

Changing rainfall patterns and their impact on freshwater ecosystems

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Introduction

Climate change and its impacts on environment have turned out to be a frontline issue for the past few decades. The greenhouse gas concentrations continue to increase due to anthropogenic activities, and have reached to 410 ppm for carbon dioxide (CO₂), 1866 ppb for methane (CH₄), and 332 ppb for nitrous oxide (N₂O) in 2019, as stated in the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, AR6, 2021). This in turn has contributed towards the warming of the atmosphere, ocean and land. Since the 1980s, each decade has been warmer than the previous one, bringing widespread and rapid changes in the atmosphere, cryosphere and biosphere. The decade, 2011-2020, was the warmest on record. Global surface temperature was 1.1°C higher in the last decade than between 1850-1900. The evidence of a warming world is well documented by the changes in rates and patterns of precipitation, increased intensity of extreme weather events like floods and droughts, sea level rise, continental ice melt, ocean acidification, increased frequency of powerful cyclones, etc. It is also inevitable that the global temperature will increase beyond 1.5°C by the middle of this century (2041-2060), relative to the baseline period of 1850-1900 (IPCC, 2021).

Water is one of the most recognized media through which human beings and ecosystems are likely to feel the impacts of climate change (World Meteorological Society, 2021). The ocean soaks up most of the heat from global warming. The rate at which the ocean is warming is strongly increased over the past two decades, across all depths of the ocean. Sea surface temperature (SST) of the tropical Indian Ocean has risen by 1°C on average during 1951-2015, markedly higher than the global average SST warming of 0.7°C, over the same period (IPCC, AR6, 2021). Likewise, freshwater ecosystems are largely affected by increasing water temperature as their water quality, in terms of dissolved oxygen levels, changes under the influence of warmer water. This in turn destabilizes the freshwater biodiversity and disrupts the overall ecological functioning (Capon *et al.*, 2021). Besides, global warming also modifies the hydrological regimes like precipitation, soil moisture, run-off, river discharge, aquifer recharge, etc. Changing rainfall patterns influence water temperatures, as reduced flows during

droughts lead to warmer waters, impacting the cold-water species like brown trout (Kernan *et al.*, 2010).

Freshwater ecosystems, though cover only a small portion of the earth's surface, play a crucial role in sustaining the biodiversity, regulating hydrological cycles and supporting livelihood of nearby populations. These ecosystems, which include rivers, lakes, wetlands, streams and aquifers, provide habitat to nearly one-third of all the vertebrates, including 40% of fish species (UNEP, 2022). Rainfall regimes are central to the structure and functioning of freshwater ecosystems, controlling inflows, recharge rates, sediment dynamics, and nutrient availability (Allan & Castillo, 2020). However, climate change has altered global and regional rainfall patterns, with projections indicating intensified hydrological extremes in many regions (Zhang *et al.*, 2025). Such alterations pose severe risks to aquatic biodiversity, ecosystem services, and water security (Vörösmarty *et al.*, 2023). This review examines the impacts of changing rainfall patterns on freshwater ecosystems, focusing on issues such as, dependence of freshwater systems on rainfall inputs; ecosystem responses to hydrological alterations; effects on water quality and broader ecological and management implications.

Impact of hydrological alterations on freshwater ecosystems

Freshwater ecosystems depend directly on rainfall for maintaining hydrological balance, flow regimes, and connectivity with terrestrial landscapes. Disruptions in rainfall intensity or timing may lead to ecological thresholds being crossed, resulting in biodiversity loss and altered ecosystem functions (Zhang *et al.*, 2025). The intensification of extreme rainfall, aggravated by climate change, has increased flooding and soil erosion, while prolonged pre-monsoon droughts have reduced river flows, creating significant hydrological stress in South Asia during monsoon season (Roxy *et al.*, 2017; Mishra *et al.*, 2021). Moderate floods can enhance productivity and connectivity, but extreme floods displace species, cause fish mortality, and degrade water quality (Reid *et al.*, 2022). Flood-driven sediment pulses may also smother benthic habitats and transport pollutants downstream (Mosley, 2022).

In Mediterranean and temperate river systems, shifting rainfall patterns are driving more frequent drying and rewetting cycles, with cascading impacts on stream

invertebrates and microbial functioning (Datry *et al.*, 2018; Peredo-Parada *et al.*, 2022). Besides, declining rainfall reduces base flows, resulting in habitat contraction, reduced dilution capacity, and increased pollutant concentrations (Wang *et al.*, 2024). Such conditions intensify oxygen depletion, disrupt migration, and accelerate eutrophication, particularly in rivers reliant on consistent flow regimes (Allan & Castillo, 2020). At the global scale, many regions have also reported reduced baseflow contributions over the past two decades, largely linked to altered rainfall-runoff partitioning (Gudmundsson *et al.*, 2019; Lehner *et al.*, 2022). Eutrophication, intensified by rainfall extremes, is characterized by excessive algal growth, hypoxia, and fish kills. The risk of harmful algal blooms is increasing globally under altered rainfall regimes (Liu *et al.*, 2021; Xiao *et al.*, 2023). Such events reduce water quality for drinking, fisheries, and recreation.

Impact of rainfall behaviour on breeding and survival of aquatic species

Many aquatic species are migratory, moving from feeding areas to spawning grounds in response to rainfall driven flows. Rainfall also determines connectivity between wetlands, rivers, and floodplains. Without sufficient rainfall, critical migration pathways dry up. Reduced rainfall also leads to low discharge rate of rivers, which makes upstream migration difficult. Excessive rainfall can cause sudden floods, which can wash fish downstream, increase turbidity, or strand them in unsuitable areas. However, a rise in river levels typically increase the availability of food and alters some limnological characteristics (e.g. causes an increase in turbidity), which subsequently supports higher survival for fish eggs and larvae (Lowe McConnel, 1987). Heavy rainfall may lead to increased runoff and excessive sedimentation, which in turn clogs fish gills, reduces visibility for feeding and buries spawning sites. The study from Orissa, conducted during 1981-2010, found that rising temperature and shifting rainfall reduced fish spawn in the Mahanadi from 30-43 ml net⁻¹day⁻¹ to 6 ml. The breeding period in hatcheries advanced by a month, mainly due to higher water temperature and altered rainfall, which accelerated maturation and spawning. (Das *et al.*, 2012).

Impact of rainfall behavior on breeding and survival of amphibians and reptiles

Both amphibians and reptiles are ectothermic and heavily dependent on environmental conditions for reproduction, survival, and population persistence. Climate change has imposed low survival rates of amphibians at the adult stage, mainly due to mild winters during hibernation, and heavy rainfall and drought during breeding activity. The

study by Cayuela *et al.* (2016) showed that severe drought significantly reduced the survival and fecundity of the endangered yellow-bellied toad (*Bombina variegata*) in France. Juvenile and adult survival dropped by 12% and 10%, while fecundity declined by 31% during drought years. Similarly, reptiles respond to climate change through behavioral changes, such as choice of nesting site, depth, and breeding time (Fuentes *et al.*, 2009). Reptiles that have temperature-dependent sex determination (TSD) are especially vulnerable to even minor shifts in incubation conditions. (Carter & Janzen, 2021). On the other hand, deficit moisture regimes can result in decreased hatching success and small hatchling size in reptiles (Dayananda *et al.*, 2021).

Impacts on wetlands and riparian vegetation

Wetlands are critical ecosystem that supports diverse bird species, offering them safe places to nest, feed, and breed. Wetland ecosystems are vital for maintaining global biodiversity, as they provide important stopover sites for many species of migrating wetland associated birds (Londe *et al.*, 2024). However, changes in rainfall patterns due to climate change are significantly impacting these ecosystems by affecting water depth and nesting areas, thereby leading to high mortality rates. Riparian wetlands, the temporarily flooded areas along rivers and streams, are of great ecological importance because they harbour a large number of distinctive plant and animal species (Naiman *et al.*, 1993; Garssen, 2014). Riparian zones are often regarded as vulnerable due to their sensitivity to changes in precipitation and temperature. Research indicates that prolonged droughts, lasting 30 days or more can notably reduce riparian species richness and biomass. Hydric species like *Populus* and *Salix* seedlings show reduced survival, whereas drought-tolerant species like *Tamarix* can expand due to root plasticity and deeper rooting capabilities (Garssen, 2014).

Impacts on Human Dimensions

In countries, where agriculture remains the backbone of rural employment, erratic rainfall patterns, leading to floods or droughts, quickly translates into reduced income for small holder farmers and wage labourers. Communities whose livelihood depends on freshwater ecosystems, like small-scale farmers and fishers, water-linked micro-enterprise communities, etc. particularly experience economic instability as climate change driven rainfall disparity disrupts resource availability. For instance, in Zimbabwe's Zambezi River Basin, fishing households in the Binga and Kariba rural districts exhibited increased vulnerability due to declining fish productivity triggered by fluctuating rainfall patterns and extreme weather events. Under certain cases, lack of alternative livelihood options

even compels migration of the inhabitants (Mekonen, 2022). In Assam and the broader Brahmaputra-Barak basin, livelihoods closely tied to freshwater biodiversity are increasingly becoming unstable as rainfall continues to be more erratic, inviting more extremes.

On the other hand, eutrophication, caused due to excessive concentration of plant nutrient's originating from agricultural and industrial wastes and sewage, have detrimental consequences on the health of exposed animals as well as human populations. According to the World Health Organization (WHO), algal toxins can cause liver damage, gastrointestinal illness, and even neurological effects if consumed through contaminated water. Furthermore, the decay of excessive algae reduces oxygen levels, leading to the release of harmful substances like ammonia, iron, and manganese from sediments, which further complicates purification. Water treatment facilities often require advanced and costly processes, including activated carbon filtration and ozonation, to remove these contaminants (Mishra *et al.*, 2021).

Adaptation and Conservation Strategies

- 1) **Wetland and Forest Restoration:** Wetland restoration helps absorb floods, store water for dry periods, and filter pollutants, while also providing habitat for fish and migratory birds (Ramsar Convention Secretariat, 2018). Reforestation and riparian forest recovery also play key roles by stabilizing soils, reducing erosion, and moderating floods (Filoso *et al.*, 2017).
- 2) **Stronger Watershed Management:** Healthy watersheds are the foundation of climate resilience. Protecting headwaters, reconnecting floodplains, and reducing sediment and nutrient pollution can safeguard both people and nature. Global policy frameworks highlight watershed management as a vital tool for coping with climate-related water risks.
- 3) **Monitoring Rainfall and River Flows with Technology:** Adapting to shifting rainfall requires proper and timely water monitoring. Modern satellite missions like NASA's Global Precipitation Measurement (GPM) mission tracks rainfall worldwide in near-real time, while the GRACE satellites monitor groundwater and total water storage. These tools, together with ground-based hydrological stations, provide the early warning systems needed to respond to floods and droughts (Pfeffer *et al.*, 2023).
- 4) **Policy Actions:** Policy frameworks are essential to connect science and practice. Integrated Water Resources Management (IWRM) is being promoted globally to ensure that water allocation, flood control,

and ecosystem protection are planned together (UN-Water, 2024). At the same time, the Kunming-Montreal Global Biodiversity Framework (2022) calls for protecting 30% of land and inland waters by 2030, offering a major opportunity to align freshwater conservation with climate action.

Conclusion

Changing rainfall regimes are restructuring freshwater ecosystems at multiple scales. Consequences include biodiversity decline, reduced fishery yields, degraded ecosystem services, and rising water treatment costs (Reid *et al.*, 2022; Vörösmarty *et al.*, 2023). Future management must integrate hydrological forecasting, ecosystem monitoring, and community participation to safeguard freshwater systems under shifting rainfall regimes (Wang *et al.*, 2024; Zhang *et al.*, 2025). Therefore, rainfall variability under climate change is reshaping freshwater ecosystems through altered hydrology, sedimentation, nutrient enrichment, and eutrophication. These stressors compound existing anthropogenic pressures, driving ecosystems toward ecological thresholds. Proactive management and adaptive governance are essential to sustain biodiversity and ecosystem services in a rapidly changing rainfall regime.

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