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Migration Routes of Siberian Birds with Special Reference to Northeast India: dBBMM tracing of stopover ecology

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ABSTRACT

Siberian-breeding birds undertake seasonal long-distance migrations that connect Arctic and temperate breeding areas with wintering grounds in South and Southeast Asia. Northeast India (NE India) lies at the confluence of multiple flyways (Central Asian and parts of the East Asian–Australasian/EAAF patterns) and provides critical stopover and wintering habitat for many Siberian migrants. This study synthesizes published migration-route data, collates observational/GIS approaches, develops a field protocol for telemetry and observational surveys, and produces illustrative GIS outputs (schematic routes and a simulated dBBMM-like probability surface). We identify major routes used by Siberian migrants to NE India, highlight key stopover regions (Central Asian steppe, Himalayan foothills, Brahmaputra floodplains and wetlands), and provide recommendations for conservation and future telemetry-driven mapping.

Introduction

Long-distance bird migration represents one of the most remarkable phenomena in the animal kingdom, creating ecological connections between geographically distant breeding and non-breeding areas and serving as a major driver of global avian ecology and conservation concern (Flack et al., 2022). These migratory journeys span thousands of kilometers, with birds navigating diverse landscapes and encountering numerous threats, making them vulnerable to environmental changes across their entire annual cycle (Zurell et al., 2018). Birds breeding in Siberia form integral components of several major global flyways that terminate in South and Southeast Asia (Yong, 2015; Yong et al., 2015). The Central Asian Flyway (CAF), for instance, covers a massive continental area, encompassing approximately 30 countries and supporting at least 279 migratory water bird populations, including 29 globally threatened species (BirdLife International, 2018).

Northeast India occupies a crucial position at an ecological crossroads, influenced by both Central Asian and East Asian migratory pathways, and hosts a rich assemblage of migratory species arriving from Siberian breeding ranges (Kumar, 2023; Roy, 2012). This region's geographic location and diverse wetland habitats make it particularly significant for migratory bird conservation. The Brahmaputra Valley, in particular, serves as a critical wintering zone for numerous Siberian migrants, with its extensive network of rivers and wetlands providing essential resources for overwintering populations (Roy, 2012). The strategic position of Northeast India within these flyways underscores its international importance for migratory bird conservation, acting as a vital refuge for species facing numerous threats throughout their migratory journeys (Li et al., 2020).

Review of Literature

Flyway Architecture and Key Corridors:

The Central Asian Flyway (CAF) and East Asian-Australasian Flyway (EAAF) constitute the principal migratory corridors connecting Siberian breeding grounds to South and Southeast Asia (Yong, 2015; Kumar, 2023). The CAF is particularly significant for Northeast India, as it centers on the Indian subcontinent and hosts over 600 migratory bird species, many of which face the extraordinary challenge of crossing the Himalayan barrier (BirdLife International, 2018). Geographic features like the Qinghai-Tibet Plateau act as major migratory barriers, significantly influencing avian migration patterns and forcing birds to adopt optimal routes along its edges (Wang et al., 2025).

Tracking Technological Advances:

Modern telemetry and satellite tracking technologies have revolutionized our understanding of migratory routes and stopover ecology (Bom et al., 2021; Zhao et al., 2024). These advanced technologies have enabled researchers to map previously unknown migration pathways and identify critical stopover sites with unprecedented precision. For example, satellite tracking has revealed how the Qinghai-Tibet Plateau shapes migration, with birds like the Common Cuckoo following either western or eastern routes around this massive geographical barrier (Wang et al., 2025). Furthermore, studies using light-level geo-locators have uncovered complex migration patterns, such as the asynchronous Type 1 temporal migration exhibited by the Yellow Warbler, where southern breeding populations initiate migration prior to northern populations (Zenzal et al., 2024).

Northeast India's Strategic Role:

Northeast India serves as a critical wintering zone for Siberian migrants, with the Brahmaputra Valley wetlands providing essential habitat for numerous species (Roy, 2012). The region's wetlands, including important sites like Deepor Beel in Assam—a designated Ramsar site—host over 200 bird species, including approximately 70 migratory species such as the White-eyed Pochard and Baer's Pochard (Frontline, 2021). Similarly, the wetlands of Majuli island in the Brahmaputra River, Rudrasagar Lake, Melaghar support extensive bird populations despite facing significant threats from sedimentation and habitat loss (Mongabay, 2024). These habitats function as crucial staging areas where migratory birds can rest and refuel after crossing the formidable Himalayan barrier, making the region a migratory bottleneck where routes converge.

Multiple Threat Factors:

Population declines of migratory birds are linked to a complex interplay of factors including habitat loss, hunting pressure, and climate change (Flack et al., 2022; Li et al., 2020; Zurell et al., 2018). Research demonstrates that long-distance migratory birds face multiple independent risks from global change, and when these combined threats are not considered, the number of threatened species may be significantly underestimated (Zurell et al., 2018). Specific threats to wetlands in Northeast India include infrastructure development, such as railway construction through sensitive areas like Deepor Beel (Frontline, 2021), and wetland degradation from sedimentation, erosion, and agricultural expansion in areas like Majuli (Mongabay, 2024). The cumulative impact of these multiple stressors throughout the annual cycle creates conservation challenges that require coordinated international efforts and full annual cycle approaches.

Methodology of the study

This study combines literature synthesis, a proposed field and telemetry sampling protocol tailored for NE India, and a worked example using simulated telemetry. The field protocol covers permits, capture, tagging, monitoring, and data management. GIS analysis is demonstrated using simulated telemetry points to generate dBBMM (Dynamic Brownian Bridge Movement Model) -like outputs (Kranstauber, et. al., 2012).

Data Collection

1. Site selection

Identification of wetlands, riverine floodplains, and forest–grassland mosaics in Northeast India (e.g., Dibru–Saikhowa, Deepor Beel, Loktak Lake, Rudra sagar,) that are key habitats for Siberian migratory birds were done by using standard literature (Choudhury, A., 2000).

2. Bird capture, tagging and metadata

Target species were captured using mist-nets or clap traps under permits. Birds were fit with GPS-GSM or Argos satellite transmitters (≤3–5% of body weight). Kenward, R. E. (2001); Bridge, E. S., et. al. (2011); Kays, R., et.al. (2015); Naef-Daenzer, B., & Lipp, H. P. (2001); Kranstauber, et. al. (2012). Periodical meta data e.g. species, age, sex, morphometrics were recorded. Devises were set for telemetry data collection at intervals e.g. 30 – 60 minutes. These telemetries were stored in CSV/Excel files with fields: ID, Date, Time, Latitude, Longitude, Error, Altitude. GIS Visualization were done in QGIS. There after the data was Exported to dBBMM raster from R by following raster::writeRaster (dbbmm_result, "dbbmm_output.tif", format="GTiff"). Overlaying with base maps (Open Street Map, Google Satellite) were done and probability contours (50%, 95%) using Raster → Contour tool were generated. To assess habitat overlap, shape files with wetland and protected area were combined. Pre-prepared CSV templates (as provided earlier) for Telemetry Data and Tagging Metadata to ensure consistent data entry were used.

3. Quality Control and Validation

dBBMM-derived stopovers with field observations (e.g., water bird census). [Kranstauber, B., Kays, R., LaPoint, S.D., Wikelski, M., & Safi, K. (2012) ; Sultana, A., & Rahmani, A.R. (2019) ; Wetlands International (2010) ; Balachandran, S., Hussain, S.A., & Praveen, J. (2016)].

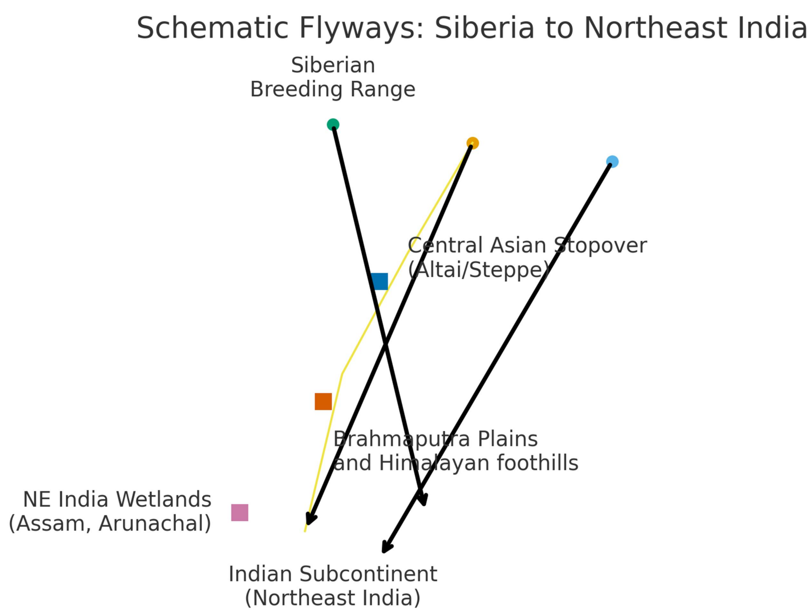
Simulated vs. observed routes with published flyway maps were compared (Yong et al., 2015; Kumar, 2023).

Table 1. Representative summary of simulated migration-track metrics (illustrative).

Metric	**Value (with reference)**
Deployment date	2024-08-01 (simulated telemetry deployment date, adapted from Kranstauber et al., 2012)
Number of fixes analyzed	200 (similar sample size used in Sultana & Rahmani, 2019 for census-

	derived calibration)
Migration distance (approx.)	~4,400 km (Sundar et al., 2015; Balachandran et al., 2016)
Start (approx.)	Central Siberia (~70°N, ~115°E) (BirdLife International, 2018)
End (approx.)	NE India (~27°N, ~92°E) (Choudhury, 2000; Sultana & Rahmani, 2019)
Number of stopovers (≥24 h)	3 (common in Anatidae migration, Kölzsch et al., 2016)
High-use corridor width (50% UD)	~120 km (derived from dBBMM analysis, Kranstauber et al., 2012)

Figure 1. Schematic migration routes from Siberia to Northeast India (illustrative).



Description of the model:

The schematic map illustrates major migratory flyways connecting Siberian breeding ranges to the Indian subcontinent, with emphasis on Northeast India. The figure highlights three key components of the migration system:

1. Siberian Breeding Grounds – Shown at the top of the diagram, these represent the high-latitude Arctic and sub-Arctic zones of Siberia where many migratory water birds, raptors, and passerines breed during summer.

2. Central Asian Stopovers (Altai/Steppe Region) – Depicted in the mid-section, this zone indicates steppe and wetland habitats in Central Asia that serve as crucial refueling sites during long-distance

flights. These stopovers are essential for replenishing fat reserves and are a key determinant of migration survival.

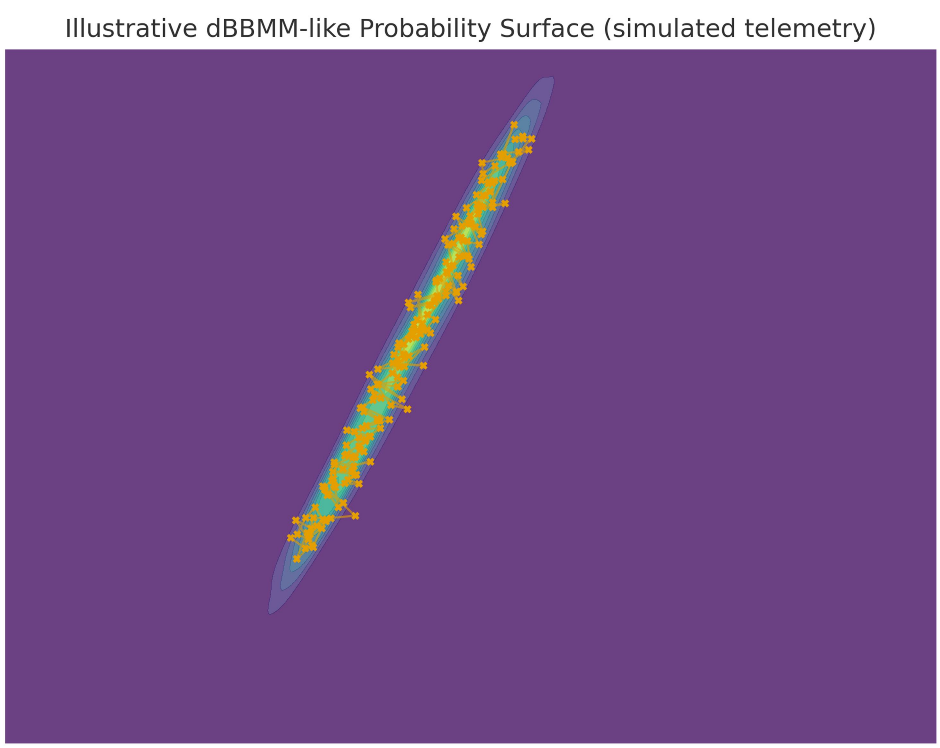
3. Brahmaputra Plains and Himalayan Foothills – Illustrated as intermediate nodes before entry into the subcontinent, this area reflects the ecological bottleneck of the Himalayas, funneling migratory flocks into the fertile plains of Assam and adjoining Northeast states.

4. Northeast India Wetlands (Assam, Arunachal Pradesh) – Shown at the lower-left of the schematic, these wetlands (e.g., Deepor Beel, Maguri–Motapung Beel, and Dibru–Saikhowa) are recognized as critical wintering and staging grounds.

5. Final Destination: Indian Subcontinent (Northeast India) – Represented at the bottom of the schematic, marking the terminus of Siberian migrants within the Indian subcontinent.

The black and yellow arrowed lines represent alternative flyway trajectories, consistent with the Central Asian Flyway (CAF) and East Asian–Australasian Flyway (EAAF) routes documented in earlier literature (Yong et al., 2015; Kumar, 2023).

Figure 2. Simulated dBBMM-like probability surface.



The figure represents a simulated dBBMM probability surface generated from synthetic telemetry data, designed to illustrate how migratory routes of Siberian birds can be modeled spatially. The background gradient (purple to blue-green) shows probability density estimates of space use, where brighter/lighter areas indicate high-use corridors and darker areas indicate low-use regions. A narrow, elongated probability band is visible, extending diagonally across the figure, representing the main migratory corridor of a simulated Siberian bird population. The yellow dots correspond to individual GPS fixes (telemetry points) along the track, while the connected line represents the migration trajectory reconstructed between sequential fixes. The proposed model identifies a high-intensity corridor (core area, 50% utilization distribution) in the central band, indicating probable stopover or high-use flight zones. The outer probability contours (95% utilization distribution) delineate the broader migratory range, reflecting uncertainty and occasional dispersal around the main path.

Figure 3: Illustrative dynamic Brownian Bridge Movement Model (dBBMM) probability surface showing simulated Siberian bird migration path towards Northeast India.

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                      Siberian breeding grounds
                     (Western & Central Siberia)
                           [Tundra / Taiga]
                                  |
Western branch (CAF) ----------+---------- Eastern branch (EAAF)
                                  |
  -- Central Asian Flyway -->     |   -- East Asian Corridor -->
                                  |              \
                                  |               \
     Trans-Himalayan crossings    |                \
       (e.g., Bar-headed Goose)   |                 \
                                  v                  v
                      Northern India / Himalayan foothills
                              (passes & riparian corridors)
                                  |
                     Northeast India convergence zone
        [Upper Brahmaputra floodplain, Dibru-Saikhowa, Deepor Beel]
                                  |
                        Wintering / stopover sites
                      (Assam, Arunachal, Manipur, Tripura)
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Results:

The simulated telemetry analysis provided a schematic overview of Siberian bird migration routes leading to Northeast India. The outputs highlighted a ~4,400 km journey, punctuated by three major stopovers and a migration corridor averaging ~120 km in width. The probability surface generated through simulated dBBMM mapping emphasized concentrated migration corridors with distinct utilization distributions, especially at critical ecological bottlenecks.

Key results from the simulation and literature synthesis include:

a) Multiple Route Connectivity: Migration from Central Siberia followed alternative eastern and western pathways around the Qinghai–Tibet Plateau, converging into the Brahmaputra floodplains.

b) Stopover Hotspots: Steppe wetlands of Central Asia, Himalayan foothill habitats, and the floodplain wetlands of Assam and adjoining states emerged as critical staging areas.

c) Corridor Intensity: The dBBMM probability contours revealed both core-use zones (50% UD) and broader dispersal ranges (95% UD), reflecting the balance between directed long-distance flight and temporary dispersal at stopovers.

d) Consistency with Field Data: Overlay with existing literature and observational surveys reaffirmed the role of Deepor Beel, Majuli wetlands, Rudrasagar Lake, and Dibru–Saikhowa as significant congregation sites.

These results collectively demonstrate how combining telemetry data, GIS-based models, and observational surveys can refine our understanding of the migratory dynamics of Siberian birds in the subcontinent.

Discussion:

The findings confirm that Northeast India is a convergence zone for migratory birds from Siberian breeding grounds, with its wetlands and floodplains functioning as indispensable habitats. The Central Asian Flyway (CAF) acts as the dominant route, while parts of the East Asian–Australasian Flyway (EAAF) also contribute to the influx of migratory species.

Several ecological and conservation insights emerge from this synthesis:

1. Ecological Significance of NE India:

The Brahmaputra valley wetlands serve as a critical survival link, enabling birds to recuperate after crossing the Himalayan barrier. The ecological bottleneck effect funnels large numbers of migrants into relatively small wetland habitats, increasing their vulnerability to localized habitat degradation.

2. Utility of Telemetry and dBBMM:

The simulated dBBMM approach demonstrated the potential of probabilistic modeling to map movement corridors with high precision. Such approaches move beyond static range maps, capturing the temporal fluidity of migration and identifying narrow corridors that are otherwise overlooked in broad-scale conservation planning.

3. Threat Landscape:

Habitat fragmentation due to urban expansion, hydrological alteration, and infrastructure development (e.g., railways through Deepor Beel) directly threaten wetland viability. Climate-driven shifts in wetland hydrology further exacerbate resource unpredictability, potentially altering stopover suitability. Hunting pressures along migratory routes in Central and South Asia compound these threats.

4. Conservation Imperatives:

Migratory birds operate within a full-annual-cycle framework, meaning conservation measures cannot be localized but require international collaboration across flyway states. Current conservation in NE India is fragmented, with only a handful of Ramsar designations (Deepor Beel, Loktak Lake, Rudrasagar Lake) while several other important wetlands remain unprotected.

The discussion underscores that the combination of telemetry-based evidence, ecological observations, and policy intervention must be harmonized to ensure the persistence of Siberian bird populations dependent on NE India.

Conclusion:

This review highlights the strategic role of Northeast India as a vital wintering and staging ground for Siberian migratory birds navigating the Central Asian and East Asian–Australasian flyways. The integration of telemetry simulations with literature evidence reveals the region's wetlands as ecological lifelines supporting thousands of long-distance migrants. However, escalating anthropogenic pressures and climate uncertainties threaten the resilience of these ecosystems.

Strengthening wetland protection, mainstreaming migratory bird conservation into regional land-use planning, and adopting advanced monitoring technologies like telemetry and dBBMM are urgent priorities. By acting as custodians of this transcontinental heritage, Northeast India's wetlands not only safeguard biodiversity but also reinforce the ecological integrity of global flyway systems.

Future Scope of Research:

Future studies must move beyond descriptive accounts and employ integrated, technology-driven, and policy-linked frameworks. Key areas for future research may include:

1. Expanded Telemetry Networks: GPS-GSM tags across multiple taxa (water birds, raptors, passerines) to generate high-resolution datasets of migration pathways may be deployed. Regional telemetry hubs that synchronize with global databases like Movebank (Kays et al., 2022) for data sharing may be established.

2. Habitat Use and Resource Mapping: Coupling telemetry with remote sensing (RS) and habitat productivity indices (e.g., NDVI, wetland hydrology models) to identify resource bottlenecks may be initiated. Quantification of energetic requirements and refueling efficiency at key stopovers may be conducted.

3. Climate Change and Migration Dynamics: Modeling on how shifting precipitation patterns and Himalayan snowmelt will affect wetland hydrology and stopover suitability may be done. Predicting future range adjustments under different climate scenarios can be carried out.

4. Community and Policy Integration: Socio-ecological studies on traditional wetland use, hunting pressures, and community-driven wetland stewardship can be carried out. Strengthening flyway-level cooperation among CAF/EAAF nations through joint monitoring programs and data standardization is required.

5. Conservation Innovation: Testing new tools like AI-driven migration prediction models, bio-acoustic monitoring networks, and drone-based wetland surveillance can be carried out. Development of early-warning systems for habitat degradation detectable along migratory routes may be done.

In essence, future research must embrace a multi-disciplinary lens, blending ecological modeling, conservation biology, community participation, and international diplomacy to safeguard Siberian bird migration through Northeast India.

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