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# Effects of Climatic Factors on Crocodilians in North India

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***Abstract*****—** *Climatic variables — especially air temperature, precipitation patterns, and river flow regimes — are critical drivers of crocodilian biology and demography. In North India, the two primary crocodilian taxa of conservation concern are the mugger (*Crocodylus palustris*) and the gharial (*Gavialis gangeticus*). Climate-driven changes influence nesting success, incubation temperatures (and therefore sex ratios via temperature-dependent sex determination), habitat availability through altered river hydrology and flooding regimes, and physiological stress. Here we synthesize recent literature and propose a research framework to quantify climate impacts on crocodilians in North India. Key findings from the literature indicate that (1) incubation temperature strongly influences sex determination in crocodilians, (2) altered river flows and flood regimes can both create and destroy suitable nesting/foraging habitats, and (3) anthropogenic habitat disturbance combined with climatic extremes increases physiological stress and mortality risk. We provide recommendations for monitoring, habitat management, and modelling approaches to inform conservation planning under future climate scenarios.*

***Keywords*****— *Crocodylus palustris, Gavialis gangeticus, climate change, temperature-dependent sex determination, river hydrology, North India, conservation.***

## I. INTRODUCTION

Crocodilians are apex predators and ecosystem engineers in riverine and wetland systems; they also serve as indicators of aquatic ecosystem health. In India, the mugger (*C. palustris*) and gharial (*G. gangeticus*) occupy a range of riverine, lacustrine and reservoir habitats in the Gangetic plains and associated tributaries of North India. Climatic drivers (temperature, precipitation, and extreme weather events) strongly modulate the physical environment used by crocodilians, and through that influence reproductive biology, juvenile survival, foraging ecology, and population dynamics. Notably, many crocodilian species exhibit temperature-dependent sex determination (TSD), making reproductive output and future population sex ratios sensitive to changes in incubation microclimate. Changes to river flow regimes (timing, magnitude, frequency) caused by altered precipitation, glacier melt, or anthropogenic flow regulation also reshape nesting beaches and prey availability. This review synthesizes current knowledge on climate impacts on crocodilians in North India and outlines a practical framework to study and manage these effects.

## II. OBJECTIVES AND RESEARCH QUESTIONS

Primary objective: synthesize evidence and provide an implementable research plan to quantify how climatic factors affect crocodilian reproductive success, population structure, and habitat suitability in North India.

Specific research questions:

1. How do ambient and nest temperatures during incubation influence sex ratios and hatchling fitness in *C. palustris* and *G. gangeticus*?
2. What are the impacts of altered hydrology (flood frequency, dry-season flows) on nesting habitat availability and juvenile survival?
3. Does exposure to climatic extremes (heatwaves, prolonged droughts, extreme floods) increase physiological stress and mortality?
4. How will projected climate scenarios alter habitat suitability and population viability over the next 30–50 years?

## III. BACKGROUND — KEY BIOLOGICAL AND CLIMATIC MECHANISMS

### 3.1 Temperature-dependent sex determination (TSD)

Crocodilians show TSD: incubation temperature during a thermosensitive period determines hatchling sex, often with narrow pivotal temperatures producing balanced sex ratios. Small directional shifts in incubation temperatures (caused by ambient warming, changes in nest shading, or altered wet–dry cycles) can produce skewed sex ratios with long-term demographic consequences. Empirical work on *C. palustris* demonstrates clear incubation temperature ranges that produce predominantly females at lower temperatures and males at slightly higher temperatures (and complex FMF patterns in some species). Therefore, increasing mean and extreme temperatures during nesting seasons may bias sex ratios.

### 3.2 River flow, nesting beaches and habitat dynamics

Riparian and sandbar geomorphology determine availability of suitable nesting sites. Climate-driven changes in monsoon timing, intensity, or glacial melt can alter sediment deposition and floodplain dynamics. Both increased extreme floods and prolonged low flows can reduce nest success — floods may inundate nests and cause clutch loss, while low flows can reduce prey base and concentrate predators. Modelling studies for gharials indicate shifting habitat suitability under climate change, including loss of critical river stretches.

### 3.3 Physiological stress and population health

Field studies have documented elevated physiological stress markers (e.g., glucocorticoid metabolites) in muggers exposed to habitat disturbance and likely compounded by climatic stressors. Chronic stress can reduce immune function, lower reproductive output and increase mortality, particularly when climatic extremes are coupled with anthropogenic pressures.

## IV. SUGGESTED METHODS (FIELD AND ANALYTICAL)

### 4.1 Study sites & design

Select 6–10 ponds across a latitudinal and hydrological gradient in North India (include Chambal, Yamuna tributaries, habitat near Crocodile Breeding Centres).

Stratify by river regulation (free-flowing vs regulated), anthropogenic disturbance, and nesting presence.

### 4.2 Climatic and hydrological data

Obtain historical and near-real-time climatic data (air temperature, precipitation) from IMD and local weather stations. Use remote-sensing products for land surface temperature where station data are sparse.

River discharge, stage and sediment transport data from Central Water Commission (CWC) and state water agencies. For future projections, use CMIP6 downscaled climate projections under RCP/SSP scenarios.

### 4.3 Nest monitoring & microclimate

Locate and monitor nests during the breeding season. Install data loggers in a subset of nests to record nest temperature and moisture at 30–60 minute intervals through incubation. Measure nest exposure (sun/shade), substrate type, vegetation cover, and distance from waterline.

Record clutch size, hatch success, hatching date, and sex of hatchlings (molecular or morphological sexing methods recommended if sexual dimorphism is absent until maturity).

### 4.4 Physiological stress metrics

Collect non-invasive samples (faeces, shed scutes) or blood (when permitted) to measure stress hormone (corticosterone/cortisol metabolites), body condition indices, and basic hematology.

**4.5 Habitat & prey surveys**

Quantify prey abundance (fish surveys, netting/echosounder), bank substrate composition, and nesting beach geomorphology annually. Map nesting beaches using drone photogrammetry to assess size and elevation relative to flow stage.

**4.6 Analytical approach**

Use generalized linear mixed models (GLMMs) to relate hatch success and sex ratio to nest microclimate and site variables; include random effects for site/year.

Use species distribution models (MaxEnt, ensemble SDMs) to project habitat suitability under current and future climate scenarios.

Apply population viability analysis (PVA) incorporating temperature-dependent sex ratios to simulate long-term demographic consequences under climate projections.

Use change-point detection to examine shifts in river flow regimes and correlate with nesting success and recruitment.

## V. LITERATURE-BASED RESULTS (SYNTHESIS)

(This section synthesizes findings from recent studies rather than presenting new field data.)

- **TSD sensitivity**: Laboratory and captive studies demonstrate that *C. palustris* exhibits TSD with narrow temperature windows producing specific sexes; small temperature shifts may change sex ratios significantly. Documented pivotal temperatures and published experimental temperature-sex curves exist for crocodilians and muggers specifically.
- **Habitat vulnerability to altered flow regimes**: Modeling and empirical studies for gharials and muggers show that river flow alterations (timing and magnitude) reduce available nesting habitat and fragment populations. Predicted climate change impacts will likely reduce continuous stretches of suitable river habitat for gharials and may shift mugger distribution in response to new reservoir/river conditions.
- **Physiological stress linked to disturbance and extremes**: Recent field work in Indian urban and semi-urban systems recorded elevated stress markers in muggers exposed to disturbance; climatic extremes (heatwaves, drought) are expected to exacerbate stress-related health declines.
- **Conservation concern and management implications**: National and regional reports highlight climate change as an emerging threat to crocodilian conservation, with calls for adaptive management (nest protection, managed releases, habitat restoration, flow regime conservation).

## VI. DISCUSSION

The combined evidence indicates that climatic variation interacts synergistically with anthropogenic threats to shape crocodilian population trajectories in North India. TSD implies that even modest warming during nesting seasons could produce sex-biased cohorts, potentially undermining effective population replacement over decades. Hydrological changes — whether from altered monsoon patterns, increased flood frequency, or regulated discharge — can rapidly change nesting beach morphology and juvenile survival. Physiological stress resulting from habitat degradation and climatic extremes reduces resilience and likely increases mortality risk. Conservation responses need to be anticipatory, combining monitoring of nest microclimate and sex ratios with habitat protection (river flow management, sandbar/nesting beach preservation), and ex-situ measures where necessary (e.g., managed incubation to ensure balanced sex ratios). Integrating long-term climate projections into species distribution and PVA models will produce actionable scenario planning for reserves and Project Crocodile interventions.

## VII. MANAGEMENT RECOMMENDATIONS (PRACTICAL ACTIONS)

- **Nest microclimate monitoring network**: Establish standardized nest-monitoring across major river systems during breeding seasons; deploy temperature loggers in representative nests to directly measure incubation conditions.

- **Adaptive nest management**: Where monitoring shows dangerous sex biases or high nest mortality (due to flooding/heat), implement managed incubation protocols (shade structures, artificial incubation at controlled temperatures, or nest relocation) as short-term emergency interventions.
- **River flow safeguards**: Work with water authorities to maintain environmental flows during nesting and early juvenile seasons to preserve nesting beaches and prey availability; avoid sudden release regimes that inundate nests.
- **Habitat restoration & protection**: Protect key sandbar and riverbank nesting habitats from sand mining, riverbank development, and excessive tourism; use river reach zoning to reduce human disturbance during the reproductive season.
- **Long-term modelling & monitoring**: Implement SDM + PVA pipelines to forecast habitat changes and demography under SSP scenarios; update management strategies iteratively as data accrue.
- **Community-based conservation**: Engage local communities as nest guardians and citizen scientists; incorporate local knowledge to time protective measures and reduce conflict.

## VIII. LIMITATIONS AND FUTURE DIRECTIONS

- Empirical data on temperature-sex responses for wild *C. palustris* and *G. gangeticus* across North Indian climatic gradients remain sparse; targeted experimental and field studies are needed.
- Downscaling global climate model outputs to river reach scale remains challenging; hydrological modelling that couples climate, glacier/snowmelt (in headwaters), and human flow regulation is essential.
- Socioeconomic drivers (e.g., irrigation demand, dam operations, sand mining) frequently interact with climate drivers and must be included in integrated management frameworks.

## IX. CONCLUSION

Climatic factors — primarily temperature and hydrology — play central roles in shaping crocodilian reproduction, habitat suitability, and population dynamics in North India. The presence of TSD, sensitivity of nesting sites to flow regimes, and evidence of physiological stress make crocodilians vulnerable to climate change, particularly when combined with anthropogenic habitat alteration. Implementing a combined program of nest microclimate monitoring, adaptive nest management, flow protection, and predictive modelling will strengthen conservation outcomes for muggers and gharials in the region.

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