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Climate Change, Environmental Degradation and Sectoral Vulnerability in Arid and Semi-Arid Rajasthan, India: A Comprehensive Review

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Abstract

Rajasthan, India's largest state by geographical area, represents one of South Asia's most climate-sensitive arid and semi-arid regions. Over the past decade, the state has experienced pronounced climatic variability marked by rising temperatures, erratic monsoon behaviour, intensifying heat waves, declining groundwater reserves, deteriorating air and water quality, and escalating ecological stress. These changes are occurring against a backdrop of rapid urbanization, agricultural intensification, population growth, and land-use transformation, which together amplify regional vulnerability. This review synthesizes peer-reviewed research, government datasets, and institutional reports to critically examine recent climate trends in Rajasthan and their cascading impacts on water resources, agriculture, forests, biodiversity, public health, and socio-economic resilience. Emphasis is placed on the interaction between slow- onset climatic processes such as warming and groundwater depletion and extreme events including heat waves, droughts, and episodic floods. The review highlights spatial heterogeneity in climate impacts, identifies knowledge gaps in existing research, and evaluates current adaptation and governance responses. By integrating climatic, environmental, and sectoral perspectives, this article contributes a comprehensive and region-specific synthesis relevant to climate policy, adaptation planning, and sustainability science in dry land regions globally.

Keywords: Climate Change, Rajasthan, Arid Regions, Groundwater Depletion, Heat Waves, Air Quality, Biodiversity, Adaptation.

Introduction

Climate change has transitioned from a projected future risk to an experienced reality across the world's drylands. Arid and semi-arid regions are disproportionately affected due to their intrinsic climatic variability, limited water availability, and heavy dependence on climate-sensitive livelihoods. Rajasthan, occupying nearly 10% of India's landmass yet holding barely 1.2% of its water resources, epitomizes this vulnerability. The state's environmental fragility is rooted in its geography, ranging from the hyper-arid Thar Desert in the west to the semi-arid plains and hill systems of the Aravalli range in the east.

Climate change is no longer a distant or hypothetical concern; it has become a lived reality, particularly across the world's dryland regions. Arid and semi-arid landscapes are especially sensitive due to their inherent climatic variability, constrained water availability, and strong dependence on climate-dependent livelihoods such as agriculture and pastoralism. Rajasthan exemplifies this vulnerability. Covering nearly one-tenth of India's geographical area but possessing only a small fraction of its water resources, the state reflects a pronounced imbalance between environmental

demand and resource availability. Its geographical diversity—from the extremely arid Thar Desert in the west to relatively semi-arid plains and the Aravalli hill systems in the east—further accentuates its climatic sensitivity.

Traditionally, communities in Rajasthan developed adaptive strategies finely tuned to environmental uncertainty. These included rainwater harvesting systems such as johads and baoris, cultivation of drought-tolerant crops, and flexible pastoral practices that allowed seasonal mobility. Such indigenous knowledge systems historically enabled resilience against climatic stress. However, the pace and scale of contemporary climate change are placing these systems under significant strain. Observational data from meteorological stations, along with satellite-derived climate records, indicate rising temperatures, increasing frequency and duration of heatwaves, and heightened variability in monsoon patterns. Rainfall is becoming more erratic, often concentrated in short, intense bursts rather than evenly distributed seasonal precipitation.

These climatic shifts do not operate in isolation. They are compounded by human-induced pressures, including unsustainable groundwater extraction, degradation of forest cover, expansion of urban areas, and rising industrial emissions. The interaction between climatic and anthropogenic factors has led to complex, multi-dimensional stress on natural and human systems. For instance, declining groundwater levels reduce agricultural resilience, while land-use changes alter local microclimates and exacerbate heat stress.

The period between 2015 and 2025 represents a particularly significant phase in Rajasthan's climate trajectory. During this decade, the state has experienced several record-breaking temperature events, repeated drought conditions, localized flooding episodes, and worsening air quality in urban centers. These developments highlight the emergence of compound climate risks, where multiple stressors interact simultaneously. Understanding such dynamics requires moving beyond single-variable analysis toward a systems-oriented approach that integrates climate science with hydrology, ecology, agriculture, and socio-economic dimensions.

Recent scientific literature, supported by satellite observations and national datasets, underscores the interconnected nature of climate impacts in Rajasthan. Changes in temperature and precipitation patterns are influencing water availability, crop productivity, forest health, biodiversity distribution, and human health outcomes. Importantly, these impacts are not uniform across the state. Variations in topography, soil type, and land-use practices create distinct patterns of vulnerability across different agro-climatic zones. This spatial heterogeneity necessitates localized assessment and targeted intervention strategies rather than a one-size-fits-all approach.

Furthermore, slow-onset processes such as gradual temperature rise and groundwater depletion are increasingly interacting with extreme events like droughts, floods, and prolonged heatwaves. These interactions amplify risks and create cascading effects across sectors, from agriculture to public health. While several adaptation measures—such as climate-resilient agriculture, water conservation initiatives, and policy interventions—are being implemented, gaps remain in terms of scalability, integration, and long-term sustainability.

In conclusion, Rajasthan stands at a critical juncture where climate pressures and developmental challenges intersect. Addressing these issues requires a comprehensive, multi-sectoral strategy that combines scientific evidence, technological innovation, and traditional knowledge systems. Strengthening institutional capacity, promoting community-based adaptation, and ensuring sustainable resource management will be essential to enhance resilience. The urgency of

coordinated and region-specific action cannot be overstated, as the trajectory of climate change in Rajasthan will significantly influence both environmental stability and human well-being in the coming decades (Dash et al., 2009; Guhathakurta et al., 2015; IPCC, 2021).

Rajasthan's climate system is characterized by extremes—high temperatures, low and variable rainfall, frequent droughts, and intense evapotranspiration—making it inherently sensitive to climate perturbations. Recent climatic shifts have amplified these natural stressors, transforming climate change from a long-term concern into an immediate development challenge. Instrumental records demonstrate a persistent warming trend across the state, accompanied by growing rainfall unpredictability and increasing incidence of extreme weather events (India Meteorological Department, 2020). These changes are not occurring in isolation; rather, they intersect with anthropogenic pressures such as unsustainable groundwater extraction, deforestation, industrial emissions, and unplanned urban growth. These climatic stressors have profound implications for agriculture, water security, biodiversity, public health, and livelihoods, especially among vulnerable rural and urban populations. Understanding climate change in Rajasthan therefore requires a systems-based approach that integrates atmospheric processes with hydrological dynamics, ecological responses, and socio- economic transformations. This review adopts such an integrated perspective, positioning Rajasthan as a representative dryland region whose experience offers valuable lessons for climate adaptation in arid environments worldwide (Prasad & Dutta, 2019; Rao et al., 2020).

Review Points

Temperature Rise and Heat Extremes

Multiple studies confirm a statistically significant rise in mean, maximum, and minimum temperatures across Rajasthan, reflecting a persistent regional warming trend over recent decades (Kothawale & Rupa Kumar, 2005; India Meteorological Department, 2020). A particularly concerning feature of this warming is the faster increase in minimum temperatures compared to daytime maximum. Reduced nocturnal cooling intensifies cumulative heat stress, limits physiological recovery in humans and livestock, and increases crop respiration losses, thereby lowering agricultural productivity. Districts such as Churu, Barmer, and Jaisalmer have repeatedly recorded extreme temperatures exceeding 50 °C, placing Rajasthan among the most heat-stressed regions in South Asia (Dash et al., 2009). Heatwaves are no longer isolated climatic anomalies but have become recurrent, prolonged, and spatially extensive. Urban centers such as Jaipur experience compounded warming due to urban heat island effects driven by high built-up density, declining vegetation cover, and altered surface albedo (Singh, Tsiang, Rajaratnam, & Diffenbaugh, 2017). Elevated night-time temperatures significantly increase heat-related morbidity, reduce outdoor labor productivity, and sharply raise electricity demand for cooling, creating feedback loops that further exacerbate urban vulnerability under climate change (IPCC, 2021).

Rainfall Variability and Extreme Events

Unlike temperature trends, rainfall changes in Rajasthan exhibit pronounced spatial and temporal heterogeneity. While long-term averages show weak or declining trends in total annual rainfall across many districts, intra-seasonal variability has increased substantially (Pai, Sridhar, Badwaik, & Rajeevan, 2014). Rainfall is increasingly concentrated into short-duration, high-intensity events rather than evenly distributed monsoon spells, reducing effective soil moisture retention

and groundwater recharge. This shift reflects broader monsoon instability associated with climate change across the Indian subcontinent (Guhathakurta, Sreejith, & Menon, 2015).

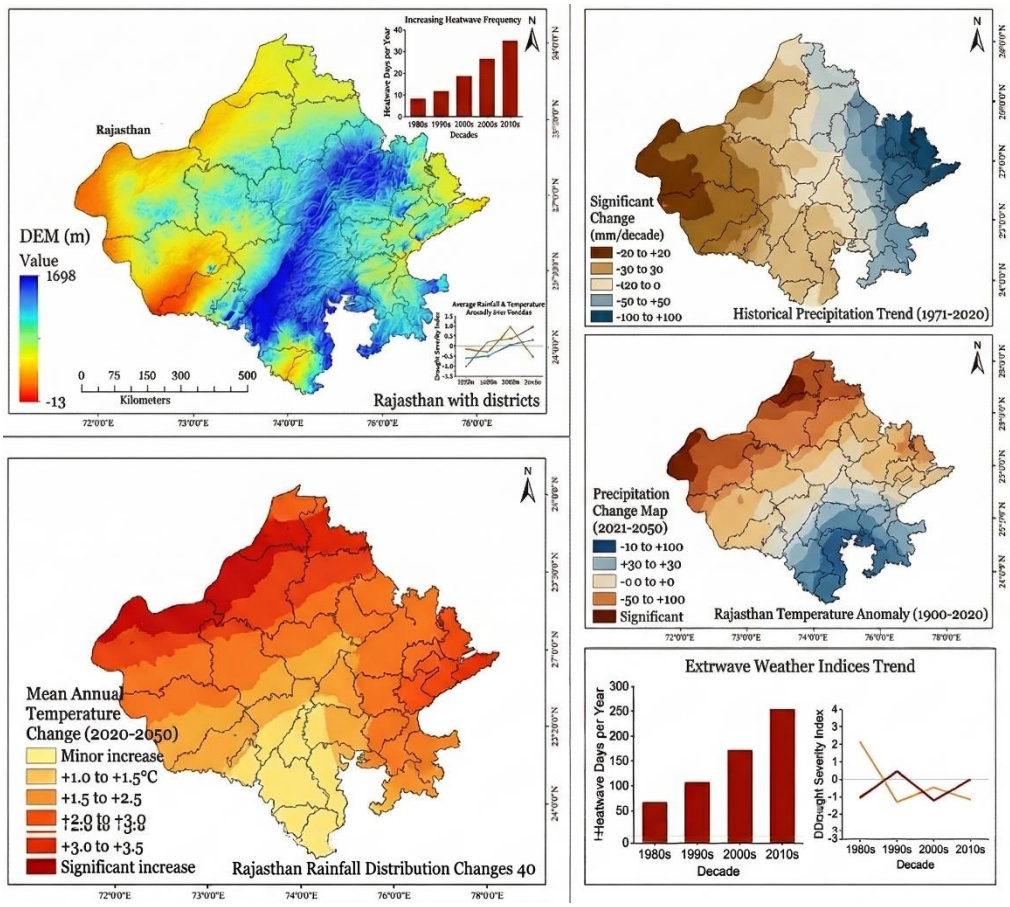

Figure 1: Research Data on Rajasthan Climate change

The restructuring of rainfall regimes has created a paradoxical coexistence of droughts and floods within the same climatic system. Western Rajasthan frequently experiences prolonged dry spells and delayed monsoon onset, while eastern and southeastern districts periodically face flash floods triggered by cloudburst events. Such variability disrupts traditional agricultural calendars, increases crop failure risk, accelerates surface runoff losses, and overwhelms urban drainage infrastructure (Prasad & Dutta, 2019). The growing unpredictability of rainfall thus represents a major challenge for water resource planning and climate-resilient development in the state.

Air Quality Degradation

Air pollution has emerged as a major environmental health challenge in Rajasthan's rapidly growing urban and industrial clusters. Persistent exceedances of PM_{10} and $PM_{2.5}$ concentrations above national standards have been documented in cities such as Jaipur, Jodhpur, and Kota (Central Pollution Control Board, 2022). Major anthropogenic sources include vehicular emissions, industrial operations, construction activity, road dust resuspension, and biomass burning, while natural sources such as desert dust storms contribute significantly to particulate loading during dry seasons. Climate change indirectly aggravates air quality deterioration by increasing atmospheric stagnation during heatwaves and enhancing dust mobilization under arid conditions. Higher temperatures accelerate photochemical reactions, promoting the formation of ground- level ozone, while reduced wind circulation limits pollutant dispersion (Mukherjee, Bhanja, &

Wada, 2020). The combined burden of heat stress and poor air quality significantly elevates respiratory and cardiovascular health risks, particularly for children, elderly populations, and outdoor workers, underscoring the strong linkage between climate change and public health vulnerability in Rajasthan.

Groundwater Depletion and Water Stress

Groundwater constitutes the primary source of water for agriculture, domestic consumption, and industry in Rajasthan. However, groundwater extraction far exceeds natural recharge across most districts, with recent assessments indicating development levels exceeding 140%, placing large areas in the "over-exploited" category (Central Ground Water Board, 2023). Intensive irrigation, cultivation of water-demanding crops, and limited surface water availability have driven unsustainable abstraction, particularly in arid and semi-arid zones.

Climate change acts as a powerful stress multiplier by increasing evapotranspiration rates and intensifying rainfall variability. Rising temperatures elevate irrigation demand, while erratic monsoon patterns reduce recharge efficiency, accelerating groundwater decline (Shah, 2019). Falling water tables increase pumping depth and energy costs, disproportionately affecting small and marginal farmers and widening rural socio-economic inequality. Simultaneously, groundwater quality deteriorates through saline and fluoride intrusion, posing serious drinking water risks (Kumar, Patel, & Singh, 2018). Surface water bodies, already stressed by pollution and sedimentation, further constrain overall water availability under changing climatic conditions.

Forest Cover Change and Ecological Quality

Although recent assessments indicate marginal increases in total tree cover in Rajasthan, these numerical gains mask substantial declines in moderately dense and open forest categories (Forest Survey of India, 2023). The expansion of scrubland suggests ecological degradation rather than true forest recovery, reflecting pressures from grazing, fuelwood extraction, and land-use conversion. Key drivers of deforestation include agricultural expansion, mining, infrastructure development, and large-scale renewable energy installations. Forests in Rajasthan perform critical ecological functions by regulating microclimates, conserving biodiversity, stabilizing soils, and enhancing groundwater recharge, particularly in the Aravalli range. Declining forest quality weakens ecosystem resilience and amplifies climate impacts by increasing surface temperatures, reducing moisture retention, and disrupting habitat connectivity (IPCC, 2021). Loss of forest heterogeneity also undermines ecosystem services essential for rural livelihoods. Effective forest conservation therefore requires shifting focus from mere increases in tree numbers to long-term ecological integrity, native species restoration, and community-based forest management.

Biodiversity Loss and Species Vulnerability

Rajasthan's biodiversity faces mounting pressure from habitat loss, climatic stress, and increasing fragmentation. Grassland, desert, and dry deciduous ecosystems are particularly vulnerable due to their narrow ecological tolerance ranges. The critically endangered Great Indian Bustard exemplifies the severity of biodiversity decline, with populations threatened by habitat conversion, infrastructure expansion, and collision- related mortality (Forest Survey of India, 2023). Climate-induced shifts in vegetation composition, combined with invasive species expansion and water scarcity, further destabilize wildlife habitats. Rising temperatures alter breeding cycles, migration patterns, and species interactions, increasing extinction risk for climate-sensitive flora and fauna (Guhathakurta et al., 2015). Although conservation

programs exist, their effectiveness is constrained by limited spatial coverage, enforcement challenges, and weak integration with land-use planning. Strengthening biodiversity resilience in Rajasthan requires landscape-level conservation, climate-adaptive protected area management, and alignment of development policies with ecological sustainability.

Agricultural Impacts and Food Security

Agriculture in Rajasthan remains predominantly rain-fed and highly sensitive to climatic fluctuations. Rising temperatures shorten crop growth periods, accelerate evapotranspiration, and increase terminal heat stress, particularly for rabi crops such as wheat and mustard (Birthal et al., 2014). Erratic rainfall patterns heighten the risk of crop failure and yield instability, undermining food security and rural incomes. Staple crops including pearl millet, pulses, and oilseeds exhibit increasing inter-annual yield variability under changing climatic conditions. Climate change also intensifies pest and disease pressures by extending breeding cycles, increasing survival rates, and enabling pest range expansion (Indian Council of Agricultural Research, 2022). Combined with declining water availability, these factors raise production costs and reduce farm profitability, accelerating rural distress and climate-induced migration. Without effective adaptation, continued climate stress threatens the long-term viability of agriculture in Rajasthan, with serious implications for regional food systems and socio-economic stability.

Adaptation Practices and Governance Gaps

Farmers, communities, and institutions in Rajasthan are increasingly adopting adaptation strategies such as crop diversification, micro-irrigation, rainwater harvesting, and climate-resilient crop varieties (Rao, Rejani, & Osman, 2020). Traditional water management systems, including johads, tankas, and khadins, are being revived in some regions, demonstrating the value of indigenous knowledge in enhancing climate resilience. However, adoption remains uneven due to limited institutional capacity, fragmented governance structures, inadequate extension services, and socio-economic constraints faced by smallholders (NITI Aayog, 2021). Policy interventions often operate in sectoral silos, weakening coordination between water, agriculture, forestry, and urban planning. Effective adaptation requires integrating scientific climate information with local practices, strengthening governance frameworks, and ensuring equitable access to resources and technology. Addressing these governance gaps is critical for scaling adaptation efforts and reducing climate vulnerability across Rajasthan. However, adoption remains uneven due to limited institutional capacity, fragmented governance, inadequate extension services, and socio-economic constraints. Effective adaptation requires integration of scientific knowledge with local practices and stronger policy coordination.

Conclusion

Climate change in Rajasthan is not a single environmental phenomenon but a systemic transformation reshaping natural systems, livelihoods, and development trajectories. Rising temperatures, rainfall volatility, water scarcity, pollution, and ecological degradation interact to create compound risks that disproportionately affect vulnerable populations. While adaptation efforts are underway, current responses remain insufficient relative to the scale and complexity of emerging challenges. A holistic, region-specific, and equity-oriented approach is essential to safeguard Rajasthan's environmental and socio-economic future.

Future research should prioritize high-resolution climate modeling, district-level vulnerability assessments, and long-term ecological monitoring. Policy efforts must integrate climate adaptation with water governance, urban planning, biodiversity conservation, and public health. Strengthening institutional capacity, promoting nature-based solutions, and scaling community-driven adaptation will be critical for building resilience in Rajasthan and other dryland regions globally.

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Conflict of Interest

The authors declare no conflict of interest.

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