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Impacts of Climate Change on Aquatic Environments in Bundelkhand Region

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Abstract

Climate change has emerged as a significant global concern, impacting both terrestrial and aquatic ecosystems. Aquatic systems, in particular, face major challenges due to disruptions in biological community structures and alterations in vital life processes. Bundelkhand, located in the central part of India, is highly vulnerable to climatic extremes, and the ongoing climate change has further intensified these challenges. While the impacts of climate change on marine environments are well-documented, its effects on inland waters, especially in regions like Bundelkhand remain limitedly studied. In inland waters, climate-induced changes in temperature can disrupt the thermal stratification and circulation patterns of aquatic systems, thereby affecting overall ecosystem productivity. One of the critical consequences is the reduction in oxygen solubility with rising water temperatures, leading to hypoxic conditions that impose thermal and physiological stress on fish. Moreover, the increased atmospheric CO_2 dissolves in water, forming carbonic acid and lowering the pH, thereby creating an acidic environment that further stresses aquatic organisms. In response to these challenges, aquaculture systems are increasingly focusing on the use of stress-tolerant and climate-resilient fish species as an adaptive strategy to ensure sustainability in a changing climate.

Keywords: Bundelkhand, Climate change, Thermal stress, Aquaculture, Adaptation

1. Introduction

Climate change is one of the most pressing global challenges of the present era and has severe impact on primary production sectors such as aquaculture and fisheries. These changes are largely attributed to the increased atmospheric concentrations of greenhouse gases (GHGs), particularly carbon dioxide (CO_2), which has risen by approximately 40% since the pre-industrial era (Brander, 2010). Because of this changes, over the past few decades, India has witnessed a drastic change in rainfall patterns and extreme weather events, temperature fluctuation which has affected both terrestrial and aquatic ecosystems (Galappaththi et al., 2022; Ainsworth et al., 2023). These effects are most pronounced in the central India with noticeable droughts and heatwaves likely affecting the ecological sustainability and agricultural produce from aquatic systems. Such conditions are becoming more evidently observed in Bundelkhand region with extreme weather patterns. Bundelkhand is a geographically distinct region in central India which spans parts of southern Uttar Pradesh and northern Madhya Pradesh, covering a total of 14 districts. Temperature trends demonstrate accelerated warming with mean maximum temperatures increasing by 0.28°C from 1980-2005 and annual temperatures rising 0.5-2.0°C per century, significantly exceeding global rates. Extreme heat events have intensified, with Banda recording 52°C in 1995 causing with projections of 2-3.5°C rise at near future. The region experienced dramatic drought pattern transformation from once every 16 years in the 18th-19th centuries to annual occurrence now, representing exponential frequency increase. Datia district faced nine drought years within twelve years (1998-2009), while monsoonal rainfall decreased to half of long-term averages over two decades, creating continuous 4-5year drought conditions. Precipitation patterns show severe disruption with twelve of thirteen districts experiencing declining rainfall trends (1981-2020) at 0.49-2.16 mm per year reduction (Jatav and Singh, 2023). Critical water stress exists with 1,600 mm annual evapotranspiration versus less than 1,000 mm rainfall, creating substantial deficit exacerbated by hard rock terrain, groundwater overexploitation, and declining water tables. Current conditions represent the most severe water scarcity this century. Vulnerability assessments classify Bundelkhand among India's most climate-vulnerable regions, with over 90% of farmers perceiving increased heat and drought frequency. Climate impacts compound socio-economic vulnerabilities through mass migration, agricultural decline, and livelihood insecurity by having limited adaptive capacity from rainfed agriculture dependence and restricted diversification options. It is evident that, Bundelkhand represents a climate hotspot where accelerated temperature rise, exponential drought, altered precipitation patterns, and limited adaptive capacity converge to amplify climate effects beyond typical regional variations (Gupta, 2024).

2. Climate Vulnerable Aquatic Environments

The Bundelkhand region, spanning southern Uttar Pradesh and northern Madhya Pradesh, possesses a complex network of inland water bodies that are vital for irrigation, drinking water, and inland fisheries. Key rivers such as the Betwa, Ken, Dhasan, Paisuni, and Mandakini traverse this semi-arid terrain, supporting both agriculture and rural livelihoods. Major reservoirs like Rajghat, Matatila, and Barwa Sagar, along with numerous traditional ponds and tanks, serve as essential water storage and aquaculture systems (Avtar et al., 2011). However, these freshwater ecosystems are increasingly threatened by climate-induced stressors, including rising temperatures, erratic rainfall, and prolonged droughts, which undermine their ecological balance and water security. Freshwater ecosystems in Bundelkhand, due to their limited thermal and chemical buffering capacity, are particularly vulnerable to climate variability. Unlike glacial-fed systems, rivers such as the Sindh, which originates from the Malwa Plateau in Vidisha, MP, are rain-fed and reliant on monsoon patterns (Prakash et al., 2017). With increasing global temperatures, thermal stratification disrupts mixing processes and biogeochemical cycling, leading to oxygen-depleted zones that stress aquatic organisms. Shifts in precipitation and runoff further destabilize flow regimes and water quality. While marine productivity is projected to decline by 3–9% by 2100, the response of freshwater systems remains uncertain (Cheung et al., 2021).

3. Climate Change Effects on Thermal Circulation

Inland aquatic environments experience a phenomenon called thermal stratification, where water separates into layers based on temperature. Because of temperature based density variation, warmer water stays on top (epilimnion), a middle layer shows rapid temperature change (thermocline), and colder water settles at the bottom (hypolimnion). This is followed by seasonal turnover, a mixing process that occurs when water temperatures and densities become uniform, allowing the entire water column to circulate. This stratification and turnover is crucial for aquatic productivity because seasonal mixing events redistribute nutrients from nutrient-rich bottom waters to the photic zone, while circulate oxygen from the surface to deeper waters, support phytoplankton growth and maintain healthy habitat conditions for diverse aquatic species (Azadi et al., 2021). However, climate change is intensifying this stratification by creating greater temperature differences between surface and bottom waters, resulting in a stronger, more persistent thermocline that acts as a more effective barrier preventing mixing between layers. Stronger temperature differences between surface and deeper water layers (called thermal stratification) can harm freshwater ecosystems. This reduces the natural mixing of water, which normally brings nutrients up and oxygen down. As a result, the surface water becomes low in nutrients, and the bottom layers lose oxygen, creating low-oxygen (hypoxic) zones that are harmful to fish and other aquatic life. These changes disrupt normal seasonal cycles that support phytoplankton growth, fish reproduction, and migration. In the long run, this lowers the productivity of aquatic ecosystems and threatens both biodiversity and the human communities that rely on these water bodies for food and livelihood (Hordoir and Meier, 2012).

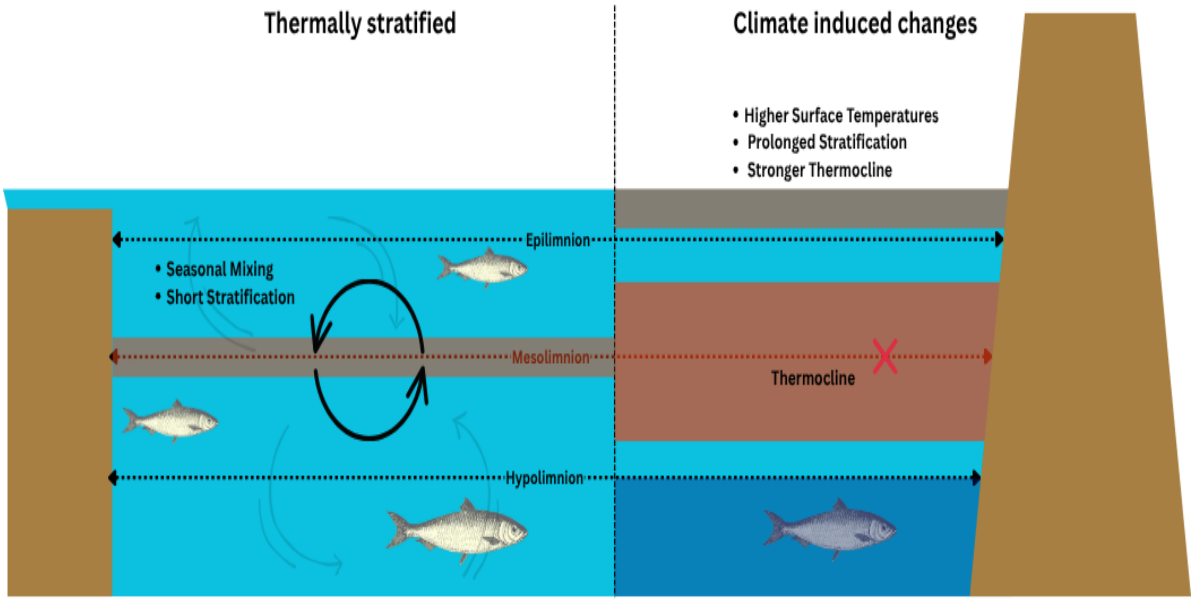

Figure 1. Climate induced impact on thermal regimes of reservoir

4. Thermal Stress to Aquatic Organisms

Thermal stress in aquatic organisms arises when water temperatures exceed their optimal physiological range, leading to significant metabolic and cellular disturbances (Singh et al., 2025). As water warms, fish experience an accelerated metabolic rate, which increases their oxygen demand. However, warmer water holds less dissolved oxygen, creating a mismatch between the oxygen needed and what is available, thereby posing a serious threat to survival. Elevated temperatures can also cause protein denaturation, disrupting vital enzymatic functions such as ATP production, membrane stability, and cellular transport. Additionally, chronic heat exposure triggers the release of stress hormones, which suppress immune responses, inhibit growth, and impair reproductive capacity. Climate change exacerbates these challenges through rising temperatures, which outpace the natural adaptive capacities of many fish species. This is especially critical in shallow freshwater systems, which have limited ability to buffer thermal fluctuations (Islam et al., 2022).

***Table 1. Physiological and ecological impacts of climate change on aquatic organisms**

Impact Category	Key Effects
Temperature stress	Reduced oxygen availability; increased metabolic stress; higher energy demands
Growth & reproduction	Slower growth rates; disrupted breeding cycles and timing; reduced reproductive success

Food & feeding	Changes in food availability and quality; altered feeding behavior; shifts in prey species distribution
Migration patterns	Disrupted migration timing and routes; movement toward cooler waters; blocked access to spawning areas
Disease & parasites	More disease outbreaks in warmer water; weakened immune responses; emergence of new parasites and pathogens
Habitat loss	Shrinking suitable habitats; drying of wetlands and shallow waters; loss of cool-water refuges
Water quality	Lower dissolved oxygen levels; increased concentration of pollutants; decreased pH affecting fish health
Species competition	Spread of invasive warm-water species; decline of native cold-water species; altered predator-prey dynamics

***(**Sarkar et al., 2021; Kumar et al., 2024)

In response to heat stress, fish produce heat shock proteins (HSPs), a group of highly conserved molecular chaperones that assist in protein refolding, prevent aggregation of denatured proteins, and maintain cellular homeostasis under stress. Among them, HSP70, HSP90, HSP60, and small HSPs are particularly significant, and their expression is directly linked to the thermal tolerance of different fish populations (Alfonso et la., 2021). Recognizing the protective role of HSPs, aquaculture and conservation programs have begun incorporating them into management strategies. These include selective breeding for fish with naturally higher HSP expression, thermal preconditioning (exposing fish to mild heat stress during early development), dietary interventions to support HSP function, and experimental gene editing to enhance thermal resilience. Furthermore, gradual temperature acclimation in aquaculture systems, combined with HSP monitoring, is being used to promote adaptive responses without causing harm. However, the complexity of thermal adaptation and potential trade-offs with other physiological functions highlight the need for continued research to develop sustainable, climate-resilient fisheries and aquaculture practices (Kaur et al., 2025).

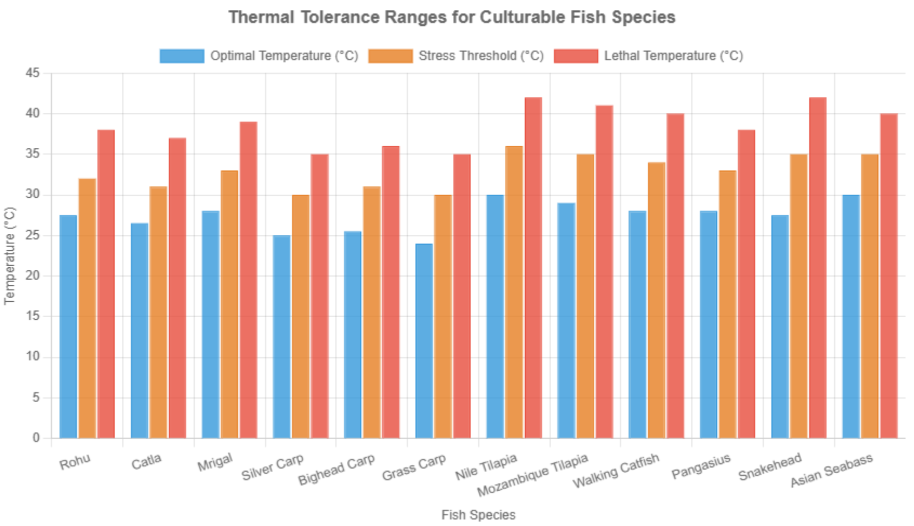

Figure 2. Thermal tolerance range for culturable fish species

5. Impact of Climate Change on Physicochemistry of Inland Waters

Climate change fundamentally alters inland water chemistry through interconnected processes that disrupt aquatic ecosystem functioning. Rising temperatures reduce dissolved oxygen solubility exponentially, with water at 35°C holding 40% less oxygen than at 10°C, while simultaneously increasing biological oxygen demand by 2-3 times per 10°C rise through accelerated metabolic rates. Enhanced thermal stratification prevents oxygen circulation, creating persistent anoxic bottom zones where bacterial decomposition further depletes available oxygen reserves, establishing expanding hypoxic areas that threaten aquatic life survival. Atmospheric CO_2 absorption systematically acidifies inland waters as dissolved CO_2 forms carbonic acid and releases hydrogen ions, lowering pH levels (Bukaveckas et al., 2024). Freshwater systems, lacking strong carbonate buffering capacity unlike marine environments, become particularly vulnerable to acidification. Climate-enhanced organic matter decomposition produces additional CO_2 and organic acids, while altered precipitation introduces acidic rainfall or concentrates existing acids during droughts, creating pH conditions that affect nutrient availability, metal solubility, and species survival when levels drop below 6.5 or exceed 8.5. Microbial activity undergoes dramatic transformation as temperature increases accelerate bacterial metabolism following Q_{10} temperature coefficients, approximately doubling activity per 10°C rise. This enhances decomposition rates and nutrient cycling while shifting community composition toward heat-tolerant species, potentially altering ecosystem functions (Yang et al., 2024). Stratification creates distinct microbial zones promoting anaerobic bacteria in oxygen-depleted bottom waters that produce methane and hydrogen sulfide, while increased temperatures may enhance pathogenic microorganism survival and virulence, threatening aquatic and human health (Dehghani et al., 2024).

Temperature elevation significantly impacts dissolved salts and ionic concentrations through increased evaporation that concentrates total dissolved solids, elevating electrical conductivity and mineral content. Enhanced solubility of most salts increases calcium, magnesium, sodium, potassium, sulfate, and chloride concentrations, though calcium carbonate shows inverse solubility, precipitating at higher temperatures and altering alkalinity. Altered precipitation patterns create dramatic concentration-dilution cycles that destabilize ionic equilibria and chemical profiles (Meng et al., 2024). These changes trigger comprehensive chemical system alterations including disrupted redox conditions that create distinct oxidizing surface and reducing bottom zones, affecting metal speciation and nutrient cycling pathways. Nitrogen chemistry shifts as warmer temperatures favor denitrification while increasing ammonia toxicity, phosphorus dynamics change through altered sediment interactions and internal loading, and carbon cycling accelerates affecting dissolved organic carbon and greenhouse gas production. Trace metal chemistry becomes more complex as changing pH, oxygen, and organic matter alter metal binding and bioavailability. These interconnected modifications create novel chemical environments that may exceed native species adaptation capacity while favoring invasive species, fundamentally restructuring inland aquatic ecosystem chemistry and threatening long-term sustainability (Neokye et al., 2024; Chen et al., 2025).

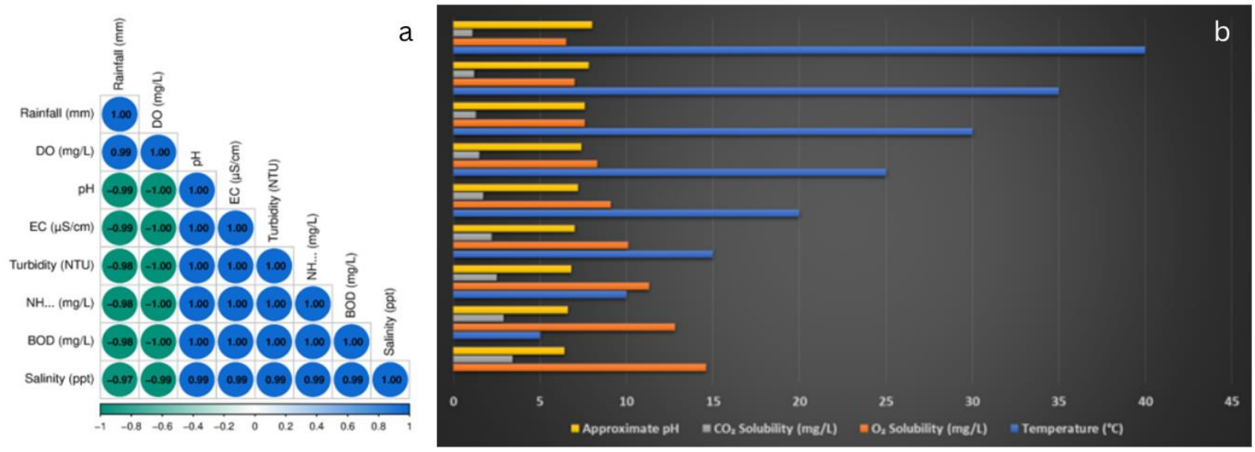

Figure 3. (a) Correlation of climate induced effect on the physicochemical parameters in aquatic system, (b) Solubility and pH variation in response to temperature rise.

6. Conclusion

The Bundelkhand region represents a critical climate hotspot where accelerated warming, exponential drought frequency, and altered precipitation patterns create severe threats to inland aquatic ecosystems. Rising temperatures intensify the compounding stressors that fundamentally restructure water chemistry. Thermal stress on aquatic organisms, particularly fish, manifests through metabolic disruption, reproductive failure, and habitat loss, requiring innovative adaptation strategies including heat shock protein research and thermal tolerance enhancement. The convergence of climate impacts with limited adaptive capacity makes Bundelkhand's aquatic environments particularly vulnerable, threatening both ecological sustainability and human livelihoods dependent on these freshwater resources.

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