

CHAPTER 15

**Monsoon and Water in a Changing Climate**

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Roxy Mathew Koll

*“Everything depends on the rain.”*

~Matadin Meena,  
75-year-old farmer from Rajasthan

## Roxy Mathew Koll

**Dr. Roxy Mathew Koll** is a climate scientist at the Indian Institute of Tropical Meteorology (IITM), Ministry of Earth Sciences, Pune. He did his Ph.D. in Ocean and Atmospheric Dynamics from Hokkaido University, Japan.

Koll has made breakthrough contributions to the research, monitoring, and modeling of climate and extreme weather events over the Indo-Pacific region. His work has advanced the scientific understanding of monsoon floods and droughts, terrestrial and marine heatwaves and cyclones. His research has influenced state-to-national climate policies and disaster management strategies. He is a Lead Author of the IPCC Reports and the former Chair of the Indian Ocean Region Panel. He actively collaborates with citizen science networks, local governments and media to bring science to society.

Koll received the Rashtriya Vigyan Puraskar (National Science Award), the highest recognition in the field of science, technology and innovation in India in 2024. He was conferred a Fellow of the American Geophysical Union (AGU) and was awarded the AGU Devendra Lal Medal for outstanding research in Earth and Space Sciences in 2022.

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**I**ndia's intimate relationship with the monsoon and water shapes its culture and economy. Today, climate change is altering our connection with water, with its impacts rippling through the monsoon, glaciers, rivers and oceans, affecting every citizen.

The geographical location of India, surrounded by tropical waters at one end and the Himalayas at the other, was once the region's forte, but no longer. The Indian Ocean is warming at the fastest rate and the Himalayan glaciers are melting rapidly. As a result, the subcontinent is witnessing a trend of rising floods, landslides, droughts, heatwaves and cyclones. This is affecting the food, water and energy security of the region, deeply endangering lives and livelihoods. India has become the poster child of climate change.

This chapter explores these interconnected challenges, highlighting water risks in a warming world while emphasising actionable solutions.

### **Escalating Water Stress**

Globally, water systems are under unprecedented strain, exacerbated by rising temperatures that intensify evaporation, disrupt precipitation patterns and amplify extreme weather

events. Currently, over a third of the global population faces water stress, a figure expected to reach half the population by 2050, as demand continues to outpace supply. This crisis is not merely one of scarcity but inequity, where the most vulnerable communities bear the heaviest burden. Urban centres dominate resource consumption, leaving rural populations, particularly in arid and semi-arid regions, grappling with limited access to clean water.

The plight of Danganmal, a village 140 kilometres east of Mumbai, is one of the cases that illustrates these disparities. Chronic water scarcity has driven households to adopt extraordinary measures, including polygamous marriages where ‘water wives’ are tasked with fetching water for their families. This stark reality highlights the human cost of water inequity, where women shoulder the disproportionate burden of climate change.

### **Monsoon Droughts and Floods**

India’s summer monsoon rainfall during June–September accounts for 78% of its annual rainfall, directly influencing agriculture, water resources and energy security. Every year from June to September, the monsoon delivers approximately 848 mm of rain across India, amounting to 2,700 trillion litres of water—enough to provide nearly 2 million litres per person. About half of this rainwater enters rivers, with the Ganges-Brahmaputra basin alone carrying 37 million litres per second. This extraordinary natural phenomenon shapes the contours of life and livelihood in India, but it is increasingly under strain.

Since the 1950s, the monsoon’s behaviour has changed significantly. Prolonged dry spells now alternate with intense rainfall events, increasing the risk both of floods and droughts. While moderate rains spread through the monsoon season

rejuvenate the groundwater, extreme rains flush water out easily into the sea or evaporate. This causes water insecurity, following flood events, within the same season.

Regional anomalies during the monsoon season have also become stark. For instance, in 2018, Kerala experienced catastrophic flooding due to excessive rainfall, displacing millions and resulting in economic losses exceeding \$5 billion. Contrastingly, regions like Marathwada have witnessed persistent droughts, driving agrarian distress and migration.

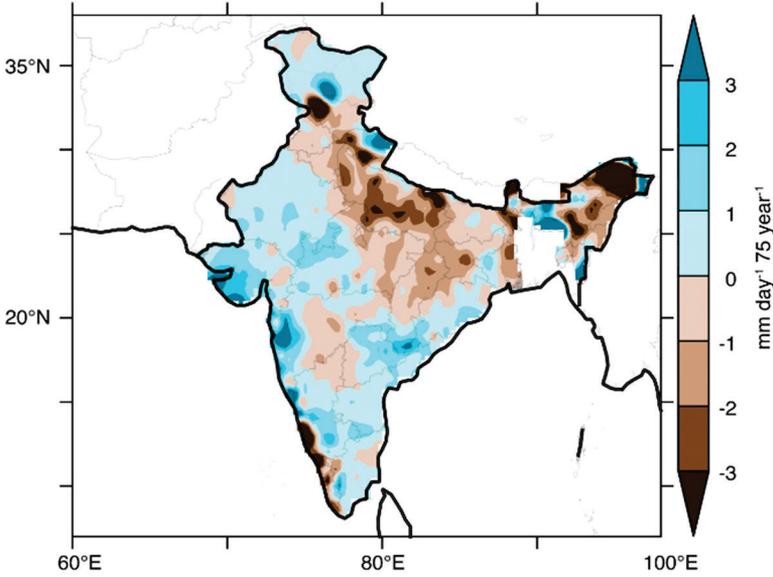
India has experienced over 325 major flood events between 1950 and 2024, reportedly killing more than 81,000 people, displacing millions and causing reported economic losses exceeding \$140 billion.

These floods are not confined to rural areas. Urban centres are becoming increasingly vulnerable. In Mumbai, urbanisation has intensified flooding, with impermeable surfaces preventing natural drainage. The floods of 2005, which brought the city to a standstill, are a stark reminder of the inadequacy of existing infrastructure to cope with extreme rainfall. Similarly, Chennai faces challenges where encroachments on wetlands and rivers exacerbate flood risks.

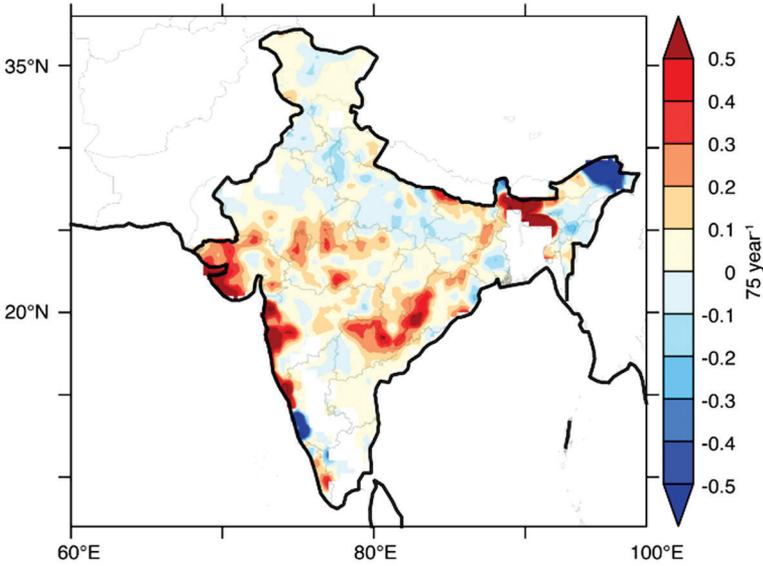
Figure 1(a) Trend in mean summer monsoon (June–September) rainfall, during 1950–2024. Brown colours indicate a long-term decline in the total amount of rainfall while green colours indicate an increase in the rainfall amount.

Figure 1(b) Trend in the frequency of extreme rainfall events over the summer monsoon, during 1950–2024. Orange-red colours indicate a rise in the number of extreme rainfall events while blue colours indicate a decrease in extreme rainfall events.

(a) Trend in mean rainfall (1950-2024)



(b) Trend in the frequency of extreme rainfall events (1950-2024)



Data from the India Meteorological Department shows that while the total amount of rainfall during the monsoon season shows a decline over several parts of India including the north and the Western Ghats (brown colours in Figure 1a), the core monsoon regions over India have witnessed a threefold rise in extreme rainfall events (red colours in Figure 1b).

Climate models suggest that extreme rain events in India could further increase multifold by the end of the 21st century, under high greenhouse gas emission scenarios. The implications of these changes are profound, with cascading effects on agriculture, water management and disaster resilience.

### **Melting Himalayan Glaciers**

The Himalayan glaciers, often referred to as Asia's water towers, are retreating at a rapid rate. Over the past four decades, glacial mass loss in the Himalayas has doubled compared to the 20th century. This trend threatens perennial rivers like the Ganges, Brahmaputra and Indus, which depend on glacial melt for dry-season flow. The ramifications are far-reaching, affecting agriculture, hydropower generation and drinking water supplies.

Seasonal variations are becoming pronounced. Glacial melt contributes to higher river discharge in winter, which temporarily benefits downstream communities. However, as glaciers shrink, less meltwater is available during the critical summer months, impacting agriculture and hydropower. This dynamic is evident in regions like Himachal Pradesh, where hydroelectric projects face decreasing water flow, undermining energy security. Moreover, glacial retreat increases the risk of glacial lake outburst floods, sudden and catastrophic events that can devastate downstream areas. An example is the glacial burst that led to massive flash floods in Uttarakhand's Chamoli district in 2021, leading to 234 reported deaths.

Addressing these challenges calls for a multipronged approach, including enhanced monitoring of glaciers, early warning systems and investment in sustainable energy alternatives.

### **Coastal Vulnerabilities**

Rising sea levels lead to saltwater intrusion and coastal erosion, and communities along India's 7,500-kilometre coastline face multiple risks. Increasing cyclones, storm surges and floods due to heavy monsoon rains heighten the threat.

Rapid ocean warming plays a major role in rising sea levels through thermal expansion of water. The warm waters also provide a consistent supply of heat and moisture to the atmosphere, intensifying cyclones and monsoon wind bursts, leading to severe storm surges.

Coastal cities are at heightened risk when these extreme events overlap, causing compound extreme events.

Cyclone Yaas in May 2021 exemplifies this phenomenon, where cyclonic storm surge, heavy rains and sea level rise combined with a high tide inundated the coastlines of Odisha, West Bengal and Bangladesh, several kilometres inland. Such 'compound floods' have the potential to submerge large parts of coastal cities for days, if not weeks. The saltwater intrusion damages agriculture for years and contaminates freshwater, threatening food and water security in coastal districts.

Adaptation strategies must be holistic, integrating local knowledge with scientific advancements. For coastal communities, this could mean creating early warning systems, developing resilient infrastructure and implementing ecosystem-based adaptation programs.

Mangroves have been shown to mitigate the impact of strong cyclone winds and demonstrate an ability to recover

after sustaining damage. They also serve as natural floodplains, absorbing floodwaters caused by cyclonic storm surges. However, mangroves may not function effectively as a defence in all coastal regions. More research is needed to identify optimal solutions, likely involving a combination of natural and engineered defences, to provide comprehensive protection for vulnerable coastal areas.

### **Public Health Implications**

Seawater inundation along the coast is linked to an increased risk of cholera outbreaks, as the bacteria responsible for cholera, *Vibrio cholerae*, often attach to zooplankton in coastal waters. When sea levels rise, the bacteria spread through flooding and contamination of freshwater sources in low-lying areas, leads to cholera outbreaks among coastal communities. In addition, cholera outbreaks often surge during monsoon seasons due to flooding and increased water contamination. A multifaceted approach that ensures water quality and sanitation, surveillance, social mobilisation, cholera vaccines and treatment is key to reducing cholera outbreaks.

Water insecurity arising from the climatic changes in the monsoon directly impacts public health, migration and social stability. Communities in drought-prone regions like Marathwada face crop failures, debt and distress migration. In contrast, flood-affected regions struggle with waterborne diseases and infrastructure loss. Dengue, a climate-sensitive vector-borne disease, illustrates the link between monsoon variations and health.

Studies show that warm temperatures and moderate rains during the monsoon season create optimal conditions for *Aedes* mosquito breeding, leading to an increase in dengue cases, whereas heavy rains can flush out breeding sites and reduce outbreaks. In

Pune, a dengue hotspot, mortality rates rise significantly during years with evenly spread moderate rainfall. Future projections suggest that rising temperatures and altered monsoon patterns could increase dengue-related mortalities in Pune by up to 112% by the end of the century under high-emission scenarios.

Dengue adaptation measures include utilising prediction models, promoting community-driven vector control programs and strengthening healthcare responses. Removing stagnant water and using larvicides are critical measures to curb breeding. Public health campaigns to raise awareness can further bolster these efforts.

### **River Interlinking and Climate Implications**

River interlinking, proposed as a solution to manage India's water distribution imbalance, has sparked both optimism and controversy. The project envisions connecting major rivers in India through a network of 15,000 km of canals and 3,000 reservoirs, with the capacity to annually transfer 174 billion cubic metres of water. This ambitious USD 168 billion initiative aims to redistribute water from surplus to deficit basins, increasing the irrigated area by 30 million hectares. While it promises to mitigate droughts and reduce flood risks, emerging research highlights its potential ecological and climate implications.

Recent studies indicate that river interlinking can alter local climates, particularly the monsoon. According to the research, the proposed river interlinking projects could potentially lead to an increase in September rainfall of up to 10% in some parts of the Ganga, Godavari and Krishna basins while reducing the rainfall by up to 12% in several arid regions of the country, namely parts of Madhya Pradesh, Odisha, Chhattisgarh, Uttarakhand, Rajasthan and Gujarat.

Extensive interlinking affects regional hydrological cycles by altering evapotranspiration patterns and atmospheric moisture distribution, potentially weakening the monsoon system. Moreover, changes in land use due to canal construction and water transfer could impact local ecosystems, displacing biodiversity and affecting livelihoods dependent on riverine resources. Available preliminary research highlights the delicate balance between interlinking benefits and risks, emphasising the need for comprehensive impact assessments.

Policymakers must carefully evaluate these projects, prioritising localised water management strategies over large-scale interventions. Integrating advanced hydrological models and environmental safeguards can ensure that interlinking initiatives align with sustainability goals while minimising unintended consequences.

### **Adaptive Measures and Way Forward**

Advanced forecasting tools and data-driven approaches offer hope. Improved weather models, such as those developed under India's National Monsoon Mission, enhance early warning systems, enabling better preparedness regarding water-related risks. Research and development by institutions like the CSIR - Central Salt and Marine Chemicals Research Institute, have introduced cost-effective desalination technologies, providing potable water to coastal and drought-hit regions.

Community engagement through citizen science initiatives, like the Meenachil River and Rain Monitoring Network in Kerala, empowers locals to monitor and manage water resources. Policy interventions must integrate scientific insights with grassroots needs and ecosystem restoration, including reforestation, wetland preservation and sustainable agriculture that can buffer against extreme events.

Startups and research institutions are developing technologies for efficient water use and recycling. Smart irrigation systems, powered by artificial intelligence, are helping farmers optimise water use, while decentralised wastewater treatment plants are addressing urban water woes. These efforts are now scattered, but public-private partnerships are proving instrumental in scaling such solutions. Initiatives under the United Nations' Sustainable Development Goals (SDGs) provide frameworks for achieving water security through global cooperation.

India's water journey from source to sea is at a crossroads. Climate change presents formidable challenges but also opportunities for innovation and resilience. By investing in scientific research and development, community-driven adaptation and sustainable practices, India can safeguard its water heritage for future generations. This collective effort will ensure that water is not merely a resource, but the very lifeline for all.

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