Climate Change Impacts on Wetland Ecosystems and Migratory Water Bird Populations in Rajasthan, India: A 25-Year Analysis

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Abstract: ***Climate change threatens the survival of wetland ecosystems in semi-arid areas, which has a ripple effect on biodiversity, ecosystem services, and the fauna that depends on them. This research investigates the effects of climate change on six significant wetlands in Rajasthan, India, over a 25-year timeframe (2000-2025), evaluating temperature trends, precipitation patterns, water bird population dynamics, plant responses, and wetland resilience. The results show that the mean temperature rose by a lot (1.5–1.9°C) and the summer peak temperature rose by a lot (2.7–3.4°C) at all locations. This caused the evaporation rate to rise by 24–38% and the water level to fall by an average of 38%. Annual precipitation dropped considerably by 10.6% ($p < 0.01$), with monsoon precipitation dropping 12.4% and rainfall variability rising 38.2%. These variations in water levels caused a lot of migrating waterbirds to die off (16.5–27.0%), delayed their journey by 9–14 days, and made it harder for them to reproduce (23–41% less successful). Wetland vegetation communities underwent significant rearrangement, characterised by a 48% reduction in submerged vegetation, a 32% decrease in emergent macrophytes, and an increase of up to 52% in invasive species. The climate resilience study showed that various ecosystems were more or less vulnerable. For example, well managed protected wetlands like Keoladeo National Park and Jaisamand Lake were more adaptable than urban or specialised habitats like Mansagar Lake and Sambhar Lake. The results show that we need to act quickly to come up with comprehensive climate adaptation plans. These should include better water management, restoring habitats, and working together across borders to protect wetlands and migratory bird populations as climate change speeds up.***

Keywords: climate change, wetland ecosystems, temperature rise, precipitation Rajasthan

1. Introduction

Climate change is one of the biggest and fastest-growing dangers to biodiversity throughout the world. It has especially bad effects on wetland ecosystems in areas with limited water (Erwin, 2009; Finlayson et al., 2013). Wetlands, which only comprise 5–8% of the land surface, offer ecological services that are far more significant than their size would suggest. These functions include cleaning water, controlling floods, storing carbon, and providing important habitat for a wide range of animals (Davidson, 2014; Mitsch & Gosselink, 2015). But these ecosystems are more vulnerable to climate change than ever before because they rely on certain hydrological regimes, are sensitive to changes in temperature, and are located at the boundary between land and water systems (Junk et al., 2013; Gibbs, 2000).

Semi-arid regions, characterized by naturally limited and variable water availability, experience particularly acute climate change impacts on wetland ecosystems (Döll & Flörke, 2005). These regions are expected to see temperature rises beyond world norms, heightened hydrological variability characterised by increased frequency of droughts and floods, and augmented evapotranspiration, which exacerbates water shortages (IPCC, 2021). Wetlands in semi-arid areas are under more stress because to less water coming in, faster evaporation, changes in the timing of water flow, and worse water quality (Erwin, 2009; Kingsford & Basset, 2012).

Rajasthan, the biggest state in India, shows these problems via its huge network of wetlands that maintain biodiversity that is important to the world in a landscape that is becoming more challenged by climate change (Vijayan, 1991; Kumar et al., 2005). Wetlands in the area are important places for resident animals to live and for migratory waterbirds to spend the winter. Every year, hundreds of thousands of birds from dozens of species stop here on their journey to the Central Asian Flyway (Islam & Rahmani, 2004). But these ecosystems are under greater and more stress from the climate, such as rising temperatures, less rain, more variable weather, and more severe weather events (Maji et al., 2010; Gupta et al., 2014).

Climate change affects wetlands in several ways that are all interrelated. As temperatures rise, evapotranspiration rates go up, which lowers the amount of water available and raises the temperature of the water to levels that are too high for many aquatic creatures to handle (Erwin, 2009). Changes in rainfall patterns change the way water flows, which messes with the natural processes that have developed over time (Burkett & Kusler, 2000). These hydrological changes have a ripple effect on wetland ecosystems, changing the chemistry of the water, the availability of habitats, the dynamics of the food web, and the distribution of species (Burkett et al., 2005; Finlayson et al., 2013).

Migratory waterbirds are particularly sensitive indicators of climate change impacts on wetland ecosystems due to their reliance on geographically dispersed wetland networks, predictable resource availability, and susceptibility to phenological mismatches (Both et al., 2006; Lehikoinen et al., 2013). Climate change impacts migratory birds via various mechanisms, including habitat degradation at breeding, stopover, and wintering sites; modified migration timing and routes; phenological asynchrony between migration and resource peaks; and heightened mortality due to extreme weather events (Møller et al., 2008; Végvári et al., 2010).

Wetland vegetation communities, which offer structural habitat, primary production, and ecosystem engineering roles, also adapt substantially to climate change (Erwin, 2009). Changes in temperature, water flow, and disturbance patterns may cause vegetation communities to shift, typically favouring stress-tolerant or invasive species over native biodiversity (Toogood et al., 2008; Capon et al., 2013). These changes in plants spread across food webs, influencing herbivores, decomposers, and higher trophic levels. They also influence how ecosystems work, such as how carbon cycles and how water is cleaned (Keddy, 2010). Even though more people are aware of how climate change is hurting wetland ecosystems, there aren't many long-term studies that look at how temperature and precipitation patterns, wildlife populations, vegetation dynamics, and resilience assessments all work together. This is especially true for semi-arid areas (Finlayson et al., 2013). The majority of current studies concentrate on specific wetlands, particular species or taxonomic groupings, or brief temporal periods that fail to differentiate climatic trends from natural variability (Erwin, 2009; Gardner et al., 2015). Moreover, little research systematically evaluates varying climate sensitivity across wetlands to guide adaptation prioritisation and resource distribution (Poff et al., 2002). This work addresses these information gaps by a thorough examination of the consequences of climate change on six key wetlands in Rajasthan over a 25-year period (2000-2025). This study look at how various wetlands respond to climate change to find patterns of susceptibility and help plan for how to deal with it. Our results provide essential data for climate adaptation programs and illustrate the extensive effects of climate change on semi-arid wetland ecosystems.

2. Methodology

2.1 Study Area

The study was conducted across six major wetlands of Rajasthan, India (23°3′–30°12′ N; 69°30′–78°17′ E), representing a range of wetland types, salinity regimes, management conditions, and geographic settings within the state's semi-arid landscape (~342,000 km²). The selected wetlands included Sambhar Lake, Keoladeo National Park, Mansagar Lake, Jaisamand Lake, Pushkar Lake, and Ana Sagar Lake.

Rajasthan experiences an arid to semi-arid climate with highly variable annual rainfall (100–650 mm), extreme temperature fluctuations (<0°C in winter to >50°C in summer), and high evapotranspiration. These wetlands are ecologically significant, supporting resident biodiversity and migratory waterbirds along the Central Asian Flyway. Site selection enabled assessment of differential vulnerability and resilience to climate change across environmental gradients.

2.2 Climate Data Collection and Analysis

Climatic data on temperature and precipitation were obtained from Indian Meteorological Department stations and supplemented with satellite-based datasets (MODIS LST and TRMM/GPM) to address spatial and temporal gaps. Data quality control included homogeneity testing and cross-validation. Analyses focused on temperature trends, extreme heat thresholds (>45°C), precipitation variability, drought indices, and extreme rainfall events. Evaporation was estimated using the Penman–Monteith method, while wetland surface area and water-level changes were derived from Landsat and Sentinel imagery. Trends were assessed using Mann–Kendall tests and Sen's slope estimator ($\alpha = 0.05$), with comparisons between early (2000–2010) and recent (2015–2025) periods.

2.3 Waterbird Population Monitoring

Wintering waterbirds were monitored from November to February using standardized wetland-wide counts, point counts, and photographic verification. Six focal species representing different ecological guilds were selected. Migration phenology was assessed using arrival and departure thresholds, while breeding success was inferred from juvenile-to-adult ratios. Population trends were analysed using generalized additive models, accounting for survey effort and wetland identity.

2.4 Vegetation Assessment

Wetland vegetation was assessed through annual field surveys during peak growth (August–September) using stratified random sampling across vegetation zones. Plant cover, species composition, stress indicators, and invasive species presence were recorded. Remote sensing indices (NDVI and NDWI) were used to evaluate vegetation productivity and land–water dynamics. Changes in community composition were quantified using Bray–Curtis dissimilarity.

2.5 Climate Resilience Assessment

Climate resilience was evaluated using an IPCC-based vulnerability framework incorporating exposure, sensitivity, and adaptive capacity. A composite vulnerability index was calculated and normalized (0–10 scale) to classify wetlands into resilience categories. This approach facilitated identification of key drivers of vulnerability and prioritization of targeted adaptation strategies.

2.6 Statistical Analysis

All statistical analyses were conducted using R statistical software version 4.0.3 (R Core Team, 2020). Temporal trends were examined via Mann-Kendall tests and Sen's slope estimators. Variations between used timeframes Utilization of Student's t-tests or Mann-Whitney U tests contingent upon data distribution evaluated using Shapiro-Wilk tests. Generalized additive models examined non-linear demographic patterns. The vegan program was used for community dissimilarity estimations in multivariate vegetation analysis (Oksanen et al., 2019). Statistical significance was evaluated at $\alpha = 0.05$ consistently. Results are expressed as mean ± standard deviation unless stated differently.

3. Results and Interpretation

3.1 Temperature Trends and Wetland Ecosystem Responses

The analysis of temperature changes in six wetlands showed that they became a lot warmer throughout the 25-year research period. This strongly supports Hypothesis 1 (Table 1). The mean temperatures of all the wetlands that were watched went up by 1.5 to 1.9 degrees Celsius, and the peak temperatures in the summer went up by an even bigger amount, by 2.7 to 3.4 degrees Celsius. These increases are far higher than the world average warming rate of around 1.1°C during the same time period. This is because Rajasthan is in a semi-arid area that is more sensitive to continental warming (IPCC, 2021).

Table 1: Temperature Trends and Wetland Ecosystem Responses (2000-2025)

Wetland Site	Mean Temperature Increase (°C)	Summer Peak Temperature Increase (°C)	Evaporation Rate Change (%)	Water Level Decline (%)	Thermal Stress Incidents in Wildlife
Sambhar Lake	1.8	3.2	+34%	42%	127
Keoladeo NP	1.6	2.9	+28%	31%	89
Mansagar Lake	1.9	3.4	+38%	47%	156
Jaisamand Lake	1.5	2.7	+24%	27%	71
Pushkar Lake	1.7	3.1	+31%	38%	104
Ana Sagar Lake	1.8	3.3	+35%	44%	138

Mansagar Lake was hit the worst, with a 1.9°C rise in the average temperature and a 3.4°C rise in the summer peak temperature. This caused the evaporation rate to rise by 38% and the water level to drop by 47%. This urban wetland is vulnerable because of several stressors that work together, such as heat island effects from nearby urban growth, limited water supplies due to competing urban needs, and a deteriorated biological state that makes it less able to handle climatic stress (Sharma & Kansal, 2011). The cascading ecological effects include habitat loss, which makes it harder for animals to find places to live; increased salinity, which makes dissolved minerals more concentrated as freshwater evaporates; thermal stratification disruption, which affects the flow of oxygen and nutrients; and degraded water quality, which makes pollutants more concentrated.

The significant rise in evaporation rates (24-38% across sites) is a critical problem for the sustainability of wetlands in arid environments, as evaporative losses progressively surpass water inputs from precipitation and surface flows. This imbalance causes water levels to drop steadily, averaging 38% across all locations. This shrinks the size of wetlands, removes shallow water habitats that are important for hatching amphibians and feeding waterbirds, and concentrates pollutants in the remaining water bodies. Thermal stress incidents in wildlife, numbering from 71 to 156 events per site, encompass heat-induced mortality in birds during extreme summer conditions with air temperatures surpassing 48°C, physiological stress impacting reproduction and immune function, and behavioural modifications, including altered activity patterns characterised by heightened nocturnal activity to evade peak daytime temperatures (McKechnie & Wolf, 2010). These events show that climate change affects animals not just by destroying their habitats but also by directly affecting their bodies.

Keoladeo National Park and Jaisamand Lake exhibited comparatively diminished climatic effects, despite significant warming, due to proactive water management strategies, including calculated water releases and pumping to sustain levels, deeper water bodies with enhanced thermal inertia that mitigate temperature extremes, and protective vegetation that regulates microclimatic conditions through shading and evapotranspiration (Erwin, 2009). These results indicate that well maintained wetlands with advantageous baseline attributes may somewhat alleviate climatic consequences, while they cannot entirely eradicate them.

3.2 Precipitation Pattern Changes and Hydrological Impacts

The precipitation analysis revealed fundamental hydrological changes threatening wetland ecosystems, providing additional strong support for Hypothesis 1 (Table 2). Annual precipitation declined significantly by 10.6% from 547mm to 489mm between the 2000-2010 and 2015-2025 periods ($p < 0.01$), representing a substantial reduction in water inputs to wetland systems already constrained by water scarcity.

Table 2: Precipitation Pattern Changes and Hydrological Impacts (2000-2025)

Parameter	2000-2010 Average	2015-2025 Average	Change (%)	Statistical Significance
Annual precipitation (mm)	547	489	-10.6%	$p < 0.01$
Monsoon precipitation (mm)	412	361	-12.4%	$p < 0.01$
Winter precipitation (mm)	45	38	-15.6%	$p < 0.05$
Rainfall variability (CV)	0.34	0.47	+38.2%	$p < 0.01$
Extreme rainfall events (>100mm/day)	2.3/year	3.8/year	+65.2%	$p < 0.01$
Drought frequency (days <1mm rain)	287	314	+9.4%	$p < 0.05$

The significant decline in monsoon precipitation (12.4%, $p < 0.01$) is critical, as June–September rainfall constitutes the principal annual water input sustaining wetland hydrology and productivity. Reduced monsoon rainfall shortens hydroperiods, lowers water levels, and intensifies water scarcity during peak pre-monsoon evaporation. Winter precipitation also declined markedly (15.6%, $p < 0.05$), threatening migratory waterbirds dependent on wetlands between November and February. Reduced winter rainfall constrains aquatic vegetation and invertebrate production, degrades habitat quality, and limits groundwater recharge that supports dry-season baseflows. Rainfall variability increased substantially, with the coefficient of variation rising by 38.2% ($p < 0.01$), indicating a shift toward erratic precipitation. Concurrently, extreme rainfall events (>100 mm day^{-1}) increased by 65.2% ($p < 0.01$), despite an overall decline in total rainfall, reflecting a transition from steady precipitation to intense, short-duration storms. While such events temporarily inundate wetlands, they also promote erosion, turbidity, nutrient runoff, and eutrophication, while failing to sustain wetlands during extended dry intervals. Drought frequency increased by 9.4% ($p < 0.05$), prolonging dry spells, accelerating water-level declines, concentrating pollutants, and imposing stress on wetland-dependent fauna. These altered precipitation regimes disrupt long-established ecological processes, including breeding phenology, migration timing, and rainfall-triggered plant germination. The statistical significance of observed trends confirms that these changes represent persistent climate shifts rather than natural variability, underscoring the need for adaptive interventions such as monsoon water harvesting, enhanced storage capacity, and improved wetland connectivity.

3.3 Climate Change Impacts on Migratory Waterbird Populations

Migratory waterbird populations exhibited significant climate-linked declines across all six focal species, supporting Hypothesis 3. Population reductions ranged from 16.5% to 27.0%, with the bar-headed goose showing the greatest decline (27.0%). Arrival dates were delayed by 9–14 days, while departure dates showed species-specific shifts, indicating altered migration phenology. These declines reflect cumulative climate impacts across the migratory cycle, including reduced breeding success in source regions, degraded stopover habitats, and declining wintering-ground quality in Rajasthan. Breeding success declined by 23–41% across species, suggesting compromised physiological condition due to reduced food availability, increased heat stress, and heightened disease risk during wintering. Greater flamingos exhibited particularly severe impacts, with a 17.4% population decline and a 41% reduction in breeding success, reflecting their dependence on shallow saline wetlands that are highly sensitive to evaporation-driven water-level and salinity fluctuations. Overall population declines threaten wetland ecosystem functioning by reducing nutrient cycling, seed dispersal, and trophic interactions. These findings highlight the urgent need for climate-adaptive wetland management, including habitat restoration, water-level regulation, and coordinated conservation efforts along the Central Asian Flyway.

3.4 Wetland Vegetation Response to Climate Variables

Wetland vegetation research showed big changes caused by temperature in plant groups that support the structure and function of these ecosystems. This is more proof for Hypothesis 4 (Table 4). Submerged vegetation lost 48% of its cover. This was mostly because of rising temperatures that are too high for many aquatic plant species to handle and more cloudy water from wind-driven sediment resuspension in shallower bodies of water caused by falling water levels.

Table 4: Wetland Vegetation Response to Climate Variables

Vegetation Type	Cover Change 2000-2025 (%)	Dominant Climate Driver	Stress Indicator Score	Species Composition Change	Invasive Species Increase
Emergent macrophytes	-32%	Water level decline	7.8	Moderate (34%)	+47%
Submerged vegetation	-48%	Temperature increase, turbidity	8.9	Severe (61%)	+28%
Floating plants	-29%	Evaporation, nutrient change	7.2	Moderate (38%)	+52%
Wetland trees/shrubs	-21%	Drought frequency	6.4	Low (22%)	+18%
Salt-tolerant species	+34%	Salinity increase	5.8	Moderate (41%)	N/A

The loss of submerged vegetation has severe implications for wetland food webs, as these plants form the primary forage for herbivorous waterbirds, provide critical nursery habitat for fish and invertebrates, and regulate dissolved oxygen levels. High stress indicator scores (8.9/10) and substantial compositional change (61% dissimilarity) indicate a fundamental restructuring of submerged plant communities, with climate-sensitive species being replaced by stress-tolerant, low-diversity assemblages that deliver reduced ecosystem services. Emergent macrophytes declined by 32%, largely due to falling water levels that reduced shallow-water habitat availability and disrupted soil moisture conditions required for growth. Concurrently, invasive species increased by 47%, reflecting the tendency of disturbed environments to favour opportunistic taxa that displace native vegetation and alter ecosystem functioning. Floating vegetation declined by 29% as a result of increased evaporation and altered nutrient dynamics. However, invasive floating species expanded sharply (+52%) in eutrophic wetlands, forming dense mats that restricted light penetration, depleted dissolved oxygen, and accelerated ecosystem degradation. Wetland trees and shrubs decreased by 21%, primarily due to recurrent drought stress that limited seedling establishment and increased mortality during extreme dry periods. These losses reduce nesting habitat, riparian shading, and shoreline stabilisation. Salt-tolerant species increased by 34% in response to climate-driven salinisation caused by elevated evaporation and reduced freshwater inflows. This shift from freshwater to brackish or saline conditions has displaced freshwater-dependent species and reduced biodiversity. Salinisation is advanced in Sambhar Lake and emerging in freshwater wetlands, where halophytes are increasingly colonising marginal zones. Collectively, these vegetation changes disrupt wetland food webs and ecosystem processes, affecting waterbirds, invertebrates, fish populations, and higher trophic levels. Reduced vegetation cover also impairs nutrient cycling, carbon sequestration, and water purification, undermining the ecological integrity and resilience of wetland ecosystems.

3.5 Climate Resilience Assessment and Adaptive Capacity

The climate resilience assessment offered a thorough framework for comprehending varying wetland vulnerability and prioritising adaptation efforts (Table 5). The results indicated significant variance in climate resilience due to disparities in exposure, sensitivity, and especially adaptive ability.

Table 5: Climate Resilience Assessment and Adaptive Capacity

Wetland Site	Climate Exposure Score	Sensitivity Score	Adaptive Capacity Score	Overall Vulnerability Index	Climate Resilience Ranking
Keoladeo NP	7.2	6.8	8.4	5.6	High
Jaisamand Lake	6.8	7.1	7.9	5.9	High
Sambhar Lake	8.9	8.4	5.2	8.1	Low
Mansagar Lake	8.4	8.7	4.8	8.5	Very Low
Pushkar Lake	7.6	7.8	6.1	7.3	Moderate
Ana Sagar Lake	7.9	8.1	5.7	7.6	Moderate

Keoladeo National Park exhibited the highest climate resilience despite substantial climate exposure, reflecting its strong adaptive capacity derived from protected status, proactive management, habitat heterogeneity, landscape connectivity, and robust institutional support through Ramsar and UNESCO designations (Vijayan, 1991). Its low vulnerability score underscores the role of effective water management infrastructure and habitat mosaics in buffering climatic stress. Jaisamand Lake similarly showed moderate resilience due to its large storage capacity, forested catchment, low pollution levels, and regulated management, which collectively dampen short-term climatic variability (Kumar et al., 2005). In contrast, Mansagar Lake showed the highest vulnerability due to extreme climate exposure, pollution stress, limited adaptive capacity, and urban constraints on management. Sambhar Lake exhibited high exposure and sensitivity driven by salinity dynamics, but low adaptive capacity due to the ecological and practical limits of intervention in naturally saline systems, despite some inherent tolerance among halophytic communities (Williams, 2002). Pushkar and Ana Sagar lakes displayed moderate resilience supported by active management and cultural value, but remained constrained by urban pressures and limited spatial extent. These findings highlight the need to prioritise adaptive interventions in highly vulnerable wetlands, while conserving and strengthening resilient sites as climatic refugia and models for effective adaptation.

4. Discussion

This 25-year analysis provides robust evidence that climate change has already profoundly altered wetland ecosystems across Rajasthan through interacting thermal, hydrological, and ecological pathways. The observed temperature increases (1.5–1.9°C), precipitation decline (10.6% annually), water-level reductions (mean 38%), waterbird population declines (16.5–27.0%), and extensive vegetation restructuring confirm that climate change is a present crisis rather than a future threat. Warming trends exceeding global averages reflect intensified heating in semi-arid continental interiors where reduced moisture limits evaporative cooling (IPCC, 2021). Elevated summer temperatures (2.7–3.4°C) intensify physiological stress on biota and substantially accelerate evaporation, producing persistent hydrological deficits that progressively shrink wetlands and degrade habitat quality (Döll & Flörke, 2005). Rising evaporation amplifies salinisation, concentrates pollutants, and promotes feedbacks that reduce ecosystem resilience and favour stress-tolerant species over diverse freshwater communities (Williams, 2002). Differences in water-level decline between actively managed wetlands such as Keoladeo and unmanaged systems highlight the buffering role of water management, though scaling such interventions is constrained by water availability and institutional capacity.

Precipitation decline alone does not fully explain wetland degradation; increased rainfall variability (38.2%) and extreme events (65.2%) further destabilise hydrological regimes, complicating management and disrupting ecological processes adapted to historical stability (Poff et al., 2002). Reduced winter precipitation (15.6%) undermines food availability and habitat quality during the critical wintering period for migratory waterbirds, contributing to phenological mismatches and reduced survival (Gunnarsson et al., 2005). Increased drought frequency intensifies evaporation-driven water loss, compresses remaining habitat, heightens competition and disease transmission, and can trigger abrupt shifts from vegetated marsh to dry basin states (Scheffer et al., 2001).

Waterbird population declines of 16.5–27.0% reflect cumulative climate impacts across breeding, migration, and wintering stages (Lehikoinen et al., 2013). Delayed arrival (9–14 days) reduces time available for energy accumulation and may desynchronise migration with peak resource availability, although it may also reflect limited adaptive flexibility (Végvári et al., 2010; Both et al., 2006). Declines in breeding success (23–41%) demonstrate strong carry-over effects of degraded wintering habitats on reproductive performance, emphasising the importance of conserving non-breeding areas (Gunnarsson et al., 2005). The pronounced decline in greater flamingo breeding success highlights the vulnerability of habitat specialists to climate-driven environmental change, potentially favouring generalist species over specialists (Clavel et al., 2011). These losses extend beyond species conservation, as migratory birds support nutrient cycling, seed dispersal, and trophic interactions essential to wetland functioning (Green & Elmberg, 2014). Vegetation dynamics further reveal fundamental ecosystem restructuring. The sharp decline in submerged macrophytes (48%) undermines food-web stability, water quality, and habitat complexity, while widespread increases in invasive species (18–52%) reflect the competitive advantage of opportunistic taxa under disturbance and climate stress (Jeppesen et al., 2012; Zedler & Kercher, 2004). Rising salinity, evidenced by a 34% increase in halophytic species, represents a potential regime shift from freshwater to saline systems that may be difficult to reverse in water-scarce regions (Williams, 2002). Vegetation loss also diminishes carbon sequestration, nutrient uptake, and habitat quality, impairing multiple ecosystem services (Mitsch & Gosselink, 2015).

Patterns of climate resilience demonstrate that adaptive capacity is a critical determinant of vulnerability. High resilience in well-managed wetlands such as Keoladeo illustrates the effectiveness of active management, institutional support, and habitat heterogeneity, whereas extreme vulnerability in urban wetlands highlights how limited adaptive capacity magnifies climate impacts. These findings indicate that investments in governance, management infrastructure, and resource mobilisation may yield greater resilience gains than attempts to directly offset climate exposure. Given similar climatic pressures across global drylands, the mechanisms identified here are likely representative of semi-arid wetlands worldwide (IPCC, 2021). Because migratory species connect ecosystems across continents, effective conservation will require integrated, transboundary strategies that address climate change alongside pollution, invasive species, and water extraction within a cumulative impact framework (Kirby et al., 2008; Crain et al., 2008; Sharma & Kansal, 2011).

5. Conclusion

This extensive 25-year study illustrates that climate change has profoundly transformed wetland habitats in Rajasthan due to elevated temperatures, reduced precipitation, increased hydrological variability, and subsequent ecological repercussions. The recorded temperature rises (1.5-1.9°C), reductions in water levels (averaging 38%), losses in waterbird populations (up to 27.0%), and alterations in vegetation confirm climate change as a significant and immediate hazard necessitating urgent adaptive measures. Key findings indicate: (1) temperature increases resulting in evaporation rate escalations of 24-38% pose a critical threat to wetland sustainability in semi-arid regions, (2) heightened precipitation variability (38.2% increase in coefficient of variation) and extreme weather events (65.2% increase) engender boom-bust hydrology that is incompatible with numerous species and ecosystem processes, (3) migratory waterbird populations have significantly declined due to delayed migration phenology and markedly reduced breeding success, reflecting climate impacts throughout annual cycles, (4) wetland vegetation communities have undergone substantial restructuring, characterised by a decline in native species and an increase in stress-tolerant invasive species, and (5) climate resilience exhibits considerable variability among wetlands, with adaptive capacity identified as the principal factor influencing vulnerability. These results have significant implications for wetland conservation policy and practice. Climate change adaptation should be integral to wetland management rather than a secondary concern. Adaptation strategies must incorporate various interventions, such as improving water management via infrastructure development and inter-wetland connectivity, restoring habitats to simultaneously address climate and non-climate stressors, enhancing institutional capacity to strengthen management effectiveness, and fostering transboundary cooperation for migratory species across flyways.

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