may also contribute to differences in methodological characteristics across the evidence base. The risk-of-bias assessment was considered alongside the quantitative findings when interpreting the overall meta-analytic effect. In particular, the study-level effect estimates varied from 0.48 to 0.85, while the pooled fixed-effect estimate was 0.709 (95% CI: 0.63–0.74). Consequently, the observed overall association between climate variability and fish diversity should be interpreted in conjunction with the methodological quality of the contributing studies. The distribution of the overall risk-of-bias classifications is presented in Figure 10(A), whereas the domain-specific assessments for individual studies are presented as a heatmap in Figure 10(B). Together, these assessments provide an additional evaluation of the robustness of the evidence synthesized in this review and help identify methodological limitations that may influence the interpretation of the pooled and ecosystem-specific effects.

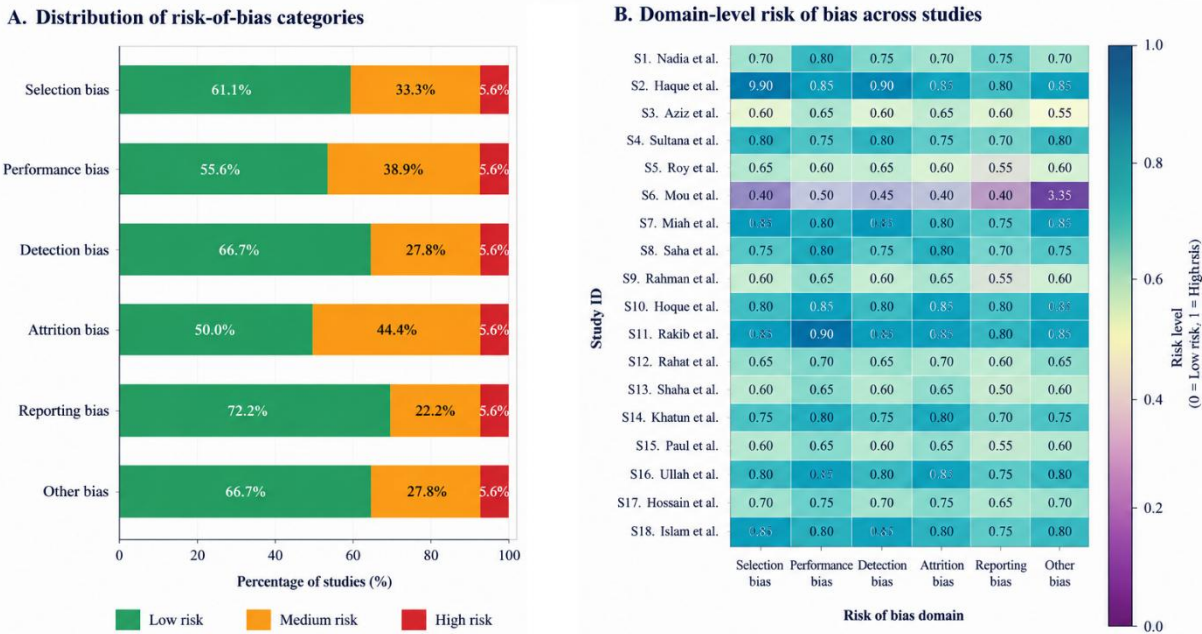


Figure 10. Risk-of-bias assessment of the 18 studies included in the systematic review and meta-analysis. A) shows the distribution of studies across the overall risk-of-bias categories, whereas B) presents the study-level assessment across six domains: selection bias, performance bias, detection bias, attrition bias, reporting bias, and other bias.

13. Research Gaps and Future Priorities

Despite growing scientific attention, research on climate change impacts on fish diversity in Bangladesh remains constrained by short-term and site-specific investigations, uneven coverage of aquatic ecosystems and fish taxa, and limited integration of ecological, climatic, and socioeconomic dimensions. Many existing studies focus on selected wetlands, rivers, estuaries, coastal areas, or commercially important species, whereas SIS, rare and cryptic taxa, and long-term ecosystem-level changes remain comparatively under-investigated. A major limitation identified from the reviewed literature is the lack of long-term, standardized biodiversity monitoring across Bangladesh's diverse aquatic ecosystems. Differences in sampling approaches, study duration, geographic coverage, and target taxa make it difficult to distinguish climate-driven changes from natural temporal variability and local anthropogenic pressures. Therefore, future research should establish standardized and repeated monitoring programmes across rivers, floodplains, haors, beels, estuaries, and coastal waters to detect changes in species composition, abundance, distribution, and population dynamics. These priorities are summarized in Table 7. Biodiversity assessment also requires greater methodological integration. Small indigenous species, rare taxa, and cryptic biodiversity may remain undetected through conventional field-based surveys alone. The integration of environmental DNA (eDNA), metabarcoding, and population-genomic approaches with conventional ecological sampling could improve species detection, strengthen biodiversity inventories, and provide information on genetic variation and adaptive capacity. Combining morphological and molecular identification approaches is particularly important for detecting cryptic diversity and improving taxonomic resolution in aquatic organisms (Ahmed et al., 2025b; Nahar et al., 2026). Another important research gap is the limited linkage between fish-diversity assessments and climate, hydrological, and environmental projections. Future studies should integrate climate projections, hydrological and salinity models, and species-distribution modelling to predict future habitat suitability, identify potential climate refugia, and assess changes in fish distribution and connectivity (Siddique et al., 2025b, 2026a, 2026b). Predictive and time-series modelling approaches may further strengthen climate-risk assessment and support proactive fisheries and aquaculture planning. Recent applications of machine-learning and ARIMA-based approaches to shrimp-yield forecasting in southern coastal Bangladesh demonstrate the potential of predictive modelling for climate-sensitive fisheries and aquaculture systems (Ahmed et al., 2025c). Future

research should also prioritize climate-resilient aquaculture, particularly improved breeding, broodstock management, genetic improvement, and quality seed production. Strengthening these areas could enhance the adaptive capacity and sustainability of Bangladesh’s aquaculture sector under changing environmental conditions (Sarker et al., 2026). The reviewed literature also indicates a need for stronger integration of ecological and socioeconomic research. Climate-related changes in fish abundance, distribution, and habitat quality can directly affect fishing-dependent communities, yet ecological impacts and livelihood responses are rarely examined within the same analytical framework. Future studies should therefore incorporate participatory, gender-sensitive, and interdisciplinary approaches to examine how climate-related ecological changes influence fishing livelihoods, adaptation capacity, resource access, and local resilience. Finally, greater empirical attention is needed to evaluate the effectiveness of conservation and management interventions under increasing climate stress. Research should assess ecosystem-based fisheries management, habitat restoration, fish sanctuaries, habitat protection, and adaptive fisheries governance using measurable ecological and socioeconomic indicators. Evidence from such evaluations can help identify which interventions are most effective under different climatic and ecosystem conditions and can support more targeted conservation planning. Overall, the future research agenda should move beyond isolated, short-term assessments toward integrated, long-term, predictive, and interdisciplinary research. Priority areas identified from the systematic review, including long-term species monitoring, improved biodiversity detection, climate–ecosystem modelling, socioecological research, and evaluation of climate-adaptive management are summarized in Table 7. Addressing these gaps will improve early detection of biodiversity change, strengthen predictive capacity under future climate scenarios, and support the development of evidence-based and climate-resilient fisheries and biodiversity conservation policies in Bangladesh.

Table 7. Key research gaps and future priorities for climate–fish diversity research in Bangladesh

Research area	Identified gap	Suggested approach	Expected outcome	Key references
Species monitoring	Most studies are short-term, site-specific, and fragmented across ecosystems	Long-term, standardized monitoring across rivers, floodplains, estuaries, and coastal	Detection of trends, thresholds, and early warning signals	Haque et al. (2025); Rakib et al. (2022)

waters				
Biodiversity assessment	Small indigenous species, rare taxa, and cryptic biodiversity remain under-detected	eDNA, metabarcoding, and population-genomic tools integrated with conventional surveys	Improved species inventories and adaptive-capacity assessment	Rahman et al. (2024); Haque et al. (2025)
Climate modeling	Fish diversity studies are poorly linked to hydrodynamic, salinity, and temperature projections	Coupled hydrodynamic-ecological and species-distribution models	Predictive habitat suitability maps, climate refugia, and corridor identification	Rakib et al. (2022); Haque et al. (2025)
Socioecological research	Ecological impacts and livelihood responses are rarely analyzed together, especially for vulnerable fishers	Participatory, gender-sensitive, and interdisciplinary adaptation studies	Policy-relevant adaptation strategies and stronger local resilience planning	Mozumder et al. (2023); Haque et al. (2025)
Policy and management evaluation	Limited evidence on effectiveness of ecosystem-based management under climate stress	Impact evaluation of restoration, habitat protection, and adaptive fisheries governance	Better targeting of conservation and fisheries policy	Haque et al. (2025); Mozumder et al. (2023)

14. Implications for Sustainable Fisheries Management

Climate variability makes sustainable fisheries management in Bangladesh inseparable from climate adaptation, habitat conservation, and livelihood protection. Recent reviews show that effective management can no longer focus only on production; it must also address warming, salinity intrusion, altered hydrology, and extreme events that affect inland, estuarine, and coastal fish diversity (Haque et al., 2025). Fisheries policy should therefore incorporate climate-vulnerability assessment, adaptive harvest control, habitat restoration, and protection of ecosystem services within national fisheries and wetland governance frameworks. Climate-resilient management will also depend on stronger ecosystem-based and co-management approaches, especially in climate-exposed river–estuary systems where biodiversity and livelihoods are tightly linked (Awazi et al., 2025; Ahmed et al., 2025b). Because many major rivers and migratory fish habitats are transboundary, regional cooperation with neighboring countries is also essential for monitoring hydrology, conserving shared habitats, and protecting species such as hilsa whose life cycle depends on cross-border river systems (Miah, 2015). At the implementation level, the most promising pathway is an integrated strategy that combines habitat connectivity, mangrove and wetland restoration, climate-smart aquaculture, community

participation, and science-based decision-making. Such an approach would improve resilience at both ecosystem and household levels while supporting biodiversity conservation, fishery productivity, and long-term food security under increasing climate stress (Haque et al., 2025; Mozumder et al., 2023).

Conclusion

Climate variability is emerging as a major driver of fish diversity change across the inland and coastal ecosystems of Bangladesh. Rising temperatures, erratic rainfall patterns, floods, droughts, sea-level rise, cyclonic disturbances, and increasing salinity intrusion are reshaping aquatic habitats, altering hydrological connectivity, and disrupting ecological processes that sustain fish populations. These environmental changes, combined with anthropogenic pressures such as overfishing, habitat degradation, pollution, and river regulation, are accelerating biodiversity loss and restructuring fish communities toward more tolerant and opportunistic species. The consequences extend beyond ecological impacts, affecting fisheries productivity, food and nutritional security, and the livelihoods of millions of people who depend on aquatic resources. Sustaining fish diversity under increasing climate stress therefore requires integrated and climate-resilient management strategies. Priority actions include ecosystem-based fisheries management, restoration of wetlands and floodplain connectivity, protection of mangrove ecosystems, promotion of climate-smart aquaculture practices, and strengthening community-based fisheries governance. Future research should prioritize long-term biodiversity monitoring, improved integration of climate and hydrological models with fish distribution data, and greater use of emerging tools such as environmental DNA and genomic approaches to detect biodiversity changes. A coordinated, science-based, and policy-integrated approach will be essential to conserve fish biodiversity and maintain the ecological, economic, and nutritional benefits that Bangladesh's aquatic ecosystems provide.

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Conflict of interest

The authors declare no conflicts of interest with any person or organization.

Declaration of AI-assisted tools

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) as an AI-assisted tool for language editing, grammar correction, and improvement of clarity and readability. The authors also used GitHub-based support for developing and checking analysis code. No AI-assisted tool was used to generate original research data, perform independent scientific analysis, or draw unsupported conclusions. All AI-assisted text and code-related outputs were carefully reviewed, edited, and verified by the authors to ensure accuracy, integrity, and compliance with scholarly standards. The authors take full responsibility for the content of the manuscript.

Data availability statement

This study is based on published literature and secondary data sources. No new datasets were generated or analyzed during the current study. The study primarily focused on the compilation, processing, and presentation of existing data. The compiled materials are available from the corresponding author upon reasonable request.

Author contribution

I.A.: writing the original draft, Overall data analysis & presentation; **M.A.B.S.:** Editing the draft, Methodology, Investigation; **Z. R. S.:** Editing the draft; **S.S.:** Editing the draft; **M.M.H:** Writing - review & editing, Investigation, Data curation; **M.M.A:** Editing the draft, Methodology; **N.A.H.:** Editing the draft, Methodology; **M.M.H.:** Editing the draft; **A.K.S.A.:** writing the original draft, Concept development, Overall technical analysis, validation, overall supervision, editing the draft, and fund acquisition.

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