STUDY ON WATERBIRD ASSEMBLAGES OF THE MIDDLE GANGA RIVER

Thesis submitted to the

Saurashtra University,

Rajkot (Gujarat)

For the award of the Degree of

DOCTOR OF PHILOSOPHY

IN

WILDLIFE SCIENCE

By

AFTAB

Registration No: 19192

WILDLIFE INSTITUTE OF INDIA

October 2025

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Under the Supervision of

Supervisor

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DECLARATION

I hereby declare that the thesis "**STUDY ON WATERBIRD ASSEMBLAGES OF THE MIDDLE GANGA RIVER**" is original research conducted by me under the supervision of **Dr. V. B. Mathur,** Former Director, Wildlife Institute of India, and co-supervision of **Dr. S. A. Hussain,** Former Scientist-G, Wildlife Institute of India. The thesis has been submitted to the **Saurashtra University, Rajkot (Gujarat)**, for the award of the degree of **Doctor of Philosophy in Wildlife Science** and has not formed the basis for the award of any other degree in this or any other university or institution of higher learning. It embodies my own work and observations, and in that respect, the investigation appears to advance knowledge on the subject. I further declare that the materials obtained from other sources have been duly acknowledged in the thesis.

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This is to certify that the work incorporated in the thesis **"STUDY ON WATERBIRD ASSEMBLAGES OF THE MIDDLE GANGA RIVER"** submitted by **Mr. Aftab** was carried out by the candidate under my supervision. To the best of my knowledge, the thesis is an original and independent research work submitted to the **Saurashtra University, Rajkot (Gujarat)**, for the award of the degree of **Doctor of Philosophy in Wildlife Science**.

Mr. Aftab has put in more than six terms of research work embodied in this thesis under our guidance and supervision. The work presented in this thesis has not been submitted for any degree of any other University or Institution.

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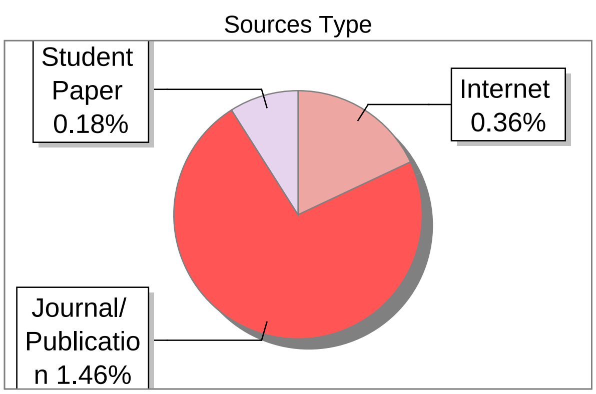

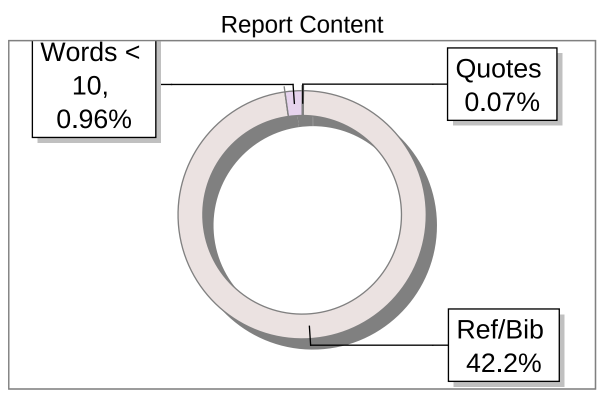

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PEER-REVIEWED JOURNALS

Usmani, A. A., Gangaiamaran, P., Mathur, V. B., Badola, R., & Hussain, S. A. (2025). An annotated checklist of aquatic avifauna in the human-dominated middle stretch of the Ganga River. Check List, 21(3), e136130. **ISSN (online): 1809-127X**

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Usmani, A. A., Gangaiamaran, P., Mathur, V. B., Badola, R., & Hussain, S. A. (2023, December 18–20). Distribution and status of storks (Family: Ciconiidae) in the Ganga River [Poster presentation]. National Conference on Water and Environment: Challenges and Opportunities for Sustainable Development (NCWE2023), Gujarat Institute of Desert Ecology, Bhuj, Gujarat, India.

Usmani, A. A., Gangaiamaran, P., Mathur, V. B., Badola, R., & Hussain, S. A. (2024, February 23–25). Status and distribution of herons (Family: Ardeidae) along the Ganga River [Poster presentation]. National Symposium on Avian Biology in Conjunction with 5th Meeting of Association of Avian Biologists in India, Graphic Era University, Dehradun, India.

Usmani, A. A., Gangaiamaran, P., Mathur, V. B., Badola, R., & Hussain, S. A. (2024, March 1). Distribution and status of species of the family Anatidae in the Ganga River [Poster presentation]. EnviroSummit 2024: International Conference on Climate Action, Ecology & Environment, Department of Environmental Studies, MIT-WPU, Pune, India.

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EXECUTIVE SUMMARY

Chapter 1

Despite occupying less than 1% of the Earth's surface and containing only 0.01% of its water, freshwater ecosystems are critical for sustaining global biodiversity, supporting approximately 10% of described species and nearly one-fourth of vertebrate diversity. The Ganga River, one of Asia's most biodiverse riverine systems, exemplifies this ecological significance, hosting a rich assemblage of aquatic species, including over 150 waterbird species, and threatened taxa such as the Gangetic River dolphin, gharial, and Indian skimmer. However, these ecosystems face severe threats from climate change, habitat degradation because of anthropogenic activities, including unsustainable development, and pollution, leading to an estimated 10,000–20,000 freshwater species being extinct or at risk of extinction globally. In India, the Ganga River is significantly impacted by the over-extraction of water from dams and barrages, industrial and sewage effluents, sand mining and riverbed agriculture, resulting in significant biodiversity loss.

Waterbirds are key indicators that reflect the health of wetland and riverine ecosystems, owing to their sensitivity to environmental changes. Their roles as pollinators, seed dispersers, predators, and nutrient cyclers emphasise their ecological importance. In the Gangetic plains, waterbirds rely on the dynamic hydrological processes of rivers and associated wetlands for feeding, breeding, and roosting. Yet, these habitats are under immense pressure from urbanisation, agriculture, and pollution, with up to 40% of India's wetlands lost over the past 50 years. The middle stretch of the Ganga River, supporting rich diversity of waterbirds and other aquatic fauna, remains understudied, with limited comprehensive data on waterbird assemblages and their responses to a range of environmental and anthropogenic factors.

This PhD thesis investigates the spatio-temporal patterns of waterbird assemblages along the middle stretch of the Ganga River, aiming to address critical knowledge gaps in their status, distribution, and ecological dependencies. The study pursues four key objectives: (1) to determine the status, distribution, and assemblage patterns of waterbirds; (2) to identify habitat features governing waterbird assemblages; (3) to assess the impacts of anthropogenic pressures; and (4) to prioritise areas for waterbird conservation. Through systematic surveys and ecological assessments, this research seeks to generate comprehensive data on waterbird diversity and evaluate the influence of habitat characteristics, such as channel depth and width, bank features, and water quality, alongside anthropogenic stressors like sand mining, solid waste dumps, pollution, and habitat fragmentation.

The thesis is structured into six chapters. Chapter 1 introduces freshwater ecosystems, the ecological significance of waterbirds, and the threats to the Ganga River. Chapter 2 describes the Ganga Basin and the study area, focusing on the middle stretch and its protected areas. Chapter 3 examines the status, distribution, and assemblage patterns of waterbirds. Chapter 4 analyses the habitat features and anthropogenic pressures shaping these assemblages. Chapter 5 identifies priority areas for conservation, and Chapter 6 synthesises the findings, offering conservation implications and recommendations.

By providing a detailed understanding of waterbird ecology and the factors influencing their assemblages, this study aims to inform science-based conservation strategies for the Ganga River. The findings will contribute to the broader goal of preserving India's freshwater biodiversity and ensuring the ecological integrity of one of its most vital riverine systems amid ongoing environmental challenges.

Chapter 2

The Ganga Basin, spanning 8,61,452 km^2 across 11 Indian states, constitutes 26.3% of India's geographical area and is the country's largest river basin. It is the world's most densely populated river basin, supporting approximately 43% of India's population, with an average density of over 700 individuals per km^2. Dominated by agricultural land (65.5%), the basin retains only 16% forest cover and 3% water bodies, reflecting significant land-use transformation. The Ganga River, India's National River, originates as the Bhagirathi from the Gangotri Glacier in the Himalayas and extends over 2,525 km through five states, supporting a rich biodiversity, including threatened species such as the Gangetic dolphin, gharial, and swamp deer. The river system, enriched by major tributaries such as the Yamuna, Ramganga, and Ghaghara, is critical for ecological and socioeconomic functions but faces pressures from anthropogenic activities.

This study focuses on the 750 km segment of the middle stretch of the Ganga River, from Balawali (Bijnor) to Sangam (Prayagraj), traversing through 17 districts in Uttar Pradesh. This stretch, part of the Gangetic Plains Biogeographic Zone, encompasses diverse hydrological and geomorphological features, including braided channels, mid-channel bars, and alluvial islands used for seasonal agriculture. Approximately 15% of this stretch lies within the Hastinapur Wildlife Sanctuary, 11% within the Upper Ganga Ramsar Site, and 3.3% within the Narora Important Bird Area, collectively supporting significant waterbird populations and other aquatic species. Key wetlands, such as the Haiderpur Wetland Ramsar Site and nearby sanctuaries, such as Shekha Lake and Lakh Bahosi, enhance the region's biodiversity by providing critical habitats and ecological connectivity.

The region's climate, driven by the southwest monsoon, results in distinct seasonal variations, with 70–80% of annual rainfall (60–160 cm) occurring between July and September. The fertile Indo-Gangetic Alluvial Plains dominate the soil profile, supporting 50% of the food grain production in India. However, river regulation through barrages at Haridwar, Bijnor, Narora, and Kanpur have altered natural flow regimes, impacting the ecological integrity of the downstream stretches and associated waterbird habitats. While these structures provide water for irrigation and drinking purposes, they disrupt seasonal flooding patterns critical for ecological processes, although reservoirs and canals also serve as surrogate habitats during droughts.

This thesis investigates the ecological dynamics of the middle stretch of the Ganga River, focusing on waterbird assemblages and their responses to habitat characteristics and anthropogenic pressures. By examining the interplay of hydrological, geomorphological, and human-induced factors, this study aims to inform conservation strategies for preserving the region's rich aquatic biodiversity and ensuring the sustainability of one of India's most vital riverine ecosystems.

Chapter 3

This study investigated the spatiotemporal patterns of waterbird assemblages along the 750 km stretch of the middle Ganga River, from Balawali (Bijnor) to Sangam (Prayagraj), to elucidate its ecological dynamics and inform conservation strategies. Freshwater ecosystems, including rivers, are critical for biodiversity but face significant threats from habitat degradation and climate change, impacting waterbird populations.

Boat-based surveys were conducted over six seasons (three pre-monsoon, April–June, and three post-monsoon, December–February) from 2017 to 2021, covering resident and migratory waterbird populations. Surveys were conducted using an inflatable boat at a speed of 6–8 km/h, with standardised timing to optimise observations. Analytical methods included rarefaction/extrapolation curves, Shapiro-Wilk tests, and diversity indices (Shannon-Weiner, Margalef's, Pielou's, Rényi) to assess species richness, diversity, and evenness. Beta diversity was partitioned using Baselga's framework to quantify turnover and nestedness, while multivariate analyses (PERMANOVA, ANOSIM, PERMDISP, NMDS) and SIMPER analysis evaluated seasonal differences in assemblage composition. Co-occurrence and nestedness patterns were analysed using R packages, including *vegan, betapart,* and *cooccur*.

This study has reported 2,34,468 waterbirds across 107 species, 25 families, and 11 orders, with an abundance ranging from 22,270 to 51,059 individuals and species richness ranging from 68 to 88 species. Charadriiformes dominated across seasons, whereas Anseriformes showed significant post-monsoon peaks. The Anatidae family was most abundant, followed by Scolopacidae and Ardeidae. The study recorded three

Vulnerable, 11 Near Threatened, and five Endangered species, with 15 protected under Schedule I of the Wild Life (Protection) Act, 1972. Species distribution varied across 15 equal 50 km stretches, with 34 species ubiquitous and seven site-specific. Beta diversity analysis indicated moderate dissimilarity ($\beta = 0.61$), driven primarily by species turnover (80.20%). Multivariate analyses confirmed significant seasonal differences (PERMANOVA: $F = 21.697$, $p < 0.05$; ANOSIM: $R = 0.334$, $p < 0.05$), with NMDS and SIMPER highlighting key species like great cormorant and ruddy shelduck as drivers of post-monsoon assemblages.

The findings underscore the middle Ganga River's ecological significance as a habitat for diverse waterbird communities, including threatened species, and its role as a critical corridor for resident and migratory populations. Seasonal variations, high turnover, and nestedness patterns highlight the dynamic nature of these assemblages, necessitating adaptive conservation strategies.

Chapter 4

This study examined the influence of habitat characteristics and anthropogenic pressures on waterbird assemblages along a 750 km stretch of the middle Ganga River, divided into 150 Basic Ecological Units (BEUs) of 5 km each. The research integrates environmental variables (e.g., channel width, flow velocity, vegetation cover) and anthropogenic variables (e.g., sand mining, riverbed agriculture, settlement proximity) to assess their roles in shaping waterbird communities. The datasets were stratified by altitudinal zones, settlement categories, and protection status to explore spatial and seasonal variations.

Waterbird abundance data, subjected to Hellinger transformation to address non-normality, were analysed using a suite of statistical methods in R, including PERMANOVA, PERMDISP, ANOSIM, SIMPER, NMDS, and beta diversity partitioning (Baselga's framework). Canonical Correspondence Analysis (CCA) was employed due to unimodal species responses (DCA gradient lengths > 4 SD), with environmental variables standardised to ensure robust ordination. Multicollinearity was minimised through Pearson correlation and Variance Inflation Factor (VIF) analyses, retaining 20 predictors.

Results revealed distinct spatial and seasonal patterns in waterbird assemblages. PERMANOVA confirmed significant assemblage differences across elevation ($F = 4.01–6.03$, $p < 0.05$), protection status ($F = 3.03–3.26$, $p < 0.05$), and settlement classes ($F = 2.02–2.18$, $p < 0.05$), though PERMDISP indicated heterogeneous dispersions in protected areas. SIMPER analysis highlighted species such as the Asian plain martin and ruddy shelduck as major contributors to assemblage dissimilarity. Beta diversity analysis showed high turnover ($\beta SIM = 70–85\%$) over nestedness, with urban areas and lower stretches exhibiting the greatest compositional heterogeneity ($\beta SOR = 0.72$ and 0.61, respectively) during pre-monsoon. CCA revealed fishing intensity, channel flow, and anthropogenic factors (e.g., built-up areas, solid waste) as primary drivers, with species like pied avocet and river lapwing showing distinct habitat preferences.

The findings highlight the middle Ganga River's role as a dynamic habitat mosaic, where environmental heterogeneity and anthropogenic pressures drive waterbird community structure. High species turnover and seasonal shifts highlight the need for adaptive conservation strategies that preserve natural flow regimes and mitigate human impacts. This study provides a critical ecological baseline for informing management practices to ensure the long-term sustainability of waterbird populations and riverine biodiversity.

Chapter 5

Conservation values were derived using three criteria: the presence of species of conservation concern (based on IUCN Red List rankings), the occurrence of island-nesting species, and the Shannon diversity index, which was normalised to a 0–1 scale and averaged to compute a composite conservation value for each BEU.

The analysis recorded 107 waterbird species, including four endangered (e.g., black-bellied tern, Indian skimmer), three vulnerable (e.g., river tern, sarus crane), 14 near-threatened (e.g., black-headed ibis, painted stork), and 75 Least Concern species, with 21.9% listed under globally threatened or near-threatened categories, underscoring the river's ecological significance. The middle stretch exhibited the highest species richness (92 species), followed by the upper (90 species) and lower stretches (88 species). Island-nesting species, such as the Indian skimmer and little tern, showed pronounced abundance in the lower stretch, whereas the river tern and river lapwing dominated the middle stretch. Shannon diversity was highest in the middle stretch (1.22 ± 0.05), followed by the upper (0.99 ± 0.08) and lower stretches (0.51 ± 0.05), with normalised values indicating moderate to high diversity (mean = 0.65).

Conservation values ranged from 0.14 to 0.86 (mean = 0.49, SD ± 0.17), revealing significant spatial heterogeneity. The upper stretch (61–87 BEU, 135 km) had the lowest mean conservation value of 0.46 (SD ± 0.14). High-value segments include BEUs 67, 69, 70, 76, and 86, covering 25 km, primarily under the Hastinapur Wildlife

Sanctuary. Low-value segments, such as BEUs 78, 80, and 81, span 15 km and are also under the Hastinapur Wildlife Sanctuary, but may face habitat degradation, possibly due to upstream pressures, despite their non-settled status.

The middle stretch (88–132 BEU) showed the lowest mean value of 0.24 (SD ± 0.06), with low-value segments, including BEU 119, BEU 111, and BEU 128–129, covering a total of 95 km area, primarily characterised as unprotected with non-settled or rural settlements, indicating potential habitat limitations or disturbances. The lower stretch (133–210 BEU) had the highest mean conservation value of 0.68 (SD ± 0.12). High-priority segments (30 BEUs) such as BEU 196, 165, 169, and 194. These segments are mostly unprotected with unsettled, rural, or urban settlements.

The findings highlight the lower stretch as a conservation priority because of its high ecological value and unprotected status, necessitating formal protection measures. The middle stretch requires urgent restoration to address low conservation values driven by anthropogenic impacts, particularly in unprotected and Upper Ganga Ramsar Site zones. The upper stretch benefits from existing protection but requires enhanced management to mitigate habitat degradation. Non-settled areas, especially in the lower stretch, are critical conservation strongholds, whereas rural and urban segments require targeted mitigation of agricultural and urban impacts. This spatially explicit analysis provides a robust framework for prioritising conservation actions, emphasising habitat restoration, connectivity, and protection to sustain waterbird biodiversity in the Gangetic floodplains.

Chapter 6

This study elucidated the conservation implications for waterbird assemblages along a 750 km stretch of the middle Ganga River. It highlights the critical threats and management priorities to ensure their long-term sustainability. The primary threats identified include habitat loss and fragmentation driven by riverbed agriculture, sand mining, water abstraction, and infrastructure development, such as embankments and barrages, which disrupt natural hydrological regimes and diminish habitat quality. These pressures have led to reduced landscape-scale habitat availability, declines in waterbird diversity and abundance, and disruptions to food webs, with multivariate analyses indicating that anthropogenic factors account for nearly half of the variation in community composition.

The river supports a diverse waterbird assemblage, including a significant proportion of migratory species, underscoring its role as a vital stopover and wintering ground within global flyways. High species turnover and pronounced seasonal variations, with Charadriiformes dominant across seasons and Anseriformes peaking post-monsoon, necessitate adaptive, season-specific management strategies to maintain varied microhabitats, such as mudflats and deeper river channels.

Conservation priorities include establishing or expanding protected areas, particularly in the biodiversity-rich lower stretch, and enhancing existing sanctuaries, such as the Hastinapur Wildlife Sanctuary. Mitigating anthropogenic pressures, such as regulating fishing, sand mining, and water abstraction, requires community-based approaches and the promotion of water-efficient agricultural practices. Continuous monitoring, leveraging standardised protocols, remote sensing, and citizen science, is essential to track temporal trends and assess conservation effectiveness.

This study advocates for the integration of river restoration into regional land use and water management frameworks, strengthening legal protections, and fostering cross-sectoral coordination. By combining functional diversity metrics, multivariate analyses, and spatial prioritisation, this research provides a robust, evidence-based framework for conserving waterbird populations and sustaining the ecological integrity of the middle Ganga River's wetland ecosystems amidst ongoing socioeconomic and environmental challenges.

CHAPTER 1
INTRODUCTION

1.1 Freshwater Ecosystems

Water is regarded as the most crucial natural resource for sustaining life on Earth; however, freshwater systems face significant risks due to anthropogenic activities (Meybeck, 2003; Vörösmarty et al., 2005). Although water covers a large portion of the planet, only approximately 2.5% of it is freshwater, with the vast majority being saline and found in oceans. Of this limited freshwater supply, an even smaller fraction is accessible for human use, making its conservation critically important (Shiklomanov, 1993). Freshwater ecosystems support 10% of the described species and nearly one-fourth of the vertebrate diversity over less than 1% of the Earth's surface, containing 0.01% of the world's total water (Dudgeon et al., 2006; Molur et al., 2011; Naiman et al., 1993; Revenga & Kura, 2003; Strayer & Dudgeon, 2010). They offer valuable natural resources for economic, cultural, aesthetic, scientific, and educational benefits (Dudgeon, Arthington, et al., 2006).

Freshwater biodiversity is globally threatened (Dudgeon, 2020; Spiller et al., 2025; Vörösmarty et al., 2010), attributed mainly to anthropogenic stressors and climate change (Alava, 2022; Dudgeon et al., 2006; Woodward et al., 2010). Accelerated glacier melting due to climate change (Battin et al., 2024; Oerlemans, 2005) leads to reduced glacial meltwater contributing to rivers (Barnett et al., 2005; Milner et al., 2009; Muhlfeld et al, 2020), which ultimately affects riverine biodiversity (Brown, 2007; Milner et al, 2017). Declines in regional species richness are a key concern, as they indicate the risk of extinction (Jacobson et al., 2012; Saboret et al, 2024).

Aquatic ecosystems are considerably modified by extensive land cover changes, urbanisation, industrialisation, and developmental projects such as dams, barrages, reservoirs, and other irrigation systems. These transformations have enhanced human access to water, although at the cost of unsustainable modifications to the natural dynamics of water systems (FCGWSP, 2004; Meybeck, 2003). The unsustainable utilisation of water resources for economic productivity invariably compromises ecosystems and biodiversity, resulting in unevaluated but significant costs (Albert et al., 2021; Vörösmarty et al., 2005). Around 65% of the global river discharge and aquatic ecosystems it supports face moderate to severe threats (Vörösmarty et al., 2010). Estimates suggest that around 10,000 to 20,000 freshwater species are either extinct or currently facing the risk of extinction (IUCN, 2024; Strayer & Dudgeon, 2010).

1.1.1 Rivers

Freshwater ecosystems, although covering only a small fraction of the Earth's surface, support a disproportionately high level of biodiversity and provide critical ecosystem services (Cooke et al., 2024; Reid et al., 2019). These ecosystems include rivers, lakes, wetlands, streams, springs, and groundwater systems, each playing a unique role in sustaining ecological and human communities. Among these, rivers are dynamic, flowing habitats that serve as lifelines across landscapes, connecting terrestrial and aquatic systems. They are intricate ecosystems on Earth, with their ecological features changing over time and from the source to the downstream areas they traverse (Chakraborty, 2021). Riparian zones are integral components of freshwater ecosystems, serving as transitional zones between aquatic and terrestrial environments and facilitating the exchange of matter and energy (Nakano & Murakami, 2001; Ward, 1998; Woodward & Hildrew, 2002). River ecosystems provide an array of resources that not only promote species richness but also attract human settlement and support economic development (Boggie et al., 2018; Capon, 2020). Despite their importance, rivers and their freshwater habitats are among the most endangered ecosystems globally (Albert et al., 2020; Dudgeon et al., 2006; Revenga & Kura, 2003). The extinction rate of freshwater fauna is projected to be five times higher than that of terrestrial species in certain areas (He et al, 2018; Ricciardi and Rasmussen, 1999).

Moreover, in densely populated floodplains across South Asia, the biodiversity and ecosystem services of rivers are under severe threat owing to a wide range of pressures (Arthington et al., 2004; Meynell et al, 2021; Tockner & Stanford, 2002). Flow alterations from dams and barrages, habitat degradation from the dumping of solid waste, industrial and domestic effluents, riverbed agriculture, boat traffic, intentional and incidental killing of aquatic species, overexploitation of freshwater resources, and exploitative fishing techniques all contribute to the decline of these vital ecosystems (Braulik et al, 2014; Dudgeon, 2000; Gergel et al., 2002; Manel et al., 2000; Oberdorff, 2022). However, this rich biodiversity faces mounting anthropogenic pressures, with approximately 30% of freshwater fauna assessed as threatened according to the IUCN criteria (Dahanukar et al. 2016; He et al, 2020; Molur et al. 2011).

1.1.2 Birds

Birds are excellent bioindicators and suitable models for studying various environmental issues (Newton, 1995). Monitoring bird assemblages is a useful indicator for assessing the general health of ecosystems (Furness & Greenwood, 1993a). Understanding the spatiotemporal patterns of bird species is crucial for understanding population dynamics and ensuring the effective conservation of species and their habitats (Hamid, 2009). Birds provide a wide range of ecosystem services (Wenny et al., 2011; Green & Elmberg, 2014). They are considered ecosystem engineers and bioindicators because of their roles as pollinators, seed dispersers, scavengers, and predators. They help maintain ecosystem stability in different ways, ranging from nutrient cycling to stimulating primary productivity (Whelan et al. 2015). Owing to their high mobility, birds swiftly respond to changes in the quality and conditions of their habitats (Morrison, 1986).

India is one of the mega-biodiverse countries (Gadgil & Rao, 1998), with four global biodiversity hotspots and seven endemic bird areas (Grimmett et al., 1998). It supports 12% (1,224 species) of the world's avian species, of which 141 are endemic to the Indian subcontinent (Grimmett et al., 1998) and 50 species are endemic to India (Dasgupta et al., 2002).

1.1.3 Waterbirds

The term 'waterbird' is considered a synonym for 'waterfowl,' and the Ramsar Convention broadly defines them as species of birds that are "ecologically dependent upon wetland" (Wetland International, 2012; Kumar et al., 2005). However, in the second edition of the Waterfowl population estimate in 1997, the waterfowl were defined more precisely as all species of the families Gaviidae, Podicipedidae, Pelecanidae, Phalacrocoracidae, Anhingidae, Ardeidae, Balaenicipitidae, Scopidae, Ciconiidae, Threskiornithidae, Phoenicopteridae, Anhimidae, Anatidae, Pedionomidae, Gruidae, Aramidae, Rallidae, Heliornithidae, Eurypygidae, Jacanidae, Rostratulidae, Dromadidae, Haematopodidae, Ibidorhynchidae, Recurvirostridae, Burhinidae, Glareolidae, Charadriidae, Scolopacidae, Thinocoridae, Laridae, Sternidae, and Rynchopidae (Wetlands International, 1997). While this strict taxonomic clarification aimed to standardise monitoring and reporting, it inadvertently led to the exclusion of certain waterbird species that utilise wetlands and the inclusion of a few species not strictly dependent on wetland habitats. Later, in the fifth edition of the Waterbird Population Estimates, the term 'waterbird' again implied a broader meaning than the strict definition of 'waterfowl' given in the second edition of the Waterbird Population Estimates (Wetlands International, 2012).

Therefore, in this study, I used the term "waterbird" for the other wetland-dependent species that were not included in the list of species and families as defined in the second edition of the Waterfowl population estimate in 1997, along with the Ramsar definition of waterbird (Wetlands International, 2012; Kumar et al., 2005).

Most wetlands designated as Ramsar sites are recognised worldwide based on criteria emphasising their significance for waterbird conservation (Green et al., 2016; Ramsar, 2024). Waterbirds sometimes act as a good indicator of the general ecological status of the wetland ecosystem. For example, changes in the abundance of ducks and coots may indicate changes in the submerged macrophyte (Wicker & Endres, 1995), and the abundance of the crested coot (*Fulica cristata*) may indicate a high diversity of aquatic plants (Green et al., 2002).

Waterbirds play a crucial role in the health and functioning of wetland ecosystems. They are important for wetlands in various ways, including the maintenance of the nutrient cycle, pest control through selective feeding on different insect pests, seed dispersal, especially for aquatic plants, cultural and economic value by attracting tourism, and serving as bioindicators (Green et al., 2016).

1.1.4 Rivers as a Habitat for Waterbirds

River ecosystems and their complex hydrological processes provide crucial resources for feeding, breeding, and roosting of waterbirds (Kingsford et al., 2010). Waterbirds play crucial roles in aquatic ecosystems as predators, herbivores, and vectors of seeds, invertebrates, and nutrients (Green and Elmberg, 2014). Their responses to hydrological variations are complex but predictable, with different foraging guilds showing distinct temporal patterns in abundance after flood events (Cumming et al., 2012). These patterns exhibit the exploitation of resource-rich patches during periods of high food availability (Cumming et al., 2012). The resilience of waterbird communities as part of the river ecosystem is governed by their ability to persist amid hydrological and geomorphological variation (Van Looy et al., 2019). However, river regulation and other anthropogenic impacts have endangered waterbird populations by reducing habitat availability and creating resource bottlenecks (Kingsford et al., 2010). The middle reaches of major river systems, such as the Ganga, serve as critical ecological corridors, supporting distinctive assemblages of resident and migratory waterbirds that utilise the diverse microhabitats created by the river's dynamic hydrology (Mohapatra et al. 2021; Sinha et al. 2019).

1.1.5 General Overview

India constitutes approximately 2.5% of the Earth's surface area, yet it is a megadiverse country, harbouring around 7-8% of the global biodiversity (Sengupta & Dayanandan, 2022; Singh et al., 2021). The diverse geography of India, extending from the Himalayas in the north to the Western Ghats in the south, has contributed to a wide range of ecosystems and biodiversity (Rodgers & Panwar 1988). The forests and wetlands of India represent important ecosystems that are crucial for biodiversity conservation. A total of 103,258 species of fauna and 55,048 species of flora have been documented in the country, with 12,095 species of plants and 28,948 species of animals identified as endemic (SSD-NSO, 2022).

The extensive freshwater ecosystems of India, comprising approximately 7,500 km of major rivers, 1.5 million hectares of reservoirs, and numerous wetlands, harbour exceptional aquatic biodiversity (Gopal & Zutshi 1998). These freshwater systems support approximately 9.7% of the global freshwater fish diversity, comprising over 2,500 fish species, of which 937 inhabit freshwater habitats, and about 40% are endemic to the Indian subcontinent (Lakra et al., 2010; Molur et al., 2011). The Ganga River basin alone hosts more than 265 fish species, including the endangered golden mahseer (*Tor putitora*), representing a remarkable ichthyofaunal diversity (Sarkar et al. 2012). In addition to fish, Indian freshwater ecosystems support diverse assemblages of aquatic invertebrates, amphibians, reptiles, waterbirds, and mammals. These aquatic habitats harbour more than 300 species of waterbirds (Kumar et al. 2005; Rahmani et al. 2016).

The Ganga River ecosystem supports a remarkable assemblage of higher aquatic vertebrates, representing one of the most biodiverse riverine systems in Asia (Behera et al., 2018). The river provides critical habitat for several threatened taxa, including the smooth-coated otter (*Lutrogale perspicillata*), Gangetic river dolphin (*Platanista gangetica*), Indian skimmer (*Rynchops albicollis*), black-bellied tern (*Sterna acuticauda*), Sarus crane (*Grus antigone*), gharial (*Gavialis gangeticus*), mugger (*Crocodylus palustris*), Indian narrow-headed softshell turtle (*Chitra indica*), and red-crowned roofed turtle (*Batagur kachuga*) (Bilgrami, 1991; Das et al., 2022; Hussain, 2002; Nawab & Hussain, 2012; Rao, 2001; Rodgers & Panwar, 1988; WII-GACMC, 2018). In addition, the floodplain wetlands and adjacent grasslands support the vulnerable swamp deer (*Rucervus duvaucelii*), as well as over a hundred species of waterbirds that depend on the dynamic habitats of the Ganga Basin (Mohapatra et al., 2021; Paul et al., 2018; Qureshi et al., 2018).

1.2 Review of Literature

1.2.1 Evolutionary and Ecological Significance of Birds

The evolutionary history and global distribution of birds have been studied extensively. According to Ali (2002), Newton (2007), and Sekercioglu (2006), birds exhibit remarkable adaptability, ecological significance, an incredible evolutionary history, and the capacity to flourish in extreme environmental conditions. Furness et al. (1993b) asserted that birds occupy almost all types of habitats, and their diversity generally acts as a good indicator of the overall health of the habitat.

India harbours 13.6% of the world's avifauna, with roughly 1263 recorded species (Praveen et al., 2016). India ranked 9th in the world in terms of the number of bird species (Lepage, 2016). The diverse wetland ecosystems of India, including rivers, support a rich diversity of waterbirds, with over 240 species recorded across important regions such as the Western Ghats, Chilika Lagoon, Sundarbans, and Gangetic Plains (Balachandran et al., 2020).

1.2.2 Birds as Bioindicators

Birds are known to be highly sensitive to changes in their surrounding conditions; hence, they can be used as bioindicators (Amat & Green, 2010; Mekonen, 2017; Padoa-Schioppa et al., 2006). Allinson (2023) estimated that approximately one in eight bird species worldwide is at risk of extinction, with many formerly common species disappearing rapidly. This alarming decline highlights the urgent need for conservation efforts to prevent imminent mass avian extinction.

According to Egwumah et al. (2017), bird population characteristics, including presence, abundance, density, mortality rate, and breeding success, can reveal ecosystem conditions. The crucial ecosystem services that birds offer, including pollination, scavenging, pest control, seed dispersal, and nutrient cycling, were emphasised by Conete (2022) and Mariyappan et al. (2023). These roles are crucial for maintaining ecological stability and promoting human well-being. However, Mariyappan et al. (2023) emphasised that the global decline in bird populations poses a significant threat to these crucial ecosystem services.

Gregory and Van Strien (2010) and Mekonen (2017) described birds as excellent bioindicators because of their sensitivity to anthropogenic influences and widespread presence. Burger and Gochfeld (2004) and Egwumah et al. (2017) studied the effectiveness of birds as bioindicators because of their position in the food chain, abundance, longevity, and ease of observation.

1.2.3 Waterbirds as Indicators and Ecosystem Contributors

Kingsford (1999) emphasises the significance of waterbirds as indicators of river and floodplain health, reflecting ecological conditions and biodiversity, while their abundance and diversity can inform effective wetland and river management strategies. Waterbirds enhance ecological functionality through various activities, including foraging and reproduction. Waterbirds are vital to wetland habitats, enhancing biodiversity and ecological functionality (Qiu et al., 2024).

Almeida et al. highlighted the importance of waterbirds as bioindicators of aquatic ecosystem health, indicating water quality, habitat structure, and food web dynamics. (2017), Bino et al. (2015), Custer and Osborn (1977), Green and Elmberg (2014), Hagy et al. (2017), and Nie et al. (2022). According to Williamson et al. (2013), waterbirds serve as ecosystem sentinels, indicating wetland health and providing measures of water quality, chemical contamination, and prey availability, thus playing a crucial role in maintaining riverine and wetland ecosystems.

Green and Elmberg (2014) and Qiu et al. (2024) highlighted the significance of waterbirds in maintaining environmental stability, inhibiting the proliferation of aquatic plants, regulating plant biomass, and enhancing biodiversity by promoting varied habitats. Amat and Green (2010), Brandis et al. (2021), Ullah et al. (2024), and Weller (1995) found that waterbirds contribute to ecosystem health by controlling insect populations, facilitating nutrient cycling, and serving as indicators of wetland and river habitat quality, thus supporting biodiversity and conservation efforts. Furthermore, Green and Elmberg (2014), Hahn et al. (2008), and Marklund et al. (2002) found that waterbirds' feeding behaviour enhances nutrient distribution and regulates plant populations in ecosystems. Hahn et al. (2008) found that waterbirds significantly contribute to nutrient cycling, particularly through guano deposition, which enhances plant growth and soil enrichment in the riparian zones. Figuerola and Green (2002) showed that grazing waterbirds not only regulate plants but also facilitate their spread in aquatic habitats, promoting colonisation and maintaining genetic connectivity among plant populations.

1.2.4 Challenges in Indian Riverine and Wetland Ecosystems

The riverine biodiversity of India is under immense pressure owing to the over-extraction of water, discharge of industrial and sewage effluents, construction of barrages and dams, and habitat fragmentation. The Ganga River has experienced significant pollution, habitat destruction, and biodiversity loss, making it one of the most endangered rivers in the world (Vass et al., 2010). The biodiversity of Indian rivers is continuously declining owing to unsustainable development, sand mining, and illegal fishing, resulting in the population decline of numerous aquatic species, such as the gharial (*Gavialis gangeticus*) and the Ganges shark (*Glyphis gangeticus*), which remain critically endangered (Das et al., 2022; Haque & Das, 2019; WII-GACMC, 2018).

The Indian waterbird population is threatened by habitat loss due to sand mining, industrial development, water pollution, and agricultural encroachment (Mishra et al., 2024; Ray et al., 2020; WII-GACMC, 2018). Wetlands in India, which support large congregations of waterbirds, are facing rapid degradation, with up to 40% of wetlands lost in the past 50 years (Adhurya et al., 2019; Foote et al., 1996). Additionally, climate change is altering the migratory patterns of many species, with birds arriving earlier or later than usual, which can disrupt the delicate balance of ecosystem interactions (Seebacher & Post 2015; Travers et al. 2015). Praveen et al. (2014) and SANDRP (2022) provided inclusive reports on the pan-Indian distribution of waterbirds in inland waters and the possible reasons for the degradation of their roosting grounds.

The Gangetic Plains are crucial for waterbird conservation and support diverse waterbird assemblages, including threatened species such as the Indian Skimmer (*Rynchops albicollis*) and Black-bellied Tern (*Sterna acuticauda*), despite facing significant threats (Singh & Sharma, 2018; Sundar, 2004). Loss and degradation of wetlands, driven by urbanisation, agriculture, and unsustainable infrastructure development, have led to significant declines in waterbird populations worldwide (Davidson, 2014; Gardner & Finlayson, 2018); for example, the degradation of Mediterranean and African wetlands possibly leads to the population decline of waterbirds such as the Eurasian Spoonbill (*Platalea leucorodia*) and the Greater Flamingo (*Phoenicopterus roseus*). Such alarming trends highlight the necessity for dedicated conservation efforts to mitigate the decline of global waterbird diversity and their habitat loss (Qiu et al., 2024). Moreover, to ensure the conservation of waterbirds and their habitats, strategies should integrate biodiversity-ecosystem functioning links and emphasise habitat protection (Qiu et al., 2024).

1.2.5 Conservation Efforts and Future Directions

Aiming to reduce the pollution load in the Ganga River, the Government of India launched the Ganga Action Plan (GAP) in 1986, which achieved limited success but laid the groundwork for future initiatives. More recently, an integrated conservation mission, Namami Gange, was launched by the Government of India in 2014 to accomplish the twin objectives of effective abatement of pollution and conservation and rejuvenation of the National River Ganga. This program aims to restore viable populations of all endemic and endangered aquatic species so that they can recolonise their full historical range and fulfil their role in maintaining the integrity of the Ganga River ecosystems (Das & Tamminga, 2012; Mathur, 2020; NMCG, 2025).

The history and status of wetland and river biodiversity conservation reflect global and national efforts to protect these vital ecosystems. India has made significant progress in conserving biodiversity, rivers, and wetland habitats. However, challenges such as pollution, habitat destruction, and unsustainable development persist. Efforts to meet sustainable resource demands while preserving the ecological balance are crucial to the future of wetland and river biodiversity in India.

1.2.6 Waterbird Studies in the Ganga River Basin and Related Areas

Saini et al. (2017) studied waterbird species in Haridwar, with significant diversity in natural wetlands compared to manmade wetlands, emphasising the importance of habitat conservation for these waterbirds. Khan et al. (2013) recorded 117 bird species at the Hastinapur Wildlife Sanctuary, with river habitats such as the Ganga and Boodhi Ganga being preferred by birds. However, agricultural pressures have led to the avoidance of areas such as Khola by waterbirds.

Ankit et al. (2024), Arya et al. (2020), Bashir et al. (2012), Joshi et al. (2021), and Rao (2001) studied avian assemblages in the middle stretch of the Ganga River. Most of these avifaunal studies conducted in the middle stretch of the Ganga River were limited to the State Wildlife Barasingha Sanctuary (formerly known as Hastinapur Wildlife Sanctuary), Haiderpur Wetland Ramsar Site, and Upper Ganga River Ramsar Site (Arya et al., 2020; Bashir et al., 2012; Joshi et al., 2021; Khan et al., 2013; Rao, 2001), and so there is a lack of a comprehensive assessment of the status of the waterbirds in the middle stretch of the Ganga River.

Jha and McKinley (2015), Kumar and Kanaujia (2017), and Sundar (2006, 2011) studied waterbirds from the agricultural landscapes in Uttar Pradesh and highlighted the importance of human-modified habitats for waterbird conservation. Akram and Ilyas (2021) observed waterbirds in the wetlands of Aligarh District in Uttar Pradesh, with notable temporal patterns in species richness, highlighting the significance of these wetlands for waterbird conservation in the Gangetic plains. Several studies on waterbirds have been conducted in several important wetlands along the middle stretch of the Ganga River, including Sachan & Yadav (2018) in the Lakh Bahosi Bird Sanctuary, Kumar & Srivastava (2013) in the Sandi Bird Sanctuary, Abbasi & Khan (2023) in the Shekha Lake Bird Sanctuary, Hilaluddin et al. (2003) in the Amroha District, Kanaujia et al. (2015) in the Lucknow District, Joshi et al. (2024) in the Saman Wildlife Sanctuary, Kumar et al. (2015) in the Nawabganj Bird Sanctuary, and Kumar & Kanaujia (2015) in the Samaspur Bird Sanctuary.

Rehman et al. (2021) and Sharma et al. (2022) studied waterbirds from the Yamuna River floodplains and observed significant seasonal variations in assemblage patterns and abundance, emphasising the role of floodplains as a crucial waterbird habitat amidst a large urban landscape. Ansari and Nawab (2015), Gupta et al. (2012), Manral and Khudsar (2013), Singh et al. (2021), and Sundar et al. (2015) studied the role of urbanisation and agriculture on waterbirds and their habitat use in the wetlands amidst the urban settings of Delhi and its surrounding National Capital Region.

1.2.7 Factors Influencing Waterbird Assemblages

Waterbird assemblages are vital components of wetland ecosystems, indicating ecological integrity and good environmental health (Qiu et al., 2024). Wetland habitats are essential for sustaining waterbird diversity, and species richness is strongly associated with wetland size (Pearson et al., 2024). Environmental variables, including water depth, nutrient availability, and seasonal fluctuations, affect the waterbird assemblages (Josens et al., 2009; Pearson et al., 2024).

Almeida et al. (2017), Brandolin and Blendinger (2016), Cintra (2015, 2019), Constantin et al. (2019), Farinós-Celdrán et al. (2017), Sebastián-González and Green (2014), Tak et al. (2010), and Ullah et al. (2024) confirmed that waterbird diversity and abundance are significantly influenced by physical habitat characteristics, including wetland size, shape, depth, isolation, shoreline complexity, and distance to shore.

Brandolin and Blendinger (2016), Che et al. (2019), Cintra (2015), Constantin et al. (2019), Farinós-Celdrán et al. (2017), Froneman et al. (2001), Sebastián-González and Green (2014), and Sonal et al. (2010) demonstrated that waterbird assemblage patterns are directly linked to vegetation structure, food availability, and trophic relationships, with emergent vegetation providing critical shelter, feeding, and nesting zones.

Che et al. (2019), Cintra (2015, 2019), Constantin et al. (2019), de Arruda Almeida et al. (2017), Sebastián-González and Green (2014), Ullah et al. (2024), and Wen et al.

(2016) demonstrated that waterbird assemblages are significantly shaped by hydrological cycles, wetland connectivity, richness of regional wetlands, and seasonal variations in water levels, creating dynamic habitat conditions that influence species distribution and abundance.

Brandolin and Blendinger (2016), Che et al. (2019), Cintra (2015), Froneman et al. (2001), Sebastián-González and Green (2014), Sonal et al. (2010), Ullah et al. (2024), and Wen et al. (2016) found that waterbird assemblages are strongly correlated with water quality parameters, including salinity, dissolved oxygen, temperature, alkalinity, and water transparency, with different species demonstrating distinct preferences across these gradients.

Recently, the foremost focus of avian ecology has been the investigation of habitat selection and habitat quality because they strongly influence avian distribution, abundance, and community structure. However, individuals use specific habitat cues that may fall into different vegetation community types (Wilson et al., 1998). Liordos and Kontsiotis (2020) designated wetlands as important critical breeding, foraging, and wintering grounds for various avian species. Freshwater wetlands harbour more than 40% of the bird species of the entire world and 12% of all animal species (Zakaria et al., 2009). Das and Saikia (2011) and Ramírez-Albores et al. (2014) found that the diversity of wintering waterbirds in a community is closely related to the structure of the vegetation, physical attributes of the habitat, foraging resources, and resting conditions.

1.2.8 Identification of Conservation Priority Areas

Identifying priority conservation areas for waterbirds in river systems and coastal wetlands is crucial for effective biodiversity protection (Bino et al., 2015; Xia et al., 2020). Bhatt et al. (2016) identified key conservation priority areas for freshwater fish in India, particularly the Sahyadri, Brahmaputra, Cauvery, and Ganga River basins, highlighting the need for immediate conservation and restoration efforts in these ecologically significant regions. Nel et al. (2012) used GIS data and stakeholder-developed criteria to describe a systematic conservation planning approach to identify priority rivers and wetlands, incorporating longitudinal and lateral connectivity, which can be applied to species conservation efforts in India. Pearson et al. (2022) suggested a whole-of-river conservation approach based on conservation ratings for river stretches based on habitat, biodiversity, and connectivity values. This approach can guide strategies related to conservation prioritisation. Das et al. (2022 & 2024) suggested priority areas for systematic conservation planning of the Gangetic dolphin in the mainstem Ganga River and its major tributaries.

Conservation efforts should focus on protecting diverse wetland habitats, as the extent and complexity of wetland mosaics can buffer the impacts on waterbirds (Pearson et al., 2024). Additionally, understanding waterbird ecology has significantly contributed to wetland conservation management, emphasising the importance of a landscape perspective in conservation programs (Guadagnin et al., 2005; Kingsford & Norman, 2002). Holistic management approaches are crucial for the long-term conservation of waterbird habitats (Pearson et al., 2024), and incorporating biodiversity-ecosystem functioning relationships is essential for addressing global waterbird diversity loss and ecosystem degradation (Qiu et al., 2024). Additionally, to ensure the conservation of waterbirds and their habitats, strategies should incorporate biodiversity-ecosystem functioning relationships and prioritise habitat protection (Qiu et al., 2024).

1.3 Rationale of the study

Waterbirds are widely recognised as effective indicators for conservation research and action, particularly in the context of widespread wetland degradation and increasing global concerns regarding biodiversity conservation. Individual waterbird species exhibit varied responses to habitat changes and human disturbance, allowing for a more comprehensive and nuanced assessment of environmental pressures on wetland ecosystems. Understanding the patterns of habitat utilisation by different species is fundamental to species biology and, consequently, critical for devising effective management and conservation strategies.

Rivers and associated wetlands in the Gangetic plains play a vital role in maintaining regional biodiversity, serving as staging grounds and wintering habitats for a wide range of migratory bird species and nesting grounds for several island-nesting waterbirds. Despite this ecological significance, limited research has focused on the avifaunal diversity in the middle stretch of the Ganga River. Existing studies have primarily concentrated on isolated segments, such as the Hastinapur Wildlife Sanctuary in the upper part of the study area, with only a few efforts dedicated to conducting systematic waterbird surveys. Previous research in the study area has generally been limited to smaller river stretches or adjacent riparian zones. Consequently, baseline data at the riverscape scale remain scarce or altogether lacking.

Although ecological assessments of wetlands have been widely conducted across different geographic regions, and many studies have emerged from various Indian states (Fentaw et al., 2022; Garg, 2015), a significant research deficit remains, specifically in the middle stretch of the Ganga River. In particular, there is a lack of integrated ecological assessments relating bird communities to habitat structures and anthropogenic pressures. This gap hinders the development of informed conservation and management interventions.

The present study seeks to investigate the spatio-temporal variations in the assemblage patterns of waterbirds along the middle stretch of the Ganga River. To address these knowledge gaps, it is necessary to generate systematic data on the status and distribution of waterbirds across the Middle Ganga River and evaluate the environmental and anthropogenic factors influencing their assemblages.

Accordingly, this study aimed to generate comprehensive and integrated information on waterbird assemblages and their relationships with ecological and anthropogenic parameters. This will not only enhance our understanding of the structure and functioning of riverine ecosystems in the Middle Ganga River but also contribute to science-based conservation planning in one of India's most ecologically and socioeconomically significant river systems.

1.4 Objectives of the research

In line with the stated aim of this study, the following specific objectives were formulated.

1. To determine the status, distribution, and assemblage patterns of waterbirds.
2. To determine the habitat features governing the waterbird assemblages.
3. To investigate the effects of anthropogenic pressures on waterbird assemblages.
4. To determine the areas to be prioritised for the conservation of waterbirds.

1.5 Research questions

This study aimed to address the following research questions.

1. What is the status, distribution, and assemblage pattern of waterbirds in the middle Ganga River?
2. What habitat features are associated with species assemblages?
3. To what extent are anthropogenic pressures affecting the waterbird assemblages?
4. Which areas need to be prioritised for the conservation of water birds?

1.6 Organisation of the Thesis

This thesis has been organised into six chapters.

Chapter 1 introduces waterbirds, the freshwater biodiversity of the Ganga River, and a review of the literature.

Chapter 2 provides an overview of the Ganga Basin, the Ganga River, the middle stretch of the Ganga River, the study area, and the protected areas falling within its limits.

Chapter 3 deals with the status, distribution, and assemblage patterns of waterbirds.

Chapter 4 highlights the habitat features and anthropogenic pressure governing waterbird assemblages.

Chapter 5 deals with the identification of the priority areas for conservation of waterbirds.

Chapter 6 describes the synthesis and conservation implications of the study.

CHAPTER 2
STUDY AREA

2.1 Ganga Basin

The Ganga Basin is India's largest river basin, spanning 861,452 km² and encompassing 11 Indian states: Uttarakhand, Himachal Pradesh, Haryana, Delhi, Rajasthan, Madhya Pradesh, Uttar Pradesh, Chhattisgarh, Bihar, Jharkhand, and West Bengal. The basin covers 26.3% of the country's total geographical area. The Ganga Basin is one of the world's most fertile areas, with a large proportion now converted into agricultural land (65.5%), with only 16% of forest cover and 3% of water bodies. The Ganga Basin is densely populated, with an average population density of 512 individuals per km² (NMCG, 2014; Sanghi & Kaushal, 2014). It harbours 500 million people and is the world's most densely populated river basin (Misra, 2011). It supports around 43% of the Indian population, with an average population density of over 700 individuals/km² (RG&CC, 2011; Sanghi & Kaushal, 2014) (Figure 2.1).

2.2 Ganga River

The Ganga River, the lifeline of the region and the largest river in India, was declared the National River of India on 4 November 2008. It originates as the Bhagirathi River at around 7,000 meters (msl) in the Gangotri Glacier of the Greater Himalayas. It is formally called the Ganga River after its confluence with the Alaknanda River at Devprayag (NMCG, 2014; Sanghi & Kaushal, 2014). After spanning 220 km, the river enters the Gangetic plains at Haridwar and traverses five Indian states: Uttarakhand, Uttar Pradesh, Bihar, Jharkhand, and West Bengal (NRCD, 2009). Several important cities along the course of the Ganga River are Haridwar, Farrukhabad, Kanpur, Prayagraj (formerly Allahabad), Mirzapur, Varanasi, Ghazipur, Buxar, Ballia, Munger, Bhagalpur, and Kolkata. The Ganga River supports rich floral and faunal diversity, including swamp deer or barasingha (*Rucervus duvaucelii*), Gangetic dolphin (*Platanista gangetica*), smooth-coated otter (*Lutrogale perspicillata*), gharial (*Gavialis gangeticus*), mugger (*Crocodylus palustris*), and saltwater crocodile (*Crocodylus porosus*) (WII-GACMC, 2018). About 10% of the river stretches of the Ganga River are protected under the Wild Life (Protection) Act, 1972, viz., Gangotri National Park, Rajaji National Park, Hastinapur Wildlife Sanctuary, Turtle Wildlife Sanctuary, and Vikramshila Gangetic Dolphin Sanctuary, safeguarding its wide range of floral and faunal components.

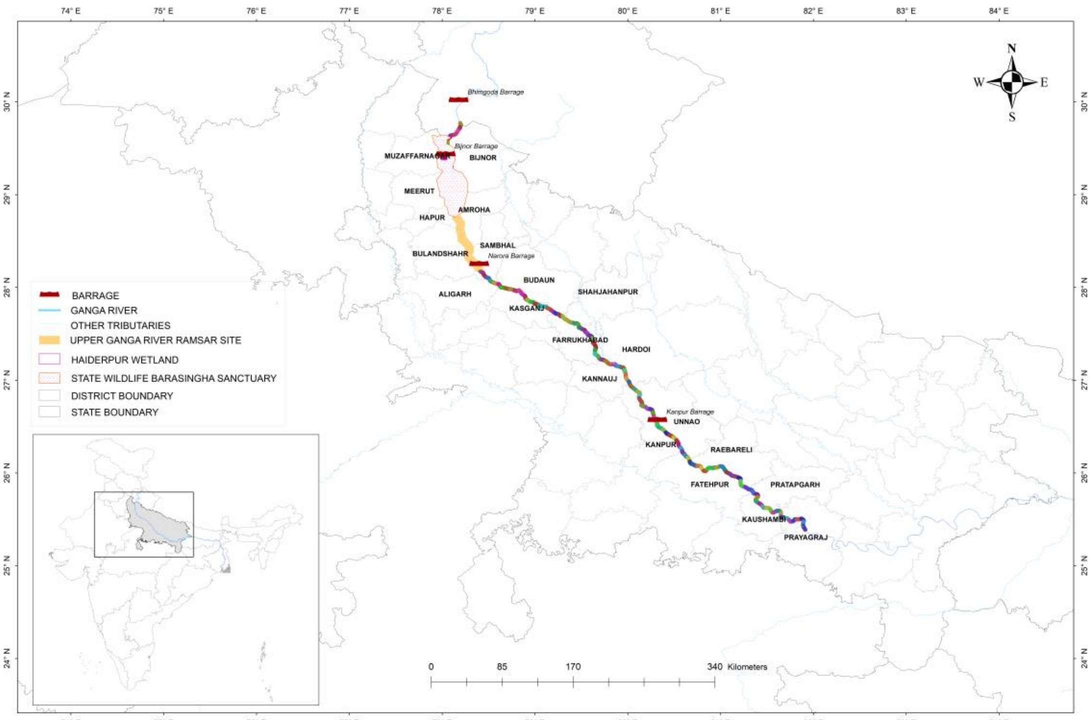

Figure 2.1: Map of the Ganga Basin, highlighting the Ganga River and its tributaries.

The Ganga River system is one of the largest in the world and comprises numerous tributaries originating from diverse physiographic features (Nishat & Singh, 2018; Singh et al., 2018). The Yamuna is the longest right-bank tributary of the Ganga River system and travels 1370 km before joining the Ganga at Prayagraj (Nishat & Singh, 2018). Other major tributaries include the Ramganga, Gomati, Ghaghara, Son, Gandak, Kosi, Mahananda, and Rupnarayan (Singh et al., 2018; WII-GACMC, 2018) (Figure 2.2). Most tributaries are glacial-fed, with high water volume and velocity (Sati, 2021).

The Ganga River is divided into three major stretches: the Upper Stretch (origin to Haridwar; 295 km), Middle Stretch (Haridwar to Varanasi; 995 km), and Lower Stretch (Varanasi to Ganga Sagar; 1235 km) (WII-GACMC, 2018).

2.3 Study Area: The middle stretch of the Ganga River

The middle stretch starts in Haridwar, where it leaves behind the Himalayas, enters the plains, and ends in Varanasi. The study was conducted in the 750 km stretch between Balawali (29°38'15.89" N; 78° 6'22.05" E) of district Bijnor and the confluence of the Yamuna River (25°25'49.17" N; 81°53'19.01" E) at Prayagraj of the middle stretch of the Ganga River. It traverses through the Haridwar, Bijnor, Muzaffarnagar, Meerut, Amroha, Hapur, Bulandshahr, Sambhal, Aligarh, Budaun, Kasganj, Farrukhabad, Hardoi, Kannauj, Unnao, Kanpur Nagar, Fatehpur, Raebareli, Pratapgarh, Kaushambi, and Prayagraj districts of Uttar Pradesh.

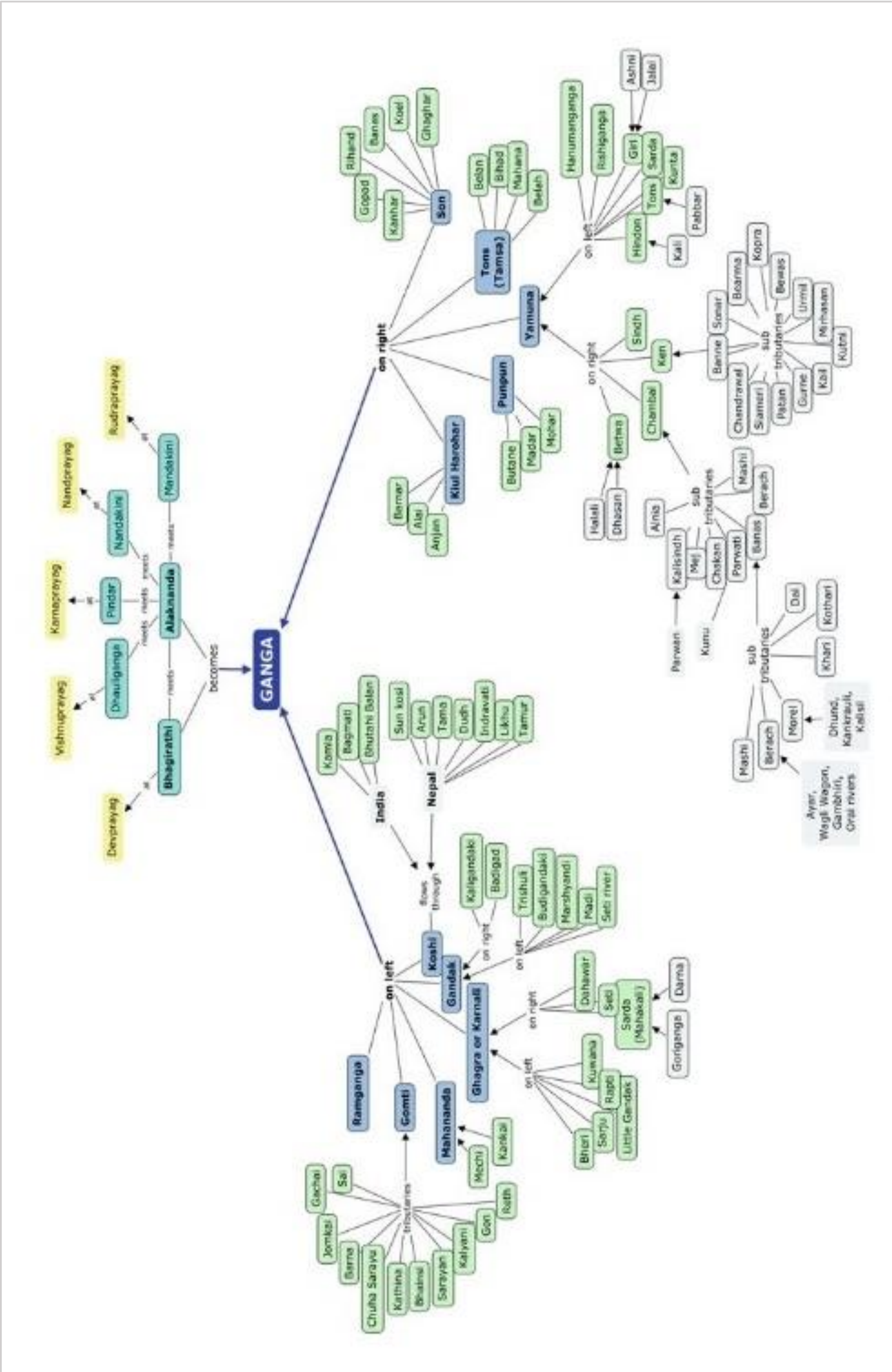

Figure 2.2: Ganga River system and its tributaries (Source: Sanghi and Kaushal, 2014).

This area falls within the Gangetic Plains Biogeographic Zone (Upper Gangetic Biogeographic Province; 7A) (Rodgers et al., 2000). The area experiences varying levels of anthropogenic pressure and habitat quality, which ultimately govern the distribution and abundance of freshwater species. Around 15% of this stretch is protected under the State Wildlife Barasingha Sanctuary (formerly Hastinapur Wildlife Sanctuary), 11% falls under the Upper Ganga Ramsar Site, and 3.3% is in the Narora Important Bird Area (Figure 2.1).

2.3.1 State Wildlife Barasingha Sanctuary (Hastinapur Wildlife Sanctuary)

A stretch of around 115 km of the Ganga River between Balawali and Brijghat in the Bijnor, Muzaffarnagar, Meerut, Hapur, and Amroha districts of Uttar Pradesh is protected as a Wildlife Sanctuary. The Sanctuary supports threatened swamp deer (*Rucervus duvaucelii*), Gangetic dolphin (*Platanista gangetica*), smooth-coated otter (*Lutrogale perspicillata*), mugger (*Crocodylus palustris*), and gharial (*Gavialis gangeticus*) (Das et al., 2022; Khan et al., 2013). This stretch is also designated as an Important Bird Area (IBA Code: IN-UP-03) and is home to several threatened avian species (IBA Criteria: A1) (Figure 2.1).

2.3.2 Haiderpur Wetland Ramsar Site

The Haiderpur Wetland is a human-made wetland formed in 1984 after the construction of the Madhya Ganga Barrage near Bijnor. This wetland is identified as a wetland of international importance (Ramsar site; No. 2463). It is located within the boundaries of the State Wildlife Barasingha Sanctuary. The Haiderpur Wetland provides habitat for numerous floral and faunal species, including approximately 226 species of birds, more than 57 species of fish, and the endangered barasingha and mugger. This Ramsar site harbours more than 1% of the global population of the greylag goose (*Anser anser*) and bar-headed goose (*Anser indicus*). The Haiderpur Wetland also supports the livelihoods of local communities and contributes to the maintenance of hydrological regimes and hazard reduction (Arya et al., 2020; Joshi et al., 2021; Ramsar Convention on Wetlands, 2025; Rana et al., 2025; Singh et al., 2022) (Figure 2.1).

2.3.3 Upper Ganga Ramsar River Site

The Upper Ganga Ramsar Site is an 80 km stretch of the Ganga River located between Brijghat and Narora. This stretch passes through the Hapur, Bulandshahr, Amroha, and Sambhal districts of Uttar Pradesh and supports a rich aquatic diversity, including Gangetic dolphins, smooth-coated otters, muggers, and gharials. It is the first Ramsar site in Uttar Pradesh (Figure 2.1). It was designated as a wetland of international importance (Ramsar Site No. 1574) in 2005 to safeguard and support populations of threatened species, such as Gangetic dolphins, gharials, and waterbirds.

2.3.4 Narora Important Bird Area (IBA)

It is a 25 km stretch of the Ganga River from Narora to Sankra in the Bulandshahr and Sambhal districts of Uttar Pradesh. This stretch is home to rich aquatic diversity, including threatened species such as swamp deer or barasingha, Gangetic dolphin, smooth-coated otter, mugger, and gharial, and a rich diversity of waterbirds whose congregation generally exceeds more than 20,000 individuals (IBA Site Code: IN-UP-10; Criteria: A1; A4iii) (Rahmani et al., 2016) (Figure 2.1).

2.3.5 Nearby Wetlands

Wetlands are among the most biodiverse ecosystems, offering critical habitats for waterbirds and other important taxa, including fish, amphibians, reptiles, and mammals (Mafabi, 2000). Wetlands located near rivers and coastlines influence waterbird abundance and richness (Hamza et al., 2024; Zhang et al., 2019), and larger wetlands closer to rivers or coasts generally support more diverse waterbird communities (Hamza et al., 2024). The dynamic ecosystems of these river-associated wetlands provide diverse habitats and function as dispersal corridors and barriers for various species, thus playing a crucial role in supporting biodiversity, particularly waterbirds (Wittmann, 2022).

However, during summer, when the wet area of the wetlands is significantly reduced, perennial water bodies, such as rivers, play a crucial role as refugia for aquatic biodiversity. These perennial riverine habitats support higher biodiversity and act as essential refuges for various aquatic species, including waterbirds, especially during summer (Davis et al., 2013; Gill et al., 2022).

Within the study area, Shekha Lake Bird Sanctuary (44 km), Lakh Bahosi Bird Sanctuary (30 km), Sandi Bird Sanctuary (17 km), Nawabganj Bird Sanctuary (28 km), and Samaspur Bird Sanctuary (15 km) are located close to the Ganga River, thereby benefiting from hydrological and ecological linkages with the Ganga River.

2.3.6 Major Hydrological/Irrigation Structures and Reservoirs

Dams and barrages create physical barriers that hinder the migration of aquatic fauna and significantly alter river geomorphology. These structural modifications disrupt natural flow regimes, affect seasonal flooding cycles, and reduce connectivity between wetlands and the main river channel, often shaping waterbird communities and riverine ecosystems. Although these changes lead to habitat degradation downstream (Figarski & Kajtoch, 2015; Kingsford, 2000). Despite these impacts, these modifications sometimes create alternative habitats for waterbirds, such as reservoirs and irrigation canals, which serve as surrogate habitats for waterbirds, particularly in arid or semi-arid regions (Baxter, 1977). These artificial habitats may support high densities of certain generalist and adaptable species. Moreover, large reservoirs can serve as important refuges during periods of drought or wetland desiccation, maintaining surface water availability and supporting waterbird assemblages when natural wetlands dry (Davis et al., 2013). The middle stretch of the Ganga River has three barrages, viz., Bhimgoda Reservoir (Upper Ganga Barrage) near Haridwar, Bijnor Barrage (Chaudhary Charan Singh Madhya Ganga Barrage), Narora Barrage (Chaudhary Charan Singh Lower Ganga Barrage), and Kanpur Barrage (Luv Kush Barrage) (Figure 2.1).

The Upper Ganga Barrage, or Bhimgoda Barrage at Haridwar, diverts significant amounts of water into the Upper Ganga Canal for irrigation. This canal system extends over 24,000 km^2 in the 10 districts of Uttar Pradesh. The Middle Ganga Barrage, near Bijnor, diverts water to the Middle Ganga Canal during the monsoon for Kharif crops. It provides irrigation to 1140 km^2 of paddy crops. The Lower Ganga Barrage at Narora diverts water to the Lower Ganga Canal for irrigation and supplies water to the Narora Atomic Power Station (NAPS). It irrigates a 5,000 km^2 area with a discharge capacity of 156 cumecs (NMCG, 2014). The Kanpur Barrage diverts water mainly for drinking purposes.

2.3.7 Geology and Geomorphology

The river stretches between Haridwar and Bijnor, which are highly braided, with mid-channel bars and large alluvial islands used for seasonal cultivation during the lean season. The stretches from Bijnor to Narora and Farrukhabad to Fatehpur are braided with significant river dynamics. The Narora to Farrukhabad and Sirathu to Allahabad channels are dominated by large mid-channel bars and islands used for agriculture during the lean season, and both banks are submerged completely during floods. The Fatehpur–Sirathu channel is more braided in the upper reaches than in the lower reaches. The river in the study area flows slightly lower, ranging between 0.124° and 0.003° (Sinha, 2017).

2.3.8 Soil

The Ganga Basin is covered by alluvial soils and is thus called the Indo-Gangetic Alluvial Plain. These are the most fertile and extensive fluvial plains in the world, producing 50% of India's total food grains and 26.3% of the geographical area inhabited by 40% of the nation's population (Jain, 2007; Pal, 2009). The area falls within the Northern Plain agro-climatic zone (Ahmad, 2017; Jain, 2007).

2.3.9 Climate

The climate of the area is mainly influenced by the southwest monsoon (Ghosh, 1991). The area observed three distinct seasons: summer (March to June), also referred to as the pre-monsoon season, is the dry season, when the river flows with its lean flow, followed by monsoon, the rainy season, when the wet southwest monsoon brings 70–80% of annual rainfall over the basin between July and September; and winter (November to February), also referred to here as the post-monsoon season. The average annual rainfall lies between 60 and 160 cm, mainly during the monsoon months (NRCD, 2009; Mishra, 2011). The study area's altitude ranges between 270 m and 99 m above sea level (Singh, 2004). The temperature ranges between 3°C in winter and 45°C in summer (Sinha et al., 2005).

CHAPTER 3
STATUS, DISTRIBUTION AND ASSEMBLAGE PATTERNS OF WATERBIRDS

3.1 Introduction

Waterbirds are a vital component of wetland ecosystems, including rivers, lakes, and marshes, and contribute to multiple ecological processes through nutrient cycling, propagule dispersal, habitat engineering, and biological control (Green & Elmberg, 2014). The integrity and sustainable use of wetland resources are closely tied to the population dynamics of waterbirds (Siriwardena et al., 2001). However, widespread degradation due to anthropogenic disturbances and climate change poses serious threats to the waterbird populations inhabiting these wetlands (Finlayson et al., 1992; Owen & Black, 1990; Vessem et al., 1997). The Millennium Ecosystem Assessment (2005) reported that 41% of the 1,138 global waterbird populations are experiencing a declining trend and require actions to address habitat loss, pollution, and climate change impacts (Millennium Ecosystem Assessment, 2005). Hence, understanding the spatial and temporal patterns of avifaunal assemblages is essential for interpreting population dynamics and for implementing effective species and habitat conservation strategies.

Assessing population parameters has long been a central focus of ecological research (Gotelli & McCabe, 2002; Weiher & Keddy, 2001; Wisz et al., 2013). Species richness, density, and diversity are widely used indicators to assess the habitat quality and ecosystem health (Johnson, 2007; Smits & Fernie, 2013). Species richness, in particular, is fundamental to many ecological concepts and models and provides a foundational measure of community and assemblage structures (Connell, 1978; MacArthur & Wilson, 1967). Estimating species richness is among the most straightforward approaches to describing regional biodiversity (Gotelli & Chao, 2013).

Despite their ecological importance, waterbird assemblage patterns and diversity in riverine ecosystems remain underexplored. Rivers are hierarchical systems characterised by unidirectional flow and multiple longitudinal, lateral, and vertical gradients, which harbour a distinct biological community structure progressively from headwaters to floodplains (Ward et al., 2002). Understanding waterbird distributions along these gradients is critical, as this information is crucial for designing protected area networks and identifying conservation priorities (Perez-Arteaga et al., 2005).

Riverine ecosystems support a rich array of biodiversity and are highly dynamic, owing to variations in flow regimes and channel morphology. Hill streams, which are marked by high flow gradients, are turbulent and energy-rich, whereas foothill zones exhibit alternating riffles and pools. In contrast, rivers in plains meander extensively, with slower flow distributing nutrients and energy across wider basins (Tanida, 2009). These upstream ecological processes influence downstream habitats and, accordingly, shape biological communities. Thus, the waterbird community composition is closely linked to the physical structure of river systems (Sidhu et al., 2010; Sinha et al., 2019).

Natural riverine habitats support diverse faunal assemblages, with birds forming one of the most prominent and widespread animal groups. Rivers host a variety of habitats that sustain numerous bird species (Knopf, 1985; Stauffer & Best, 1980). These birds play a critical role as pollinators, seed dispersers, and insect pest controllers. Consequently, understanding bird communities along river systems can inform management strategies and guide the prioritisation of riverine conservation efforts (Gergel et al., 2002; Naiman et al., 1993; Rice et al., 1980).

3.2 Methodology

3.2.1 Sampling

The boat-based continuous surveys were conducted throughout the study area between Balawali, District Bijnor, and Sangam, District Prayagraj. Three pre-monsoon (April–June) and three post-monsoon (December–February) surveys were conducted between 2017 and 2021. Pre-monsoon (PrM) surveys covered resident populations, including riverine island nesting birds, whereas post-monsoon (PoM) surveys covered both resident and winter migrants. Surveys were conducted in the pre-monsoon (summer) from 6:00 am to 9:00 am and 4:00 pm to 6:00 pm, and in the post-monsoon (winter) from 8:00 am to 12:00 pm and 3:00 pm to 5:00 pm. An inflatable boat powered by a 25 hp outboard motor at a constant speed of 6–8 km/h was used for the survey.

3.2.2 Data analysis

Rarefaction/extrapolation curves were generated using the iNEXT and ggplot2 packages in R (R Core Team, 2025) to estimate and compare the species richness (Fauzi et al., 2023; Hsieh et al., 2016). Waterbird abundance data for each season were tested for normality using the Shapiro-Wilk test (Shapiro & Wilk, 1965) and Q-Q plots (Ghasemi & Zahediasl, 2012). A significance level of 0.05 was used, with deviations from normality assessed via test results and visual inspection. A log transformation was applied to the right-skewed, non-normally distributed abundance data to normalise it (Osborne, 2002). All analyses were performed in R.

Species richness, diversity, and evenness of waterbirds were assessed using the Shannon–Weiner index (Shannon, 1948), Margalef's richness index (Margalef, 1958), and Pielou's evenness index (Pielou, 1966). The relative diversity (RDi) of waterbird families was calculated using La Torre-Cuadros et al. (2007). The beta diversity partitioning framework was assessed using Baselga's Framework (Baselga, 2012).

The following mathematical expressions were used for these indices:

Shannon-Weiner Index:

$$H^{l} = -\sum_{i=1}^{S} p_i \, In(p_i)$$

Where:

- S = total number of species.
- p_i = proportion of individuals of a species i (i.e., $p_i = \frac{n^i}{N}$)
- n^i = number of individuals of the species i.
- N = total number of individuals of all species.

Margalef's Richness Index (D):

$$D = \frac{S-1}{In(N)}$$

Where:

- D = Margalef's Richness Index
- S = total number of species (species richness)
- N = total number of individuals in the sample
- In = natural logarithm

Pielou's Evenness Index:

$$J^l = \frac{H^l}{In(S)}$$

Where:

- J^l = Pielou's Evenness Index
- H^l = Shannon-Wiener Diversity Index
- S = Total number of species (species richness)
- $In(S)$ = natural logarithm of the species richness

Relative Diversity (RDi):

$$\mathbf{RDi} = \frac{\text{Number of bird species in a family}}{\text{Total number of species across all families}} \times 100$$

Beta Diversity Partitioning Using Baselga's Framework.

To investigate the spatial patterns of waterbird assemblages and compositions across seasons, beta diversity was quantified and partitioned using the approach proposed by Baselga (2010, 2012). This framework allows the decomposition of total beta diversity into two components: turnover (species replacement) and nestedness-resultant dissimilarity (species loss or gain). The analysis was based on the presence-absence data derived from the original abundance matrix.

Total Beta Diversity (Sørensen Dissimilarity):

$$\beta sor = \frac{(b + c)}{(2a + b + c)}$$

Species Turnover (Simpson Dissimilarity):

$$\beta \text{sim} = \frac{\min(\text{b, c})}{(\text{a} + \min(\text{b, c}))}$$

Nestedness-Resultant Component:

$$\beta \text{nes} = \beta \text{sor} - \beta \text{sim}$$

Where:

a = number of species shared between both sites

b = number of species unique to the first site

c = number of species unique to the second site

The total beta diversity (βsor) ranged from 0 (identical communities) to 1 (completely different communities). Turnover (βsim) represents species replacement between sites, and nestedness (βnes) indicates species loss/gain patterns.

The abundance data were first converted to a binary matrix using the Hellinger transformation and presence-absence standardisation (Legendre & Gallagher, 2001). The *betapart* package (Baselga & Orme, 2012) in R was used to compute pairwise dissimilarities using the Sørensen dissimilarity index *(beta.pair()* function). This partitioned the dissimilarity into turnover (β_sim) and nestedness (β_sne) components while also computing the total dissimilarity (β_sor).

Species Assemblage Structure and Patterns

The co-occurrence measures were calculated using the function *cooccur* of the package *'cooccur'* in R (Griffith et al., 2016), which performs a probabilistic analysis of species co-occurrence based on a presence-absence matrix.

Multivariate Patterns of Waterbird Assemblages Across Seasons

Multivariate analyses were conducted using abundance data to assess differences in waterbird assemblage composition across various ecological and anthropogenic gradients. Non-parametric permutational multivariate analysis of variance (PERMANOVA) (Anderson, 2001) was used to test for statistically significant differences in species composition among seasons based on the Bray–Curtis dissimilarity index (Bray & Curtis, 1957). To verify whether the significant results from PERMANOVA reflected differences in group centroids rather than dispersion, a permutational analysis of multivariate dispersions (PERMDISP) was also performed. Additionally, analysis of similarities (ANOSIM) (Clarke & Warwick, 2001) was used to assess the rank-based dissimilarity between groups, providing a complementary perspective to PERMANOVA. Non-metric multidimensional scaling (NMDS) ordinations were constructed using Bray–Curtis dissimilarities derived from the abundance matrix to visualise patterns in waterbird assemblages across seasons. All multivariate analyses were implemented in R using the *vegan* package in R software.

Seasonal abundance data of bird species were analysed using the Similarity Percentage (SIMPER) method to identify the species that contributed the most to the dissimilarity between seasonal groups. SIMPER analysis was performed on the abundance matrix to quantify species contributions to the observed differences in bird community structure between the two seasons. Statistical significance was determined using p-values obtained from the analysis.

The study area was divided into 15 equal river segments of 50 km each (Sites S1–S15) to assess the site-wise waterbird assemblage patterns (Figure 3.1).

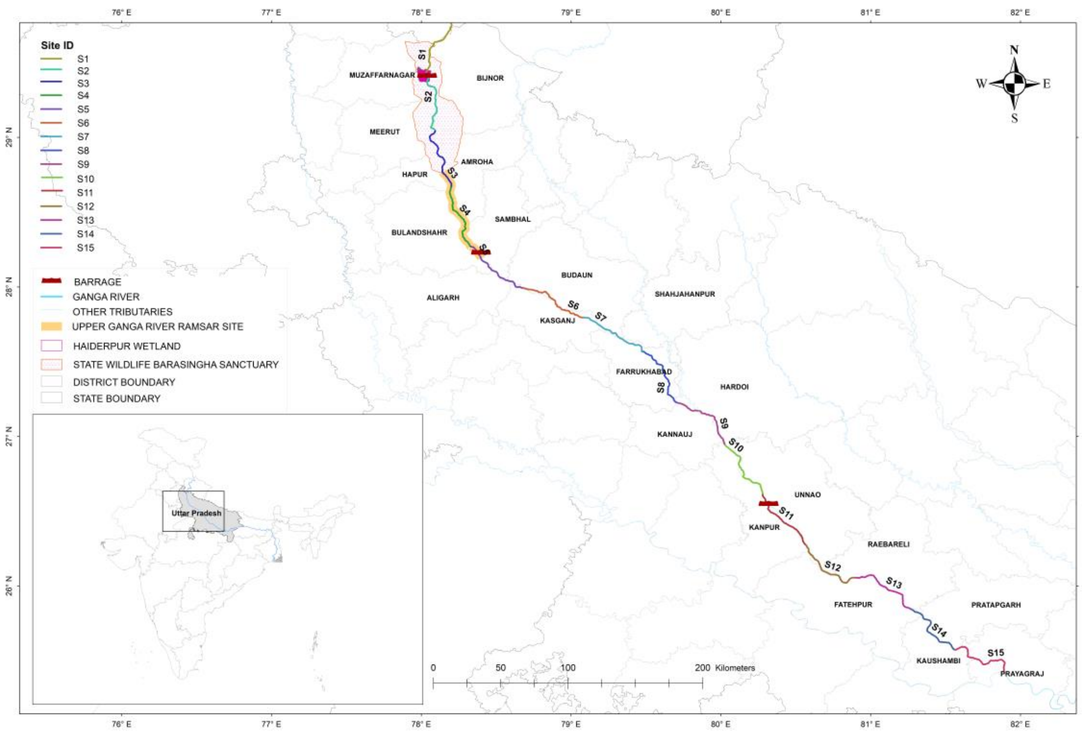

Figure 3.1: Map of Study Area Showing 15 River Segments (S1–S15).

3.3 Results

A total of 2,34,468 waterbirds belonging to 107 species, 25 families, and 11 orders were observed in the 750 km study area (Appendix I) across the six sampling seasons. Considerable fluctuations in both waterbird abundance and richness were recorded in the study area across the season. The maximum waterbird abundance (51,264 individuals) and richness (88 species) were observed in post-monsoon 2018, and the minimum waterbird abundance (32,225 individuals) and richness (74 species) were observed in post-monsoon 2019 (Figure 3.2).

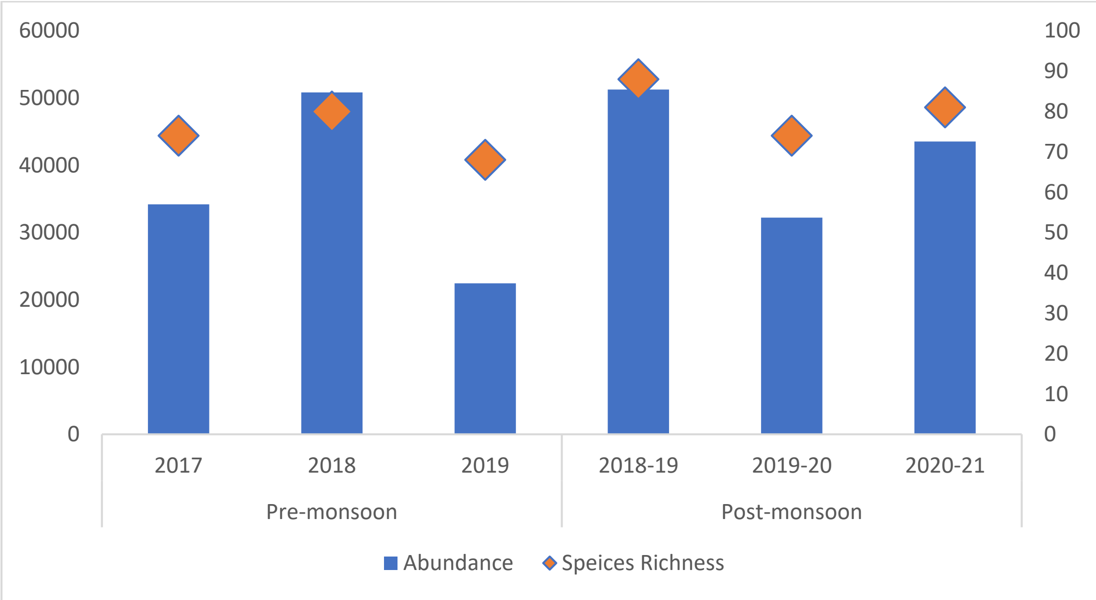

Figure 3.2: Waterbird abundance and species richness across different seasons.

The order Charadriiformes represented the maximum waterbird abundance across all seasons (pre-monsoon: 32.6%; post-monsoon: 27.0%). Anseriformes showed seasonal variation, with a substantially higher representation during the post-monsoon period (35.5%) than during the pre-monsoon period (10.6%). Suliformes show moderate consistency, ranging between 23.2% in the pre-monsoon season and 21.7% in the post-monsoon season, whereas Pelecaniformes and Ciconiiformes exhibit higher pre-monsoon presence (14.0% and 8.9%, respectively) compared to the post-monsoon presence (7.7% and 2.8%, respectively) (Figure 3.3).

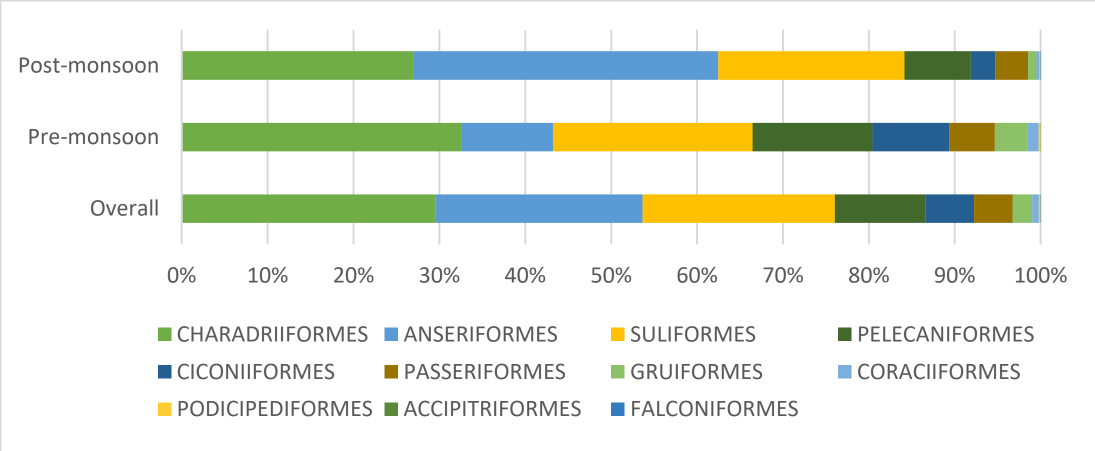

Figure 3.3: Order-wise composition of waterbird abundance across different seasons.

The Anatidae family (20 species) was most abundant in the study area, followed by Scolopacidae (14 species), Ardeidae and Laridae (9 species each), Charadriidae (7 species), Ciconiidae and Rallidae (5 species each), Motacillidae (4 species), Accipitridae, Alcedinidae, Gruidae, Hirundinidae, Phalacrocoracidae, Threskiornithidae (3 species each), Burhinidae, Jacanidae, Pelecanidae, Podicipedidae, Recurvirostridae (2 species each), Anhingidae, Falconidae, Glareolidae, Meropidae, Pandionidae, Rostratulidae were poorly represented in the stretch with single species (Figure 3.4).

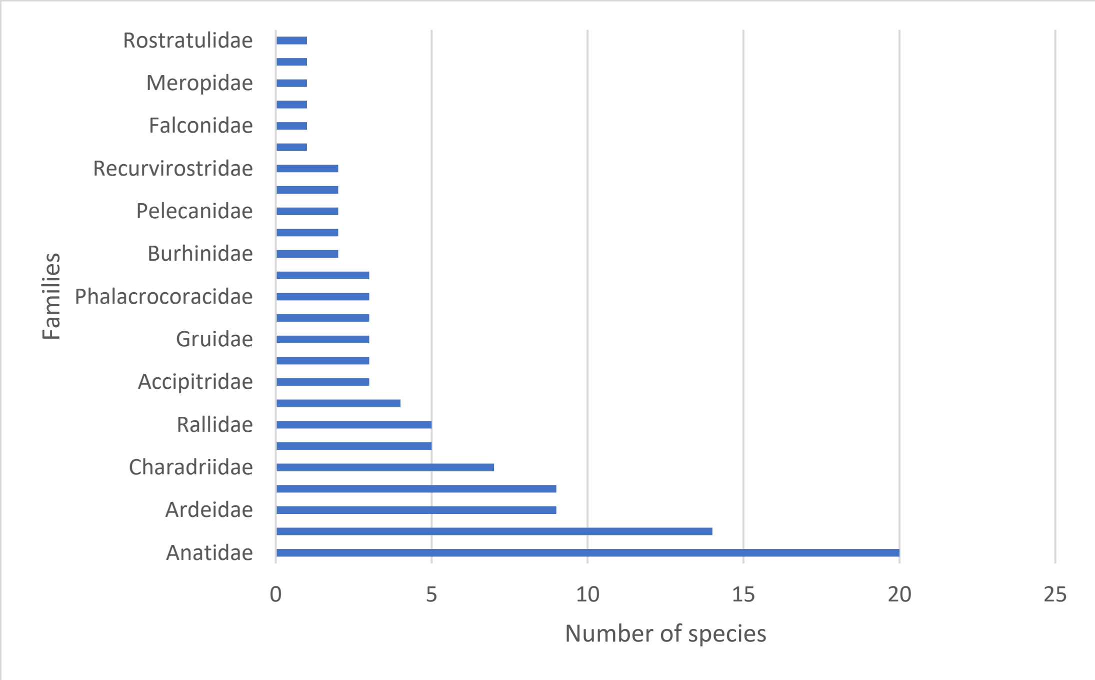

Figure 3.4: Number of waterbird species against different families.

Out of the total species observed, 15 are protected under Schedule I of the Wild Life (Protection) Act, 1972 and 19 were listed in the threatened category of IUCN RedList, viz., three Vulnerable (VU) species, 11 Near Threatened (NT) species, and five Endangered (EN) species were recorded during the survey. Among the observed waterbirds, 47 species (43.9%) were residents, 31 species (28.9%) were winter migrants, and 29 species (27.1%) were residents with winter migrants (Appendix I).

3.3.1 Rarefaction and Species Richness Estimation

The analysis of the rarefaction curve showed that the curves for post-monsoon 2018-19, post-monsoon 2019-20, post-monsoon 2020-21, and pre-monsoon 2019 had almost reached the asymptote, indicating that the species diversity for these seasons may have been successfully identified. However, the total sampling efforts were still inadequate for pre-monsoon 2017 and 2018, as the cumulative curve was exponential (Figure 3.5).

The observed species richness (68 - 88 species) among all six seasons slightly underestimated the true diversity as indicated by non-parametric estimators Chao 2 (74.9 - 97.4), Jackknife 1 (76.9 - 99.9), and Jackknife 2 (75.1 - 105.9). The 2018-19 exhibited the highest species richness across all metrics (observed: 88; Chao 2: 97.4; Jackknife 1: 99.9; Jackknife 2: 105.9). The convergence between observed and estimated richness was closest during the post-monsoon 2019-20 (observed: 74; Chao 2:75.0; Jackknife 2:75.1) (Table 3.1).

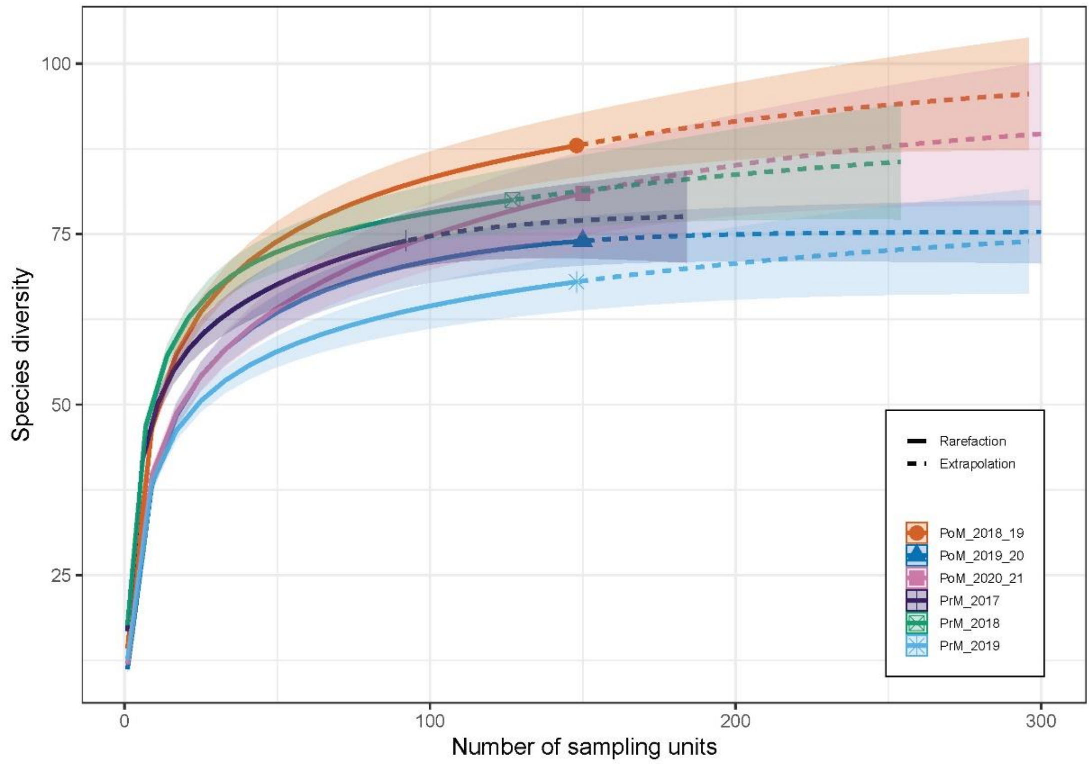

Figure 3.5: Waterbird accumulation curve based on rarefaction for each season. PoM 2018-19: post-monsoon 2018-19, PoM 2019-20: post-monsoon 2019-20, PoM 2020-21: post-monsoon 2020-21, PrM 2017: pre-monsoon 2017, PrM_2018: pre-monsoon 2018, and PrM_2019: pre-monsoon.

Table 3.1: Observed and estimated (Chao 1, Jackknife 1, Jackknife 2, and Jackknife 2) bird species richness in different seasons in the study area.

Season		Observed Species	Chao 2	Jackknife 1	Jackknife 2
Pre-monsoon	2017	74	77.24	82.9	82.03
	2018	80	89.27	87.95	93.88
	2019	68	75.15	76.94	81.9
Post-monsoon	2018-19	88	97.36	99.92	105.88
	2019-20	74	74.99	78.97	75.08
	2020-21	81	91.43	95.9	101.88

3.3.2 Assessment of Normality

The normality assessment of the waterbird abundance data for all six seasons was conducted using Shapiro-Wilk tests, which strongly suggested that the data did not follow a normal distribution pattern (0.52 and 0.78, $p<0.05$). These findings were visually corroborated by Q-Q plots, indicating consistent right-skewed distributions.

3.3.3 Species Richness, Diversity, and Evenness

Shannon-Weiner diversity ranged from 2.97 in the post-monsoon 2018–19 to 3.97 during the pre-monsoon 2017, reflecting differences in species abundance and evenness among the seasons. Margalef's richness index showed moderate variation, with values between 6.64 and 7.95, suggesting relatively stable species richness despite seasonal fluctuations. Furthermore, Pielou's evenness was lowest in the post-monsoon 2019–20 (0.16) and highest during the pre-monsoon 2019 (0.35) (Figure 3.6).

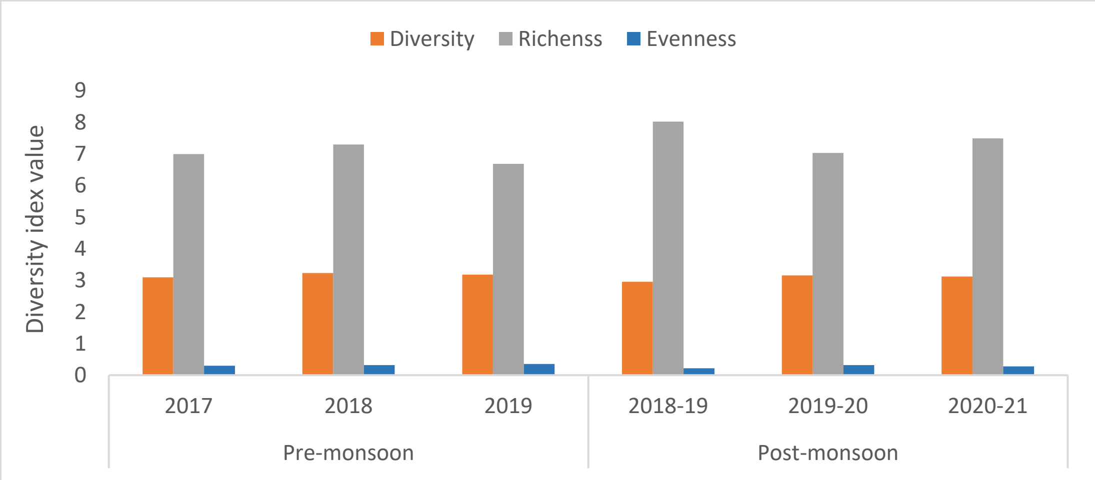

Figure 3.6: Pre-monsoon waterbird diversity across areas under varying anthropogenic pressures.

3.3.4 Distribution patterns across sites

The study area was divided into 15 equal stretches (sites) of 50 km each (S1–S15). Across all 15 sites, 34 species were consistently observed at all sites. In contrast, seven species, viz., Greater white-fronted goose, brown crake, purple swamphen, common moorhen, grey-headed lapwing, white-tailed lapwing, wire-tailed swallow, were localised and observed from a single site. The maximum species richness (86 species) was observed at Site S5, and the minimum (64 species) was observed at S14 (Appendix II).

The mean Shannon–Weiner diversity, Margalef's richness, and Pielou's evenness (±SE) during the pre-monsoon season were 2.77 (±0.10), 5.53 (±0.22), and 0.38 (±0.03), respectively. In contrast, post-monsoon values across the 15 sites were slightly lower: 2.28 (±0.12), 4.94 (±0.13), and 0.26 (±0.03), respectively.

The highest Shannon-Wiener diversity during the pre-monsoon season was recorded at S6 (3.22), while the lowest was at S2 (1.95). During the post-monsoon season, diversity was highest at S8 (2.97) and lowest at S11 (1.37). Margalef's richness during the pre-monsoon season ranged from a minimum of 3.80 (S14) to a maximum of 7.48 (S5). In the post-monsoon season, the richness values ranged between 4.09 (S11) and 6.34 (S5). Pielou's evenness was the lowest at S2 (0.14) and the highest at S6 (0.52) during the pre-monsoon season. In the post-monsoon season, evenness ranged from 0.10 (S11) to 0.513 (S8) (Figures 3.7 & 3.8).

Species richness during the pre-monsoon period ranged from 42 to 66 across the 15 study sites, with the highest richness recorded at Site S5 (66) and the lowest at Site S15 (42). In the post-monsoon period, species richness varied between 46 and 70 species, with Site S5 again exhibiting the highest richness (70 species), whereas Site S14 recorded the lowest (46 species). The overall species richness ranged from 64 to 86 species, with Site S5 showing the highest overall richness (86) and Site S14 the lowest (64) (Figure 3.9). The paired t-test revealed no significant difference in species richness between pre-monsoon and post-monsoon seasons ($t = 0.13$, $p < 0.5$).

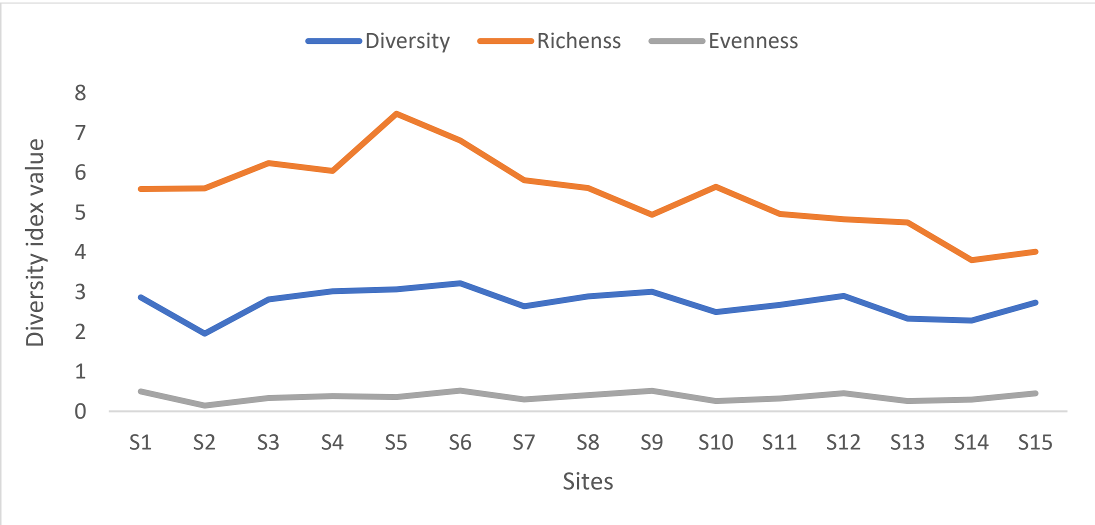

Figure 3.7: Pre-monsoon richness, diversity, and evenness across different sites.

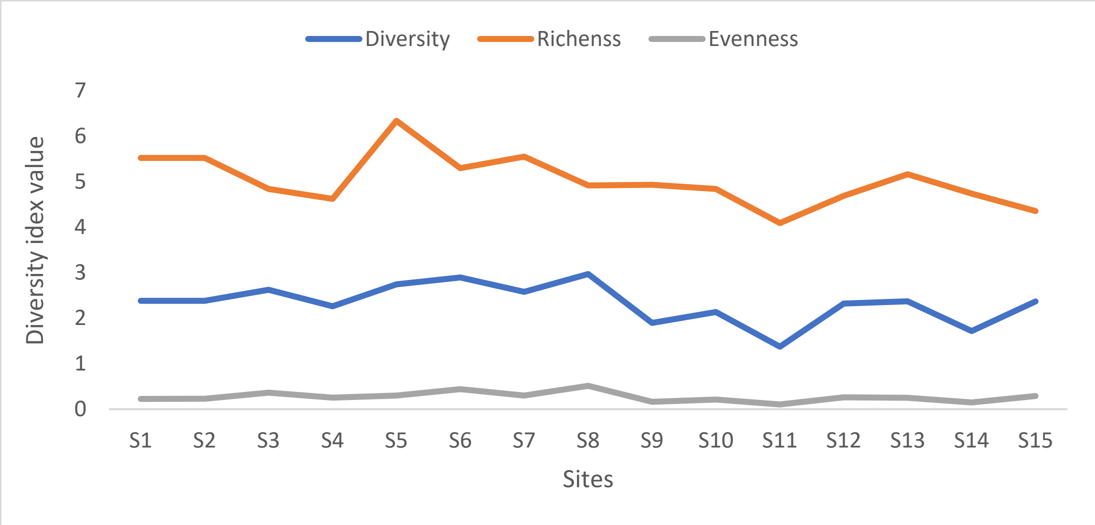

Figure 3.8: Post-monsoon richness, diversity, and evenness across different sites.

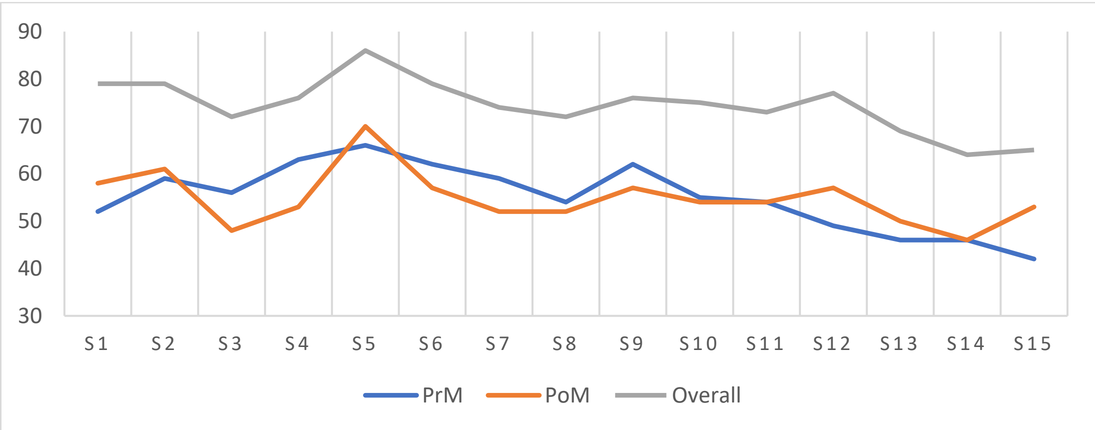

Figure 3.9: Seasonal patterns of the number of species reported from different sites.

3.3.5 Relative Diversity and Relative Abundance

Anatidae exhibited the highest overall RDi (18.69), with a notable increase in the post-monsoon season (20.62) compared with the pre-monsoon season (16.30). Scolopacidae was the second most diverse family, with a higher diversity in the pre-monsoon season (15.22) than in the post-monsoon season (14.43). The paired t-test revealed no significant difference in the family level overall abundance between the pre-monsoon and post-monsoon seasons ($t = 0.003$, $p > 0.05$) (Table 3.2).

Table 3.2: Overall and seasonal Relative Diversity Index (RDi) of waterbird families.

Family	Overall	Pre-monsoon (PrM)	Post-monsoon (PoM)
Anatidae	18.69	16.30	20.62
Podicipedidae	1.87	1.09	2.06
Rallidae	4.67	2.17	5.15
Gruidae	2.80	3.26	2.06
Ciconiidae	4.67	4.35	5.15
Threskiornithidae	2.80	3.26	3.09
Ardeidae	8.41	9.78	9.28
Pelecanidae	1.87	0.00	2.06
Phalacrocoracidae	2.80	3.26	3.09
Anhingidae	0.93	1.09	1.03
Burhinidae	1.87	2.17	1.03
Recurvirostridae	1.87	2.17	2.06
Charadriidae	6.54	5.43	7.22
Rostratulidae	0.93	1.09	0.00
Jacanidae	1.87	2.17	0.00
Scolopacidae	13.08	15.22	14.43
Glareolidae	0.93	1.09	1.03
Laridae	8.41	9.78	7.22
Pandionidae	0.93	1.09	1.03
Accipitridae	2.80	3.26	2.06
Meropidae	0.93	1.09	0.00
Alcedinidae	2.80	2.17	3.09
Falconidae	0.93	1.09	1.03
Hirundinidae	2.80	3.26	2.06
Motacillidae	3.74	4.35	4.12

Of the 107 waterbird species recorded in the study area, the 20 most abundant species accounted for approximately 82% of the total waterbird population during the pre-monsoon season and 86% during the post-monsoon season. During the pre-monsoon season, little cormorant was the most abundant (20.30%), followed by river lapwing (6.34%), Asian openbill (5.41%), and little pratincole (5.28%). In contrast, the black-headed gull and great cormorant were the most abundant, representing 14.76% and 14.23%, respectively, during the post-monsoon season, followed by little pratincole (8.51%), gadwall (7.17%), and ruddy shelduck (7.03%) (Table 3.3). The greater white-fronted goose (*Anser albifrons*), brown crake (*Zapornia akool),* and grey-headed lapwing (*Vanellus cinereus*) were observed only once during the entire study period.

Table 3.3: Twenty most abundant waterbird species observed during the pre-monsoon and post-monsoon seasons.

Pre-monsoon		Post-monsoon	
Species	**Relative Abundance**	**Species**	**Relative Abundance**
Little Cormorant	20.30	Black-headed Gull	14.76
River Lapwing	6.34	Great Cormorant	14.23
Asian Openbill	5.41	Little Pratincole	8.51
Little Pratincole	5.28	Gadwall	7.17
Sarus Crane	4.30	Ruddy Shelduck	7.03
Asian Plain Martin	4.25	Bar-headed Goose	5.08
Little Egret	4.23	Northern Pintail	3.98
Black-winged Stilt	4.07	Common Greenshank	3.04
Painted Stork	3.31	Asian Plain Martin	2.70
Ruddy Shelduck	3.20	Little Cormorant	2.68
Cattle Egret	3.05	Black-winged Stilt	2.33
Lesser Whistling-duck	2.86	Common Teal	2.08
Indian Cormorant	2.68	River Lapwing	2.04

Red-wattled Lapwing	2.13	Cattle Egret	1.68
Little Tern	2.10	Pied Avocet	1.64
Knob-billed Duck	2.04	Indian Cormorant	1.64
Common Greenshank	1.85	Red-naped Ibis	1.63
Great White Egret	1.69	Asian Openbill	1.46
Indian Spot-billed Duck	1.68	Red-crested Pochard	1.43
Temminck's Stint	1.55	Grey Heron	1.30
Total	**82.32**	**Total**	**86.41**

3.3.6 Temporal Beta Diversity Patterns: Turnover and Nestedness in Waterbird Assemblages

Beta diversity analysis of waterbirds across the pre-monsoon and post-monsoon seasons revealed pronounced temporal shifts in the community structure. Overall, beta diversity was moderate s(β = 0.61), with species turnover accounting for the majority of compositional differences between sites (80.20%), whereas nestedness contributed less (19.80%) (Figure 3.10). During the pre-monsoon season, beta diversity was higher (β = 0.63), and turnover remained the major component (77.67%) (Figure 3.11). In the post-monsoon period, beta diversity decreased slightly (β = 0.58); however, an even greater proportion was attributed to turnover (83.01%), with a corresponding reduction in nestedness (16.99%) (Figure 3.12; Table 3.4).

Table 3.4: β diversity (and its components) within and across seasons.

	ß Total	Turnover	Nestedness	% ß Turnover
Overall	0.61	0.49	0.12	80.20
Pre-monsoon	0.63	0.49	0.14	77.67
Post-monsoon	0.58	0.48	0.10	83.01

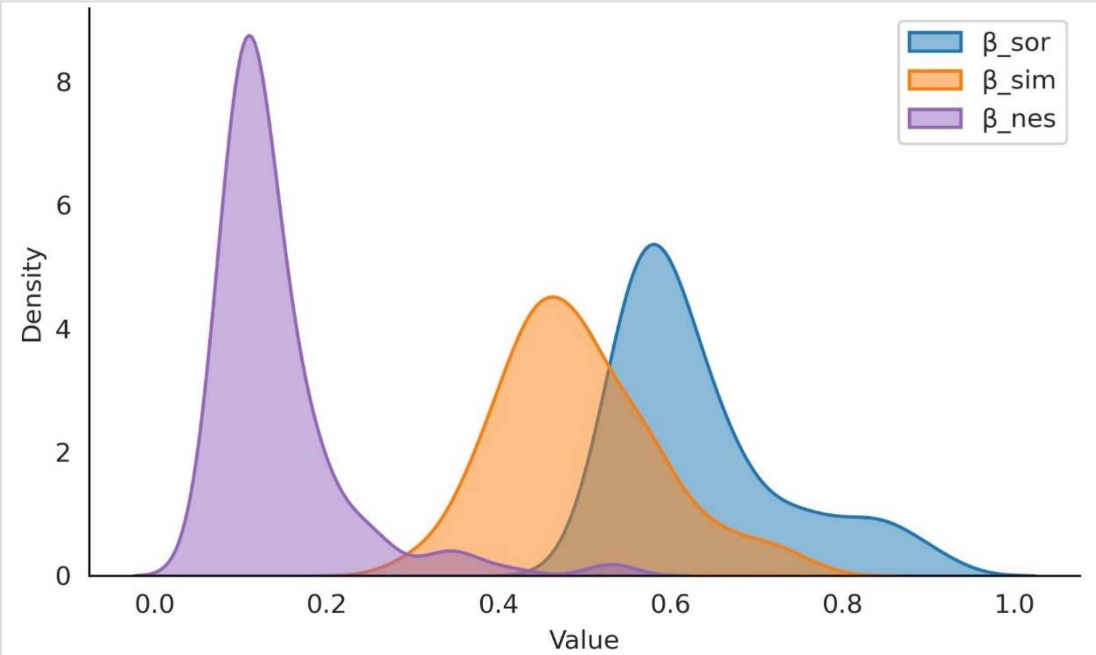

Figure 3.10: Distribution of beta diversity components in waterbird assemblages.

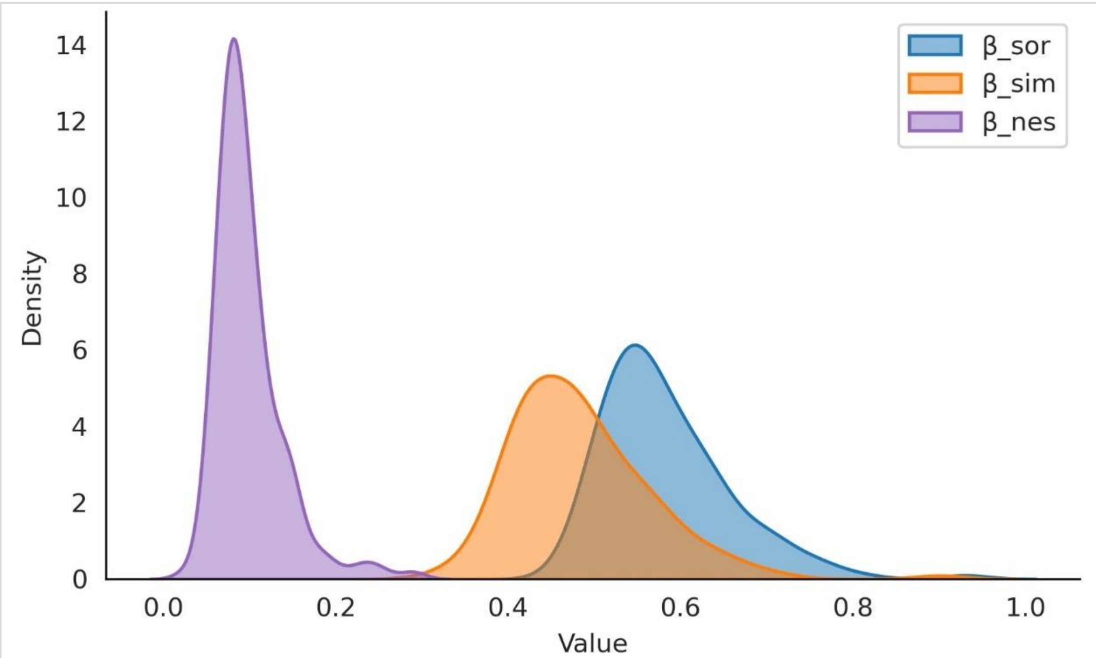

Figure 3.11: Pre-monsoon beta diversity components showing species turnover and nestedness patterns.

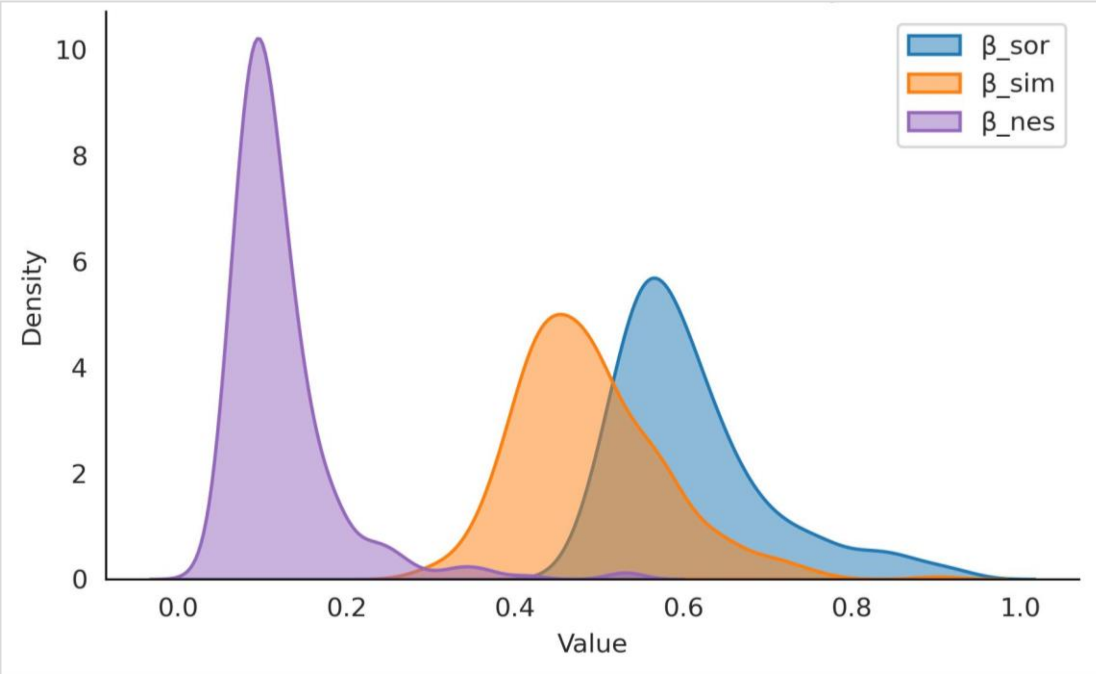

Figure 3.12: Post-monsoon beta diversity components illustrating seasonal community changes.

3.3.7 Co-occurrence of waterbird species across different seasons

Strong positive correlations ($r > 0.7$) were observed between Asian openbill and Asian woollyneck, indicating frequent co-occurrence in shared habitats during the pre-monsoon season. A distinct cluster of wading birds, including black-headed ibis, oriental darter, and painted stork, demonstrated moderate to high positive associations ($r = 0.5$-0.8). The analysis revealed three main species assemblages, with waterfowl showing weaker correlations ($r < 0.4$) with other functional groups, indicating more independent distribution patterns (Figure 3.13).

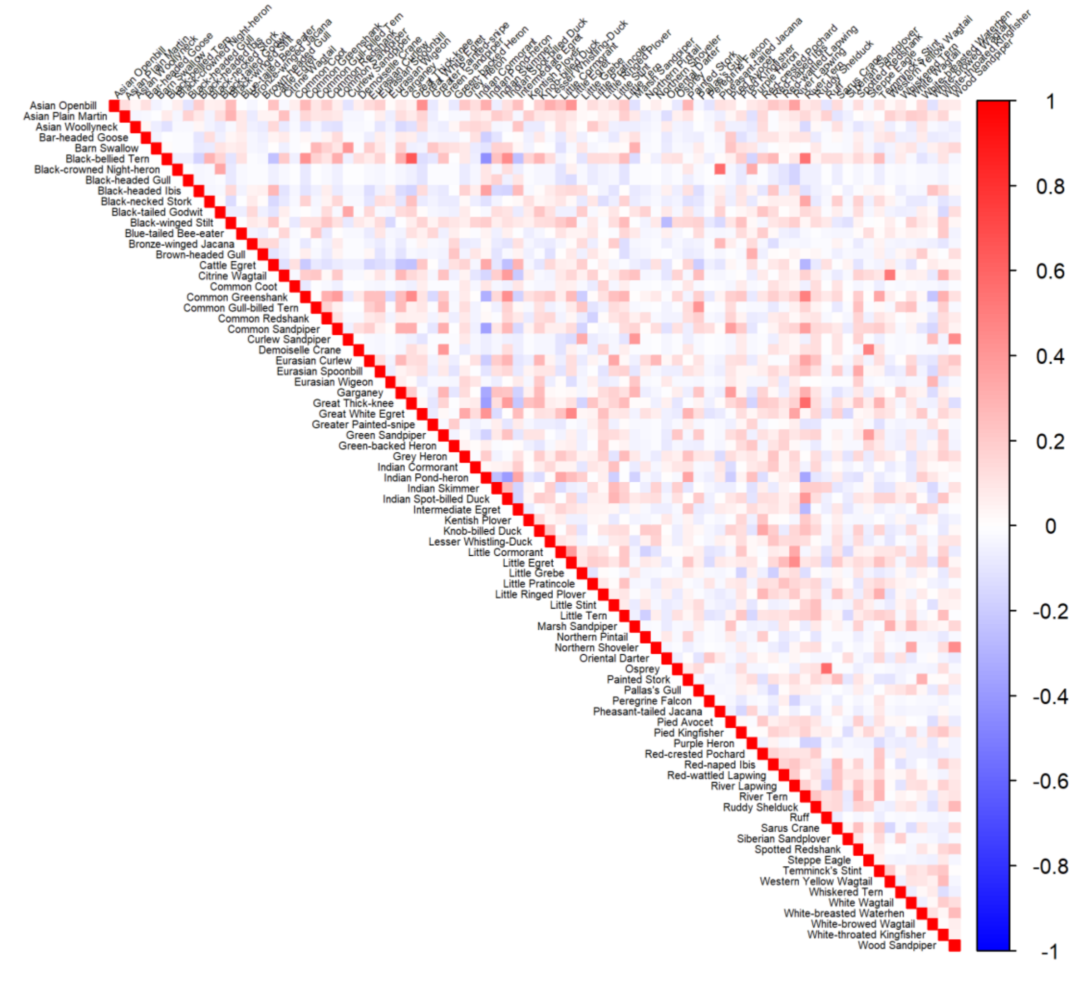

Figure 3.13: Co-occurrence patterns of waterbirds in the pre-monsoon season.

During post-monsoon, a distinct cluster comprising Black-headed Ibis, Oriental Darter, and Painted Stork exhibited moderate to strong positive associations (r = 0.45-0.70), suggesting similar habitat preferences and resource utilisation. The Lesser Whistling Duck and Cotton Pygmy-goose demonstrated weak correlations with other species (r < 0.3), indicating more independent distribution patterns across the study area (Figure 3.14).

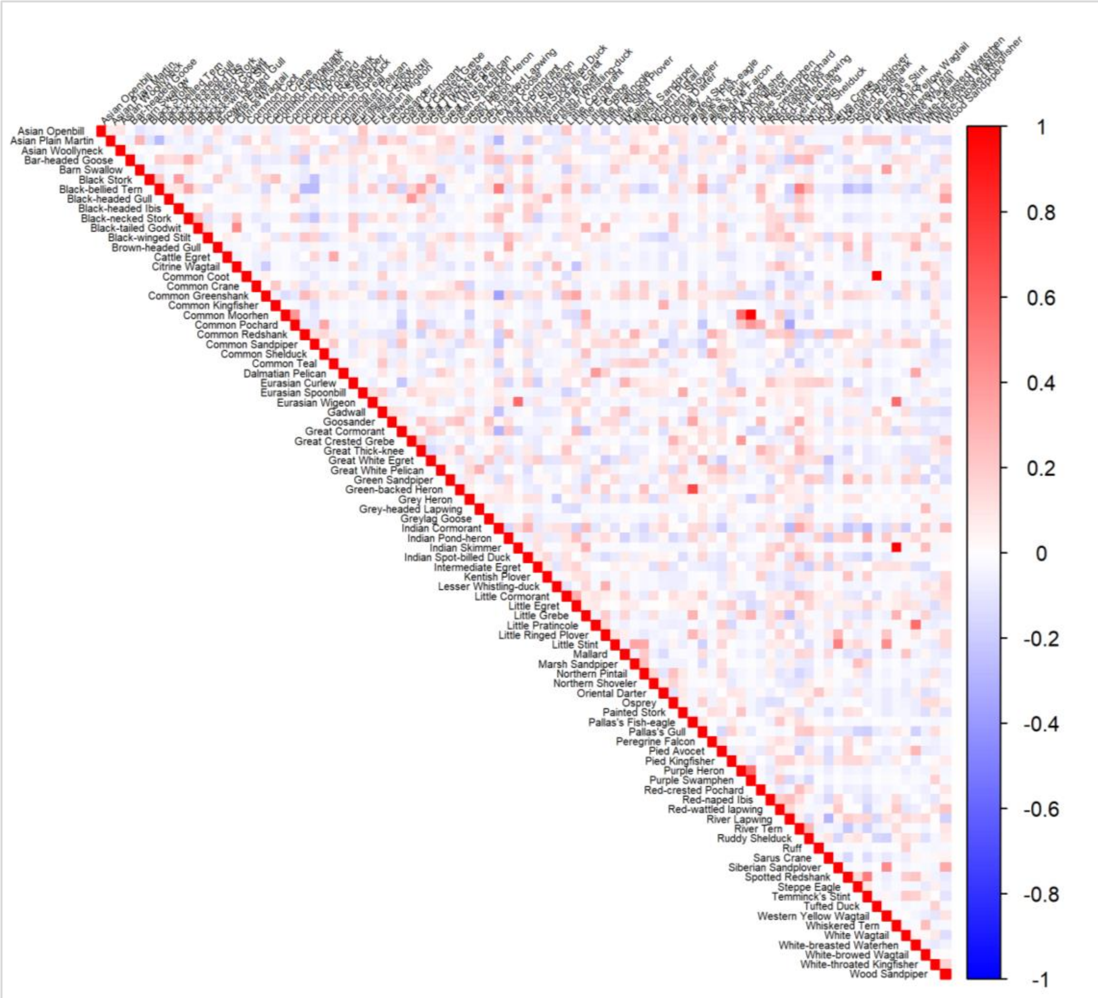

Figure 3.14: Co-occurrence patterns of waterbirds in the post-monsoon season.

The pre-monsoon co-occurrence histogram revealed a right-skewed distribution, with peak frequency occurring in the 0.2 - 0.3 range, indicating a predominance of weak to moderate species associations. A notable decline in frequency was observed for co-occurrence values above 0.4, with very few species pairs showing values above 0.6 (Figure 3.15).

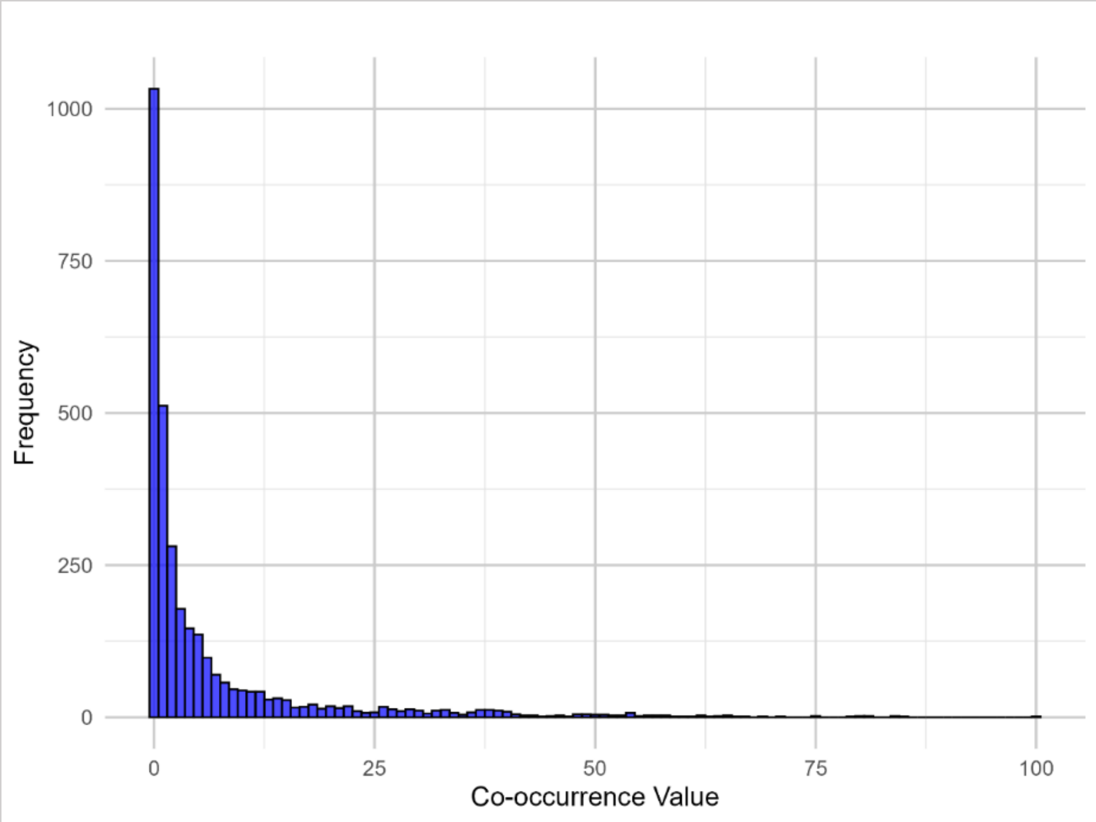

Figure 3.15: Histogram representation of co-occurrence values of the waterbird species in the pre-monsoon season.

The post-monsoon co-occurrence histogram revealed a normal distribution, with peak frequency occurring in the 0.4 - 0.5 range, indicating the predominance of moderate species associations. A gradual decline in frequency was observed symmetrically on both sides of the peak, with several species pairs exhibiting values above 0.6 (Figure 3.16).

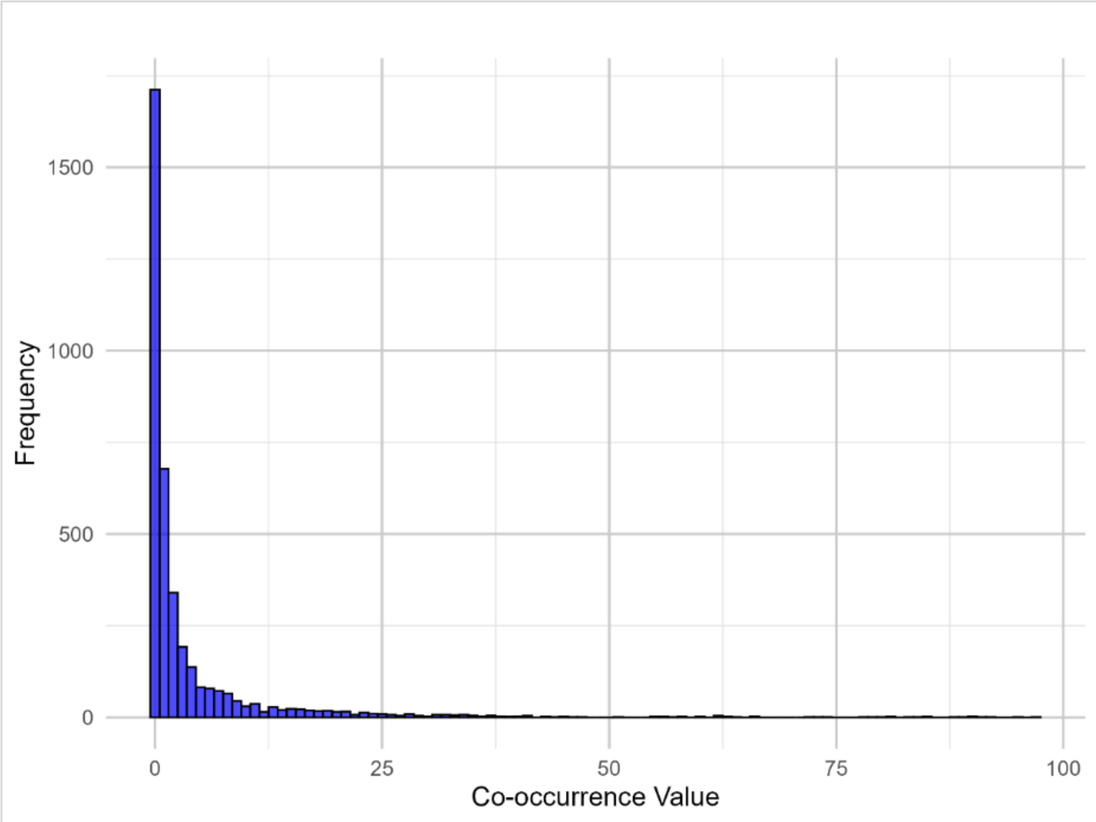

Figure 3.16: Histogram representation of co-occurrence values of the waterbird species in the post-monsoon season.

3.3.8 Multivariate Patterns of Waterbird Assemblages Across Seasons

The results of the statistical analyses revealed significant seasonal variations in waterbird species composition. PERMANOVA analysis demonstrated a substantial difference between the summer and winter assemblages ($F = 21.70$, $p < 0.05$), with a significant effect of season on community structure. This was further supported by ANOSIM analysis, which showed a moderate separation between the seasonal groups ($R = 0.33$, $p < 0.05$). However, the PERMDISP test indicated no significant difference in the multivariate dispersion between the seasons ($F = 0.17$, $p > 0.05$), suggesting that the observed differences were not due to seasonal variability in species distribution.

The NMDS plot, with a stress value of 0.27, visually confirmed the seasonal segregation of species, with clear separation of pre-monsoon and post-monsoon seasons, further substantiating the seasonal differences in waterbird assemblages (Figure 3.17).

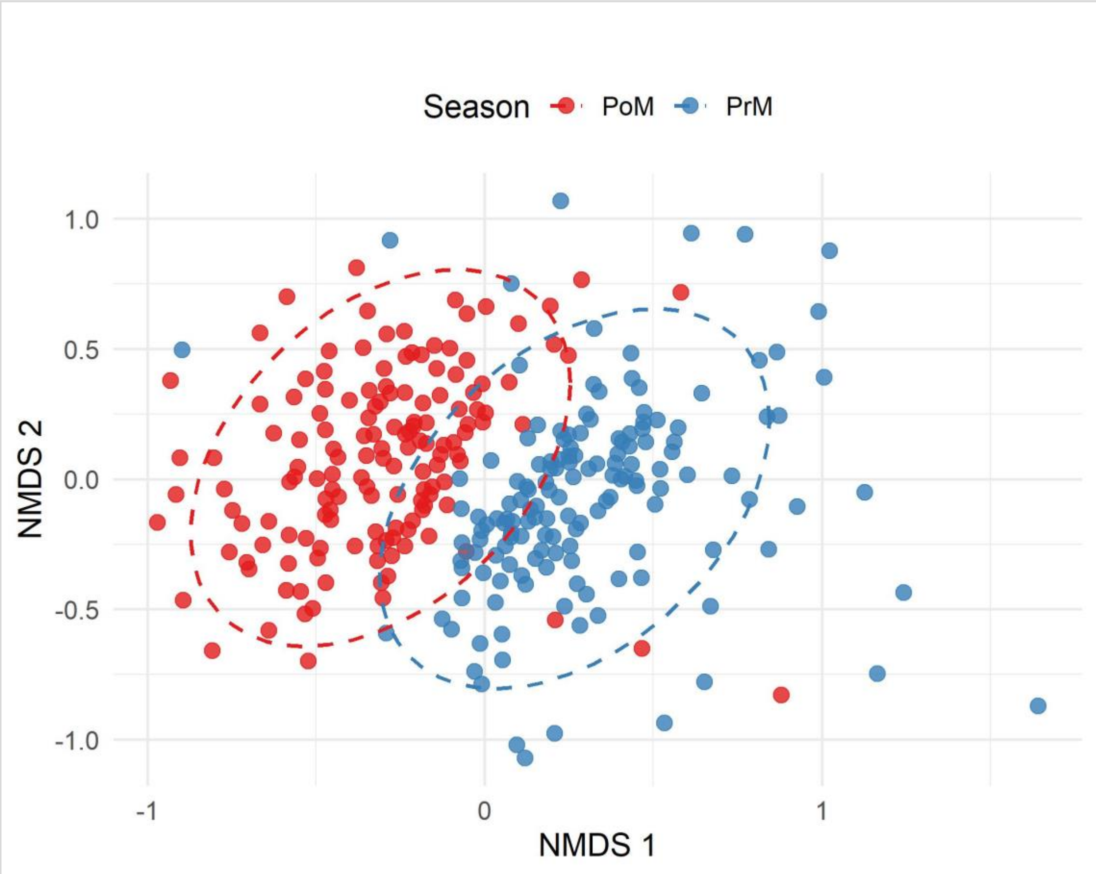

Figure 3.17: Non-metric multidimensional scaling (NMDS) plots based on Bray-Curtis represent the dissimilarity between post-monsoon and pre-monsoon.

SIMPER analysis identified 44 waterbird species with significant seasonal differences ($p < 0.05$), including the great cormorant (contribution: 0.11) and ruddy shelduck (contribution: 0.06), which dominated the post-monsoon season. Wading birds characterised the pre-monsoon season, with little pratincole (contribution: 0.04) and river lapwing (contribution: 0.04) showing significantly higher abundances, demonstrating clear seasonal habitat utilisation patterns. The cumulative contribution of significant species reached 1.0, with the top three species (great cormorant, little cormorant, and ruddy shelduck) accounting for 25.5% of the total seasonal dissimilarity between post-monsoon and pre-monsoon (Table 3.5).

Table 3.5: Waterbird Species Contributing to Seasonal Dissimilarity Between Post-monsoon and Pre-monsoon, Ranked by SIMPER Significance.

Species	Average dissimilarity	*p-value*
Great Cormorant	0.1063	0.001
Ruddy Shelduck	0.0616	0.001
Bar-headed Goose	0.0335	0.001
Common Greenshank	0.0274	0.001
sLittle Egret	0.0259	0.001
Grey Heron	0.0135	0.001
Gadwall	0.0135	0.001
Red-wattled lapwing	0.0128	0.001
Little Tern	0.0123	0.001
Pallas's Gull	0.0082	0.001
Great White Egret	0.0063	0.001
Eurasian Curlew	0.0059	0.001
Common Sandpiper	0.0038	0.001
Osprey	0.0004	0.001
River Lapwing	0.0384	0.002
Green Sandpiper	0.0021	0.002
White Wagtail	0.0007	0.003
Little Pratincole	0.0405	0.004
Indian Pond-heron	0.0083	0.004
Temminck's Stint	0.0165	0.005

Asian Woollyneck	0.0018	0.005
Red-naped Ibis	0.0234	0.006
Mallard	0.0037	0.008
Common Teal	0.0068	0.009
Common Crane	0.0070	0.010
Sarus Crane	0.0155	0.014
Common Redshank	0.0020	0.014
Black Stork	0.0008	0.023
Goosander	0.0009	0.024
Pied Kingfisher	0.0055	0.028
Cattle Egret	0.0181	0.030
Greylag Goose	0.0011	0.032
Asian Openbill	0.0301	0.033
Great White Pelican	0.0022	0.033
Common Kingfisher	0.0001	0.033
Common Pochard	0.0025	0.036
Black-bellied Tern	0.0059	0.047
Indian Cormorant	0.0438	0.050
Common Shelduck	0.0003	0.050

3.4 Discussion

This study offers a comprehensive assessment of waterbird richness, diversity, and community structure along a 750 km river stretch of the middle Ganga. These findings offer novel insights into waterbird assemblages and underscore the importance of the area as a critical riverine habitat supporting a diverse array of waterbird species and as a dynamic system characterised by distinct seasonal variations.

I observed 2,34,468 waterbirds recorded over six sampling seasons, comprising 107 species, 25 families, and 11 orders. This high species richness and abundance underline the significance of the study area for both resident and migratory waterbirds. The observed species, which was near the estimated species richness (Chao-2, Jackknife 1, and Jackknife 2), indicated that the survey captured >98% of the species present. In the 80 km stretch within the Hastinapur Wildlife Sanctuary, Khan et al. (2013) reported 53 species of waterbirds, while I recorded 87 species. Joshi et al. (2021) and Arya et al. (2020) documented 66 and 92 aquatic species, respectively, from the Haiderpur Wetland, a backwater area of the Middle Ganga Barrage on the Ganga River. Rahmani (1981) reported 30 important waterbirds from a small stretch of the Ganga River near Narora Barrage, and Bashir et al. (2012) recorded 50 waterbirds from the same area. Rao (2001) documented 48 species from a stretch between Rishikesh and Kanpur. In comparison, we recorded 62 waterbirds from this stretch. While most previous studies have focused on specific areas of the middle stretch, we covered the entire stretch, covering 750 km from Balawali in District Bijnor to Sangam in District Prayagraj, Uttar Pradesh. That resulted in 102 aquatic species from the non-protected stretch. Our study documented that 33.5% of all waterbird species and 8% of the total avifauna reported in India (Kumar et al. 2005; BirdLife International 2024).

Charadriiformes consistently represented the dominant order across all seasons, whereas Anseriformes displayed notable seasonal peaks, particularly during the post-monsoon season. The presence of well-represented families, such as Anatidae and Scolopacidae, suggests diversity in feeding guilds and habitat preferences. Importantly, the detection of three Vulnerable, eleven Near Threatened, and five Endangered species, along with 15 species listed under Schedule I of the Wild Life

(Protection) Act, 1972, affirms the conservation significance of the area at both national and international levels.

Species across the 15 sites showed a combination of broadly distributed and site-specific species, with 34 species recorded at all sites and seven restricted to a single site. Pre-monsoon values for species diversity, richness, and evenness were generally higher than post-monsoon values, indicating seasonal variation in community structure. Despite these seasonal differences, statistical analysis revealed no significant difference in species richness between the pre- and post-monsoon periods, suggesting temporal stability in the overall richness patterns.

Beta diversity analyses revealed a moderate overall dissimilarity ($\beta = 0.18$), primarily driven by species turnover (73.22%) rather than nestedness. This pattern indicated that community changes were mainly due to species replacement. The season-specific beta diversity increased during the pre-monsoon ($\beta = 0.29$) and post-monsoon ($\beta = 0.32$) periods, with turnover being the dominant component (72.79% and 86.56%, respectively). These findings highlight the seasonal restructuring of the waterbird communities.

Multivariate statistical analyses provided further support for the seasonal variation in community structure. PERMANOVA ($F = 21.70$, $p < 0.05$) and ANOSIM ($R = 0.33$, $p < 0.05$) revealed significant differences between seasonal assemblages. The NMDS ordination (stress value = 0.27) visually confirmed these differences, with a clear segregation between the summer and winter sites. PERMDISP results indicated no significant difference in multivariate dispersion, suggesting that the observed differences were attributable to actual changes in community composition rather than seasonal variability.

The study stretch is important for both resident and migratory birds and necessitates continuous protection and management. The presence of threatened and protected species requires focused action, including habitat restoration and minimising anthropogenic disturbances. High seasonal turnover calls for flexible conservation strategies that respond to temporal changes in the community composition. Continuous monitoring is essential to track trends, evaluate conservation effectiveness, and mitigate emerging threats.

This study highlights the rich avian diversity and ecological importance of the riverine corridor under investigation. The distinct seasonal dynamics, high waterbird diversity, and the occurrence of threatened species emphasise the necessity of science-based adaptive conservation planning. By establishing a detailed ecological baseline, this research provides a foundation for future studies and informed management, ensuring the long-term preservation of these vital avian communities.

CHAPTER 4
HABITAT FEATURES AND ANTHROPOGENIC PRESSURE GOVERNING WATERBIRD ASSEMBLAGES

4.1 Introduction

The cumulative response of individual organisms to ecological and environmental variation plays a critical role in shaping biological communities. Investigating patterns pertaining to the interactions between organisms and their environment have remained the soul of ecological studies for more than a century now, and birds remain one of the focal studied groups (Ghosh-Harihar & Price, 2014; Gotelli and Colwell, 2001; Grant, 1999; Price et al., 2015; Rotenberry, 1985). The decision of birds to utilise a habitat is the result of a hierarchically structured system of sequential decisions based on inherent and learnt behaviour, as well as trial-and-error testing of habitat characteristics and resources (Cody, 1981; Weller, 1999). High species richness and abundance of waterbirds in any given wetland indicate high resource quality and the availability of a mosaic of habitats (Gonzalez-Gajardo et al., 2009). This interaction between environmental factors and species responses provides a foundation for understanding local ecological dynamics, especially in sensitive aquatic ecosystems. Local-scale factors significantly influence species extinction patterns, with site-specific variations playing as critical a role as species-level vulnerabilities in driving population declines (Cowlishaw et al., 2009).

Vegetation structure, food resource availability, and trophic interactions are key determinants of waterbird assemblages, with emergent vegetation providing critical shelter, feeding, and nesting areas (Brandolin & Blendinger, 2016; Chatterjee et al., 2020; Constantin et al., 2019; Froneman et al., 2001). The study of interactions between biotic and abiotic factors becomes essential to understanding the waterbird community structure of wetlands (Dunson & Travis, 1991).

Natural riverine landscapes form linear habitats with complex land-water interactions mediated by the exchange of matter and energy (Ward et al., 2002). These support biodiverse communities, which are uniquely adapted to exploit the high turnover of habitat types characteristic of riverine ecosystems (He et al., 2018; Robinson et al., 2002). Globally, waterbirds constitute an abundant, diverse, and conspicuous element of vertebrate fauna inhabiting riverine areas (Ormerod and Tyler, 1993; Sullivan et al., 2007). They depend on riverine resources for their feeding, breeding, and roosting. Assessing the habitat requirements of waterbirds is central to understanding their distribution and abundance and can potentially enhance their roles in understanding changes in the riverine structure and underlying processes (Buckton and Ormerod, 1997).

Additionally, several species show sensitivity towards anthropogenic factors such as livestock grazing, hunting, tourism, pollutants, predation, invasion, and trampling of eggs and nests (Cardoni et al., 2008; Gan et al., 2007; Quan et al., 2002; Ramachandran et al., 2017; Tavares et al., 2015; Villamagna et al., 2012). In addition, human activities, such as extensive extraction of aquatic resources, have caused a decrease in waterbird abundance in wetlands around the globe (Aarif et al., 2014). Given that various environmental factors regulate the distribution of waterbirds around the globe, climate change may likely cause a distributional range shift of waterbird species and perhaps further lead to a decline in their population (Lehikoinen et al., 2013; Ramirez et al., 2018).

This chapter deals with a detailed assessment of natural and anthropogenic factors potentially affecting the waterbirds based on field surveys. The objective was to determine the relationship of anthropogenic, biological, hydrological, and geomorphological parameters of riverine ecosystems with waterbird assemblage structure and identify the important factors that help select river habitats for the different activities of waterbirds.

4.2 Methodology

Waterbird abundance data were collected along a 750 km stretch of river divided into 150 segments, each 5 km in length, referred to as Biodiversity Evaluation Units (BEUs) (Das et al., 2022). Observations were conducted across six sampling periods, three in the pre-monsoon and three in the post-monsoon seasons. For each BEU, species-level abundance data were compiled and averaged across the pre-monsoon and post-monsoon periods to represent seasonal values.

Environmental parameters such as channel width, channel depth, vegetation cover, bank features, and anthropogenic variables such as sand mining, riverbed agriculture, dumping of solid waste on the riverbanks, and settlement proximity were recorded for each BEU for both seasons (Table 4.1). Continuous variables were averaged across surveys; binomial variables were scored as present if observed at least once. Categorical variables such as elevation classes and protection status were uniformly coded.

The dataset was further stratified into three elevation classes: Upper (61-120 m asl), Middle (121-180 m asl), and Lower (181-240 m asl) river stretches. Additionally, settlement categories were defined as Urban (US; district headquarters), Semi-urban (SU; small towns), Rural (RS; villages), and Unsettled (US; no settlement within one km of the riverbanks). Protection status was classified into three groups: Hastinapur Wildlife Sanctuary (HPW), Upper Ganga River Ramsar Site (UGR), and unprotected (UnP) segments.

Species occurring in less than 1% of BEUs were excluded, and abundance data were subjected to Hellinger transformation to meet the assumptions of linear ordination techniques. All variables were standardised before analysis. All statistical analyses were conducted in R using RStudio. The packages *vegan* v 2.6-4 (Oksanen et al., 2022), *indicspecies* v 1.7.12 (Cáceres & Legendre, 2009), betapart (Baselga & Orme, 2012; Baselga et al., 2022), and ggplot2 (Wickham, 2016, 2023) were used for the analysis of assemblage patterns, indicator species detection, beta diversity partitioning, and visualisation, respectively. The analysis was conducted separately for pre-monsoon and post-monsoon datasets to capture seasonal variation.

Table 4.1: Description of environmental parameters used in the study.

Nature	Name of the Environmental Parameters	Data type	Description
Habitat Variables	Channel width	Continuous	Mean channel width/5 km linear stretch
	Channel depth	Continuous	Mean channel depth/5 km linear stretch
	Vegetation cover	Continuous	Dominant vegetation cover feature (Exposed/Partially Covered/Fully Covered)
	Bank features	Categorical	Dominant feature of the bank slope (Low (<45°)/medium (45°-90°)/high (>90°)
Anthropogenic variables	Sand mining	Count	Visual counts/5 km linear stretch
	Riverbed agriculture	Categorical	Presence/5 km linear stretch
	Dumping of solid waste on the riverbanks	Count	Visual counts/5 km linear stretch
	Settlement proximity	Continuous	Distance to nearest settlement: 5 km linear stretch

To assess the significance of compositional differences in assemblages across elevation, protection, and settlement classes, Permutational Multivariate Analysis of Variance (PERMANOVA) was conducted using the *adonis*() function with Bray–Curtis distances (Anderson, 2001). Homogeneity of group dispersion was tested with PERMDISP to validate PERMANOVA assumptions (Anderson, 2006).

To identify bird species contributing to differences between elevation, protection, and settlement classes, Similarity Percentage (SIMPER) analysis was performed. Only species that cumulatively explained over 50% of between-group dissimilarity were considered in the ordination interpretations (Asefa et al., 2017).

Non-metric Multidimensional Scaling (NMDS) was employed to visualise waterbird assemblage patterns across different elevational, protection, and settlement classes. NMDS was based on Bray–Curtis dissimilarity, which is robust for community data that emphasises differences in abundance while down-weighting joint absences (Schroeder & Jenkins, 2018; Lorenzón et al., 2019).

To examine patterns of species turnover and nestedness, β-diversity was assessed using the *betapart* package. Total beta diversity (βSOR) was partitioned into species turnover (βSIM) and nestedness-driven dissimilarity (βSNE). Pairwise dissimilarities were computed across elevation, settlement, and protection classes to quantify spatial heterogeneity in bird assemblages (Baselga et al., 2022).

To address multicollinearity among environmental and anthropogenic predictors, a two-step process was adopted. First, a pairwise Pearson correlation matrix was examined, and variables with high correlations ($|r| > 0.7$) were flagged for potential exclusion. Subsequently, Variance Inflation Factors (VIFs) were computed from the global RDA model, and variables with $VIF > 10$ were removed iteratively to minimise collinearity and improve model interpretability (Zuur et al., 2009).

To determine the appropriate ordination method (RDA or CCA), Detrended Correspondence Analysis (DCA) was first performed on the species abundance data. Prior to analysis, the data were subjected to Hellinger transformation to reduce the influence of double zeros and make the data suitable for linear ordination methods.

Where DCA revealed gradient lengths exceeding four standard deviation (SD) units, indicating unimodal species responses, Canonical Correspondence Analysis (CCA) was employed instead of Redundancy Analysis (RDA) (Legendre & Legendre, 2012; ter Braak, 1986) to analyse the relationships between waterbird assemblage patterns and anthropogenic, biological, hydrological, and geomorphological parameters of rivers (Legendre & Legendre, 2012; ter Braak, 1986).

Canonical Correspondence Analysis (CCA) was employed on both pre-monsoon and post-monsoon data to elucidate the relationships between waterbird assemblage and measured habitat variables (Legendre & Legendre, 2012; ter Braak, 1986). The species matrix was Hellinger-transformed to account for the double-zero (Legendre and Gallagher, 2001). Habitat variables were standardised using z-score transformation following Oksanen et al. (2022). CCA was performed using the *vegan* package in R (version 4.0.3), with statistical significance assessed through permutation tests (999 permutations, $p < 0.05$).

4.3 Results

4.3.1 Multivariate Analysis of Waterbird Assemblage Patterns

4.3.1.1 Influence of Elevational Variations in Waterbird Assemblage Patterns

PERMANOVA results demonstrated highly significant differences in waterbird assemblage composition among the three elevation classes (Upper, Middle, and Lower) in both seasons. During the pre-monsoon period, the assemblage structure varied significantly across elevation classes (PERMANOVA: $F=3.99$, $R^2=0.23$, $p < 0.05$). These differences were even more pronounced in the post-monsoon period (PERMANOVA: $F=6.04$, $R^2=0.32$, $p < 0.05$).

To ensure that the observed differences were not due to unequal within-group variability, PERMDISP was used to test for homogeneity of multivariate dispersions. The results confirmed that group dispersions were homogeneous in both the pre-monsoon and post-monsoon seasons, validating the robustness of the PERMANOVA findings and confirming that the differences in assemblage composition are genuine and not artefacts of dispersion.

ANOSIM further confirmed these patterns, with the rank-based statistic indicating moderate to strong separation between elevation classes. In the pre-monsoon season, the ANOSIM statistic was $R=0.23$ ($p < 0.05$), while in the post-monsoon season, the statistic increased to $R=0.32$ ($p < 0.05$).

The SIMPER analysis conducted for the pre-monsoon period highlighted distinct differences in avian species composition across the upper, middle, and lower stretches of the study area. Between the upper and middle stretches, the overall dissimilarity was 40.27%. The Asian plain martin was the primary contributor, with an average dissimilarity (ad) of 0.12, contributing 28.72% of the overall dissimilarity (cod). It exhibited a significantly higher mean abundance in the upper stretch (117.00) than in the middle stretch (17.27), suggesting a strong preference for the upper stretch. Other species, including the little pratincole (cod = 25.82%; ad = 0.10; ava = 54.70; avb = 30.20) and garganey (cod = 7.02%; ad = 0.03; ava = 8.74; avb = 4.60), also contributed significantly. A total of 17 species collectively accounted for 100% of the total dissimilarity. The comparison between the middle and lower reaches revealed a lower overall dissimilarity of 12.97%. The Temminck's stint was the leading contributor (cod = 22.81%; ad = 0.03; ava = 19.63; avb = 7.47), followed by the Knob-billed duck (cod

= 18.04%; ad = 0.023; ava = 12.87; avb = 1.49). The top ten species accounted for 98.70% of the dissimilarity.

The greatest dissimilarity was observed between the upper and lower reaches, with an overall dissimilarity of 12.59%. The Asian plain martin was the major contributor (cod = 81.82%; ad = 0.10; ava = 117.00; avb = 9.77), followed by the Garganey (cod = 16.59%; ad = 0.02; ava = 8.74; avb = 0.01) and Pallas's gull (cod = 0.002; ad = 1.59; ava = 1.15; avb = 0.03). These three species alone accounted for 97.80% of the dissimilarity, highlighting the pronounced ecological gradient between these reaches (Table 4.2).

The post-monsoon SIMPER analysis similarly revealed significant differences in species composition across reaches, reflecting seasonal shifts in avian distribution and habitat preference. For the upper and middle reaches, the overall dissimilarity was 48.49%. The Ruddy Shelduck (cod = 25.57%; ad = 0.12, ava = 66.74; avb = 54.02) was the dominant contributor, followed by the Bar-headed Goose (cod = 25.48%; ad = 0.12, ava = 94.48; avb = 20.43). The top seven species accounted for 79.90% of the total dissimilarity. The middle and lower reaches exhibited an overall dissimilarity of 34.58%. The Ruddy Shelduck (cod = 29.26%; ad = 0.10; ava = 54.02; avb = 11.42), followed by the Indian (cod = 17.02%; ad = 0.06; ava = 42.36; avb = 0.87), were the top contributors. The top nine species accounted for 85.80% of the total. The upper and lower reaches showed an overall dissimilarity of 19.66%. The Bar-headed goose (Cod = 51.22%; ad = 0.10; ava = 94.48; avb = 1.97) and little cormorant (Cod = 29.17%; ad = 0.057; ava = 40.04; avb = 2.62) contributed the most to the dissimilarity.

The top four species accounted for 85.20% of the dissimilarity, emphasising the significant ecological differences between these reaches (Table 4.2).

Table 4.2: Results of SIMPER analysis for elevation variations across different stretches.

Pre-monsoon					
Species	**Average dissimilarity (ad)**	**Contribution % to overall dissimilarity (cod)**	**Cumulative % of dissimilarity**	**Mean abundance of species in group A (ava)**	**Mean abundance of species in group B (avb)**
Upper (Group A)-Middle (Group B)					
Asian Plain Martin	0.11569	28.72	13.10	117.00	17.27
Little Pratincole	0.10400	25.82	24.90	54.70	30.20
Garganey	0.02827	7.02	44.00	8.74	4.60
Knob-billed Duck	0.02797	6.94	47.20	1.19	12.87
Common Greenshank	0.02694	6.69	50.20	5.44	11.18
Ruddy Shelduck	0.02657	6.60	53.30	10.96	6.13
River Tern	0.02008	4.99	68.90	4.81	8.89
Indian Spot-billed Duck	0.01888	4.69	71.00	2.56	8.11
Great Thick-knee	0.01169	2.90	85.70	0.63	3.44
Black-bellied Tern	0.00963	2.39	89.30	1.19	2.78
Marsh Sandpiper	0.00438	1.09	95.20	1.41	0.02
Common Sandpiper	0.00307	0.76	95.90	0.67	0.82
Pallas's Gull	0.00218	0.54	97.60	1.15	0.09
Black-necked Stork	0.00176	0.44	97.80	0.04	0.40
Eurasian Curlew	0.00103	0.26	99.10	0.22	0.27
Citrine Wagtail	0.00064	0.16	99.30	0.22	0.13
Ruff	0.00002	0.00	100.00	0.04	0.00

Middle (Group A) – Lower (Group B)					
Temminck's Stint	0.02958	22.81	55.30	7.47	19.63
Knob-billed Duck	0.02339	18.04	67.60	12.87	1.49
Common Greenshank	0.02108	16.26	72.60	11.18	1.94
Indian Spot-billed Duck	0.01422	10.97	80.00	8.11	0.18
River Tern	0.01255	9.68	84.60	8.89	0.12
Red-naped Ibis	0.01082	8.34	85.90	4.11	1.87
Great Thick-knee	0.00887	6.84	91.20	3.44	0.23
Black-bellied Tern	0.00671	5.17	93.60	2.78	0.17
Black-necked Stork	0.00130	1.00	98.40	0.40	0.08
Red-crested Pochard	0.00115	0.89	98.60	0.58	0.09
Upper (Group A)-Lower (Group B)					
Asian Plain Martin	0.10299	81.82	11.20	117.00	9.77
Garganey	0.02088	16.59	68.80	8.74	0.01
Pallas's Gull	0.00200	1.59	97.80	1.15	0.03
Post-monsoon					
Upper (Group A)-Middle (Group B)					
Ruddy Shelduck	0.12398	25.57	15.00	66.74	54.02
Bar-headed Goose	0.12355	25.48	29.90	94.48	20.43
Little Cormorant	0.07558	15.59	39.00	40.04	20.61
Indian Cormorant	0.06517	13.44	46.90	10.11	42.36
Indian Spot-billed Duck	0.02514	5.18	66.50	5.19	9.59
Pallas's Gull	0.02217	4.57	69.20	9.56	3.89
River Tern	0.01236	2.55	79.90	8.00	1.73
Mallard	0.01154	2.38	81.20	2.81	2.82
Eurasian Wigeon	0.00901	1.86	84.90	4.30	0.18
Black Stork	0.00425	0.88	93.30	1.33	0.05
Great White Egret	0.00400	0.82	94.30	1.70	0.25
Goosander	0.00396	0.82	94.80	1.33	0.45
Black-necked Stork	0.00137	0.28	98.50	0.74	0.20

Osprey	0.00107	0.22	98.70	0.41	0.14
Black-headed Gull	0.00092	0.19	99.10	0.63	0.02
Pallas's Fish-eagle	0.00042	0.09	99.60	0.15	0.00
Common Kingfisher	0.00038	0.08	99.70	0.07	0.02
Black-headed Ibis	0.00008	0.02	100.00	0.04	0.00
Middle (Group A) – Lower (Group B)					
Ruddy Shelduck	0.10117	29.26	31.20	54.02	11.42
Indian Cormorant	0.05886	17.02	37.70	42.36	0.87
Common Greenshank	0.03763	10.88	57.20	3.64	18.91
River Lapwing	0.02449	7.08	63.10	3.91	11.30
Indian Spot-billed Duck	0.02213	6.40	65.60	9.59	0.27
Common Crane	0.01938	5.60	67.70	8.27	3.08
Grey Heron	0.01792	5.18	71.80	4.57	8.60
Eurasian Curlew	0.01492	4.31	79.00	6.43	0.86
Black-bellied Tern	0.00956	2.76	85.80	3.16	1.04
Common Pochard	0.00789	2.28	89.50	4.36	0.00
Common Sandpiper	0.00676	1.95	91.00	2.25	1.32
Sarus Crane	0.00498	1.44	92.80	1.98	0.53
Little Grebe	0.00456	1.32	93.30	2.34	0.01
Green Sandpiper	0.00443	1.28	93.80	1.34	0.31
Red-wattled lapwing	0.00412	1.19	94.70	1.50	0.43
Red-crested Pochard	0.00265	0.77	96.90	0.98	0.04
Lesser Whistling Duck	0.00247	0.71	97.20	1.27	0.00
White-browed Wagtail	0.00099	0.29	99.10	0.32	0.10
Wood Sandpiper	0.00055	0.16	99.50	0.23	0.03
Citrine Wagtail	0.00033	0.10	99.70	0.20	0.00
Upper (Group A)-Lower (Group B)					
Bar-headed Goose	0.10069	51.22	32.00	94.48	1.97
Little Cormorant	0.05734	29.17	55.60	40.04	2.62
Pallas's Gull	0.01929	9.81	68.90	9.56	1.12
River Tern	0.01073	5.46	85.20	8.00	0.38

Black Stork	0.00379	1.93	93.60	1.33	0.00
Great White Egret	0.00371	1.89	94.50	1.70	0.44
Black-necked Stork	0.00104	0.53	98.50	0.74	0.01

Non-metric Multidimensional Scaling (NMDS) ordination also revealed distinct patterns in waterbird assemblages across elevation classes in both pre-monsoon and post-monsoon seasons. The NMDS stress values (0.15 for pre-monsoon; 0.17 for post-monsoon) fell within acceptable ranges (< 0.20), supporting the reliability of the ordination results (Figures 4.1 & 4.2).

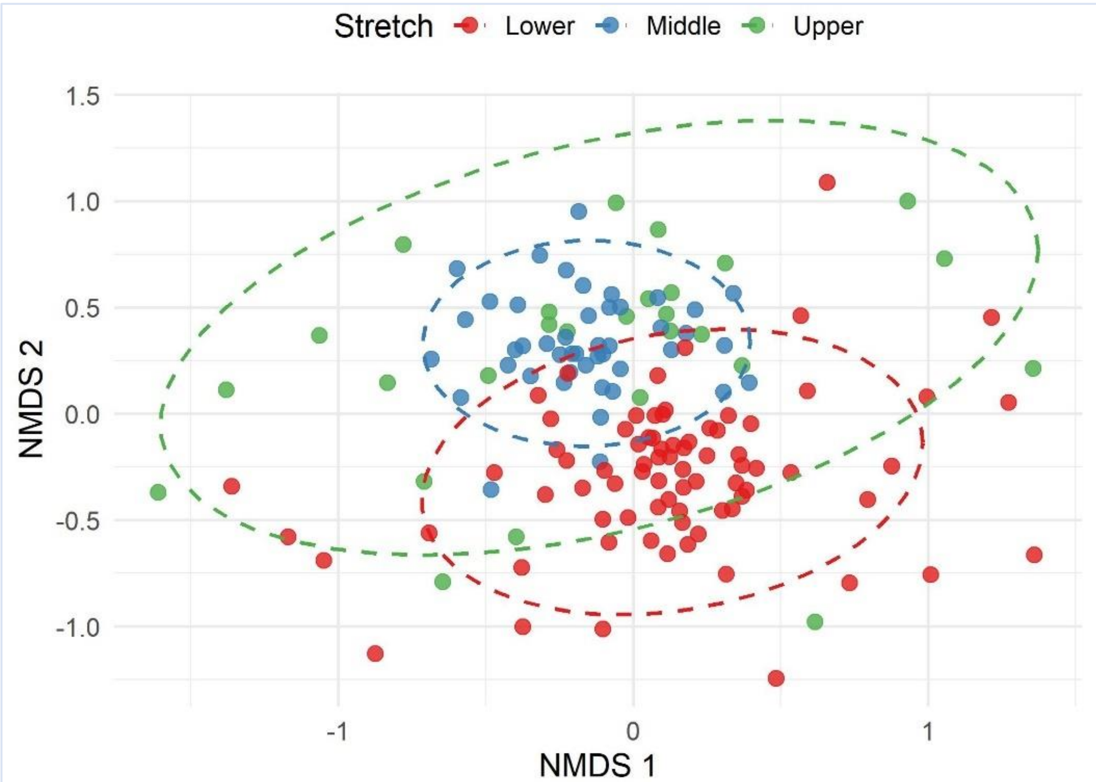

Figure 4.1: NMDS results for pre-monsoon elevation variations.

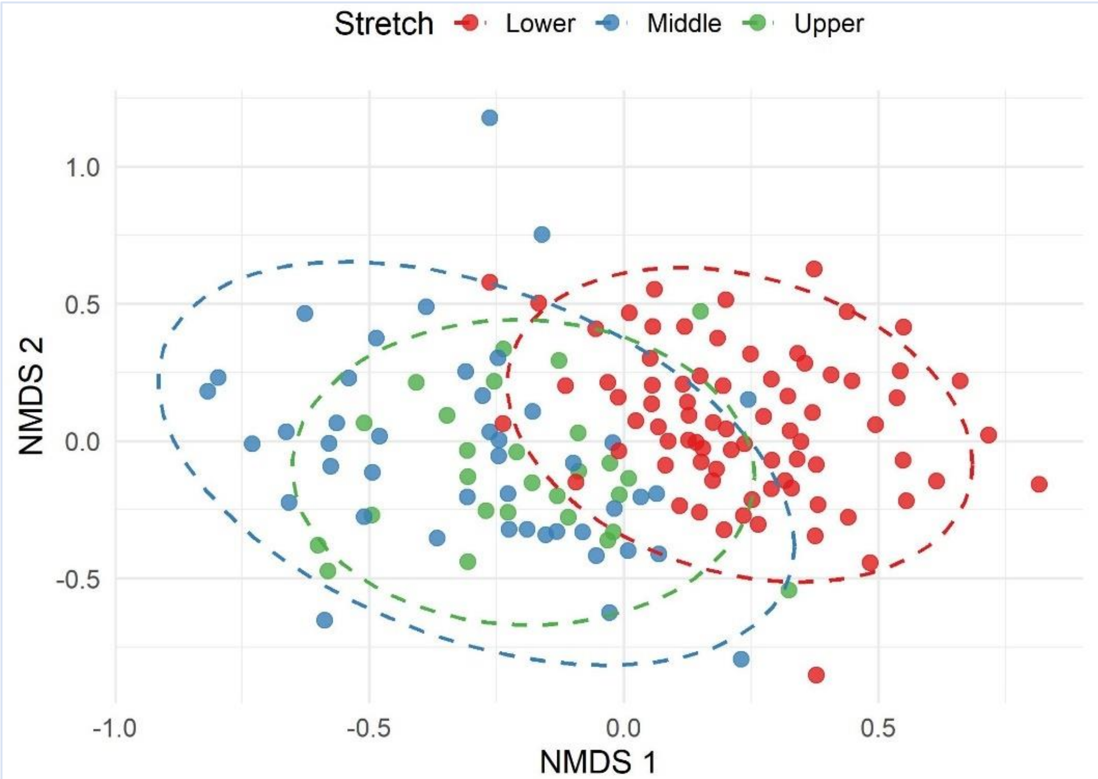

Figure 4.2: NMDS results for post-monsoon elevation variations.

4.3.1.2 Influence of Protection Classes on Waterbird Assemblage Patterns

PERMANOVA analysis demonstrated significant differences in waterbird assemblages among the protection classes in both seasons. During the pre-monsoon season, protection class explained a significant proportion of the variation in assemblage structure ($F = 3.03$, $R^2 = 0.04$, $p < 0.05$), explaining 3.9% of the total variation in waterbird assemblage composition that could be attributed to differences in protection classes.

The post-monsoon season revealed a similar pattern of significant assemblage differentiation among the protection classes ($F = 3.27$, $R^2 = 0.04$, $p < 0.05$), with protection classes explaining 4.3% of the total variation in assemblage structure. The consistent significance across both seasons ($p < 0.05$) indicates that the protection class effects on waterbird assemblages were robust and persistent throughout the season.

PERMDISP analysis revealed significant differences in multivariate dispersion among the protection classes in both seasons, necessitating careful interpretation of the PERMANOVA results. During the pre-monsoon season, the test for homogeneity of multivariate dispersions was significant ($F = 3.46$, $p < 0.05$), indicating that the assumption of equal dispersions among the protection classes was violated. This finding suggests that the significant PERMANOVA result may be partially influenced by differences in within-group variability, rather than solely reflecting differences in assemblage centroids. The post-monsoon season showed a stronger violation of the dispersion homogeneity assumption ($F = 4.45$, $p < 0.05$), with the significance level being more pronounced than that in the pre-monsoon period. The slight increase in the F-statistic from pre-monsoon to post-monsoon (3.46 to 4.45) suggests that protection-related differences in assemblage variability become more pronounced in the post-monsoon period.

ANOSIM analysis provided rank-based confirmation of assemblage differences among protection classes, supporting the PERMANOVA findings while offering additional insights into the strength of separation between groups. During the pre-monsoon season, ANOSIM detected significant assemblage differences among the protection classes ($R = 0.14$, $p < 0.05$), with the R-statistic indicating weak but meaningful separation between the groups. The R-value of 0.14 suggests that while assemblages are distinguishable among protection classes, there is a considerable overlap in assemblage composition. The post-monsoon season showed a slightly weaker but still significant separation among the protection classes ($R = 0.10$, $p < 0.05$). The significant p-values in both seasons ($p < 0.05$) confirmed that the observed assemblage differences were unlikely to have occurred by chance. However, the relatively low R-statistics in both seasons indicate that protection class effects, while statistically significant, represent moderate ecological differences rather than complete assemblage turnover among protection classes.

The SIMPER analysis for the pre-monsoon season elucidated distinct patterns in avian species composition across the Hastinapur Wildlife Sanctuary (HPW), Upper Ganges River Ramsar Site (UGR), and Unprotected (UnP) stretches, highlighting ecological gradients and differences in species distribution. For the comparison between HPW and UGR, the overall dissimilarity was 17.75%. The knob-billed duck (cod = 25.59%; ad = 0.045; ava = 26.00; avb = 1.39) was the primary contributor, followed by the common greenshank (cod = 18.21%; ad = 0.032; ava = 6.91; avb = 21.60). The top nine species accounted for 99.20% of the dissimilarity. The dissimilarity between UnP and UGR was 14.21%. The knob-billed duck (cod = 30.79; ad = 0.044; ava = 2.72; avb = 26.00) was again dominant, followed by the common greenshank (cod = 22.74%; ad = 0.03; ava = 2.84; avb = 21.60). The top five species accounted for 83.50% of the dissimilarity. The top 13 species contributed to 100% of the dissimilarity. Between UnP and HPW, the overall dissimilarity was notably higher (27.17%). The Asian plain martin was the dominant contributor (cod = 45.50%; ad = 0.12; ava = 137.35; avb = 11.45), followed by the little pratincole (cod = 30.79%; ad = 0.08; ava = 13.64; avb = 54.22). The top ten species contributed to 100% of the dissimilarity (Table 4.3).

The post-monsoon SIMPER analysis revealed significant seasonal shifts in species composition across the HPW, UGR, and UnP reaches, reflecting changes in habitat preferences and in ecological conditions. A comparison between HPW and UGR showed an overall dissimilarity of 40.34%. The bar-headed goose (cod = 3017; ad = 0.12; ava = 101.04; avb = 15.87) was the primary contributor, followed by the little cormorant (cod = 23.27%; ad = 0.09; ava = 37.04; avb = 37.80). These nine species accounted for 99.60% of the dissimilarity. For UnP versus UGR, the overall dissimilarity was 14.14%. The red-naped ibis (cod = 56.62%; ad = 0.080; ava = 48.87; avb = 5.01) and Indian spot-billed duck (cod = 23.80%; ad = 0.03; ava = 2.24; avb = 13.13) were the dominant contributors. Eight species accounted for 99.80% of the dissimilarity. The dissimilarity between UnP and HPW was 22.34%. The bar-headed goose (cod = 51.75%; ad = 0.11; ava = 9.45; avb = 101.04) and little cormorant (cod = 27.05%; ad = 0.06; ava = 7.01; avb = 37.04) were the primary contributors. The total of eight species accounted for 83.10% of the dissimilarity (Table 4.3). These patterns demonstrate that a small number of species, often with strong preferences for particular protection classes, are primarily responsible for the observed differences in waterbird assemblages along the river during the post-monsoon season.

Together, these results from both seasons underscore the importance of protected areas in supporting key waterbird species and maintaining community distinctiveness in the region. SIMPER analysis highlighted that a limited set of species, each with distinct protection class associations, drives the majority of community dissimilarity observed along the river.

Table 4.3: Results of SIMPER analysis for protection variations across seasons.

Species	Average dissimilarity (ad)	Contribution % to overall dissimilarity	Cumulative % of dissimilarity	Mean abundance of species in group A (ava)	Mean abundance of species in group B (avb)
Pre-monsoon					
HPW (Group A) – UGR (Group B)					
Knob-billed Duck	0.04541	25.59	37.70	1.39	26.00
Common Greenshank	0.03232	18.21	54.10	6.91	21.60
Little Stint	0.03129	17.63	61.40	8.91	14.20
Garganey	0.02566	14.46	67.30	8.09	10.80
River Tern	0.01990	11.21	76.90	1.78	19.00
Spotted Redshank	0.01548	8.72	80.60	0.96	17.87
Common Sandpiper	0.00301	1.70	96.90	0.78	1.40
Western Yellow Wagtail	0.00119	0.67	98.70	0.09	0.33
Citrine Wagtail	0.00084	0.47	99.20	0.26	0.27
Northern Shoveler	0.00081	0.46	99.30	0.00	0.40
White Wagtail	0.00073	0.41	99.50	0.17	0.20
Common Gull-billed Tern	0.00061	0.34	99.60	0.00	0.40
Demoiselle Crane	0.00021	0.12	99.90	0.00	0.07
UnP (Group A) – UGR (Group B)					
Knob-billed Duck	0.04377	30.79	28.50	2.72	26.00
Common Greenshank	0.03232	22.74	54.90	2.84	21.60
River Tern	0.02005	14.10	70.00	1.90	19.00
Indian Spot-billed Duck	0.01822	12.82	72.20	2.04	10.67
Spotted Redshank	0.01504	10.58	83.50	1.36	17.87

Blue-tailed Bee-eater	0.00582	4.09	94.00	0.13	8.33
Common Sandpiper	0.00298	2.10	96.60	0.23	1.40
Western Yellow Wagtail	0.00100	0.70	98.30	0.02	0.33
White-breasted Waterhen	0.00083	0.58	98.80	0.12	0.40
Northern Shoveler	0.00076	0.53	99.00	0.00	0.40
Common Gull-billed Tern	0.00059	0.42	99.30	0.00	0.40
Citrine Wagtail	0.00058	0.41	99.40	0.02	0.27
Demoiselle Crane	0.00019	0.13	100.00	0.00	0.07
UnP (Group A) - HPW (Group B)					
Asian Plain Martin	0.12365	45.50	13.80	11.45	137.35
Little Pratincole	0.08369	30.79	33.60	13.64	54.22
Ruddy Shelduck	0.02452	9.02	64.60	3.96	12.87
Garganey	0.01919	7.06	66.80	0.86	8.09
Whiskered Tern	0.01026	3.78	84.20	0.42	2.70
Marsh Sandpiper	0.00514	1.89	95.30	0.18	1.65
Pallas's Gull	0.00254	0.93	96.80	0.03	1.35
Common Sandpiper	0.00246	0.91	97.10	0.23	0.78
Eurasian Wigeon	0.00030	0.11	99.90	0.02	0.09
Ruff	0.00002	0.01	100.00	0.00	0.04
Post-monsoon					
HPW (Group A) – UGR (Group B)					
Bar-headed Goose	0.12171	30.17	14.30	101.04	15.87
Little Cormorant	0.09390	23.27	38.00	37.04	37.80
Red-naped Ibis	0.09219	22.85	48.80	19.30	48.87
Indian Spot-billed Duck	0.03586	8.89	66.10	6.09	13.13
Pallas's Gull	0.02669	6.62	73.30	12.17	4.07
Common Pochard	0.01611	3.99	77.30	0.00	9.00
Northern Shoveler	0.01217	3.02	82.10	0.26	11.00

Great White Egret	0.00424	1.05	94.00	1.91	0.40
Common Kingfisher	0.00057	0.14	99.60	0.09	0.07
UnP (Group A) – UGR (Group B)					
Red-naped Ibis	0.08005	56.62	35.60	5.01	48.87
Indian Spot-billed Duck	0.03365	23.80	62.60	2.24	13.13
Common Pochard	0.01716	12.14	72.70	0.52	9.00
Little Grebe	0.00727	5.14	91.00	0.46	3.67
Common Moorhen	0.00171	1.21	97.70	0.00	0.47
Purple Swamphen	0.00073	0.52	99.30	0.00	0.20
Citrine Wagtail	0.00056	0.40	99.50	0.05	0.27
Purple Heron	0.00026	0.18	99.80	0.02	0.07
UnP (Group A) - HPW (Group B)					
Bar-headed Goose	0.11562	51.75	30.30	9.45	101.04
Little Cormorant	0.06042	27.05	46.90	7.01	37.04
Pallas's Gull	0.02600	11.64	69.90	1.58	12.17
River Tern	0.01056	4.73	83.10	1.16	7.57
Black Stork	0.00457	2.05	92.70	0.02	1.57
Great White Egret	0.00422	1.89	93.20	0.37	1.91
Osprey	0.00101	0.45	98.70	0.16	0.35
Black-necked Stork	0.00100	0.45	98.80	0.16	0.48

Non-metric Multidimensional Scaling (NMDS) ordination revealed clear patterns in waterbird assemblage structure across protection classes during both the pre-monsoon and post-monsoon seasons. In the pre-monsoon period, waterbird assemblages exhibited pronounced stratification by protection class, with Hastinapur WLS (HPW), Upper Ganga Ramsar (UGR), and unprotected (UnP) sites forming distinct clusters in the ordination space (Figure 4.3).

In the post-monsoon season, the NMDS ordination showed a higher overlap among the protection classes. While some clustering by protection was still evident, the boundaries between the HPW, UGR, and UnP communities became less distinct, with UGR and UnP exhibiting substantial convergence in the ordination space (Figure 4.4).

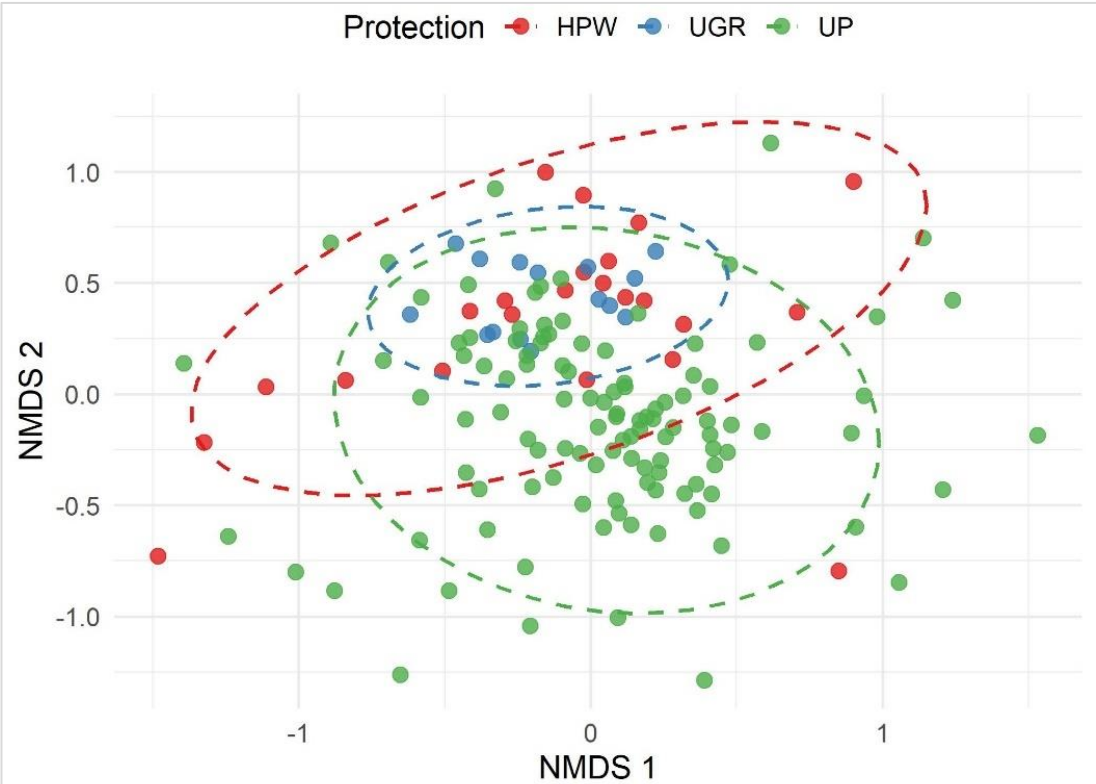

Figure 4.3: NMDS results of pre-monsoon for protection level.

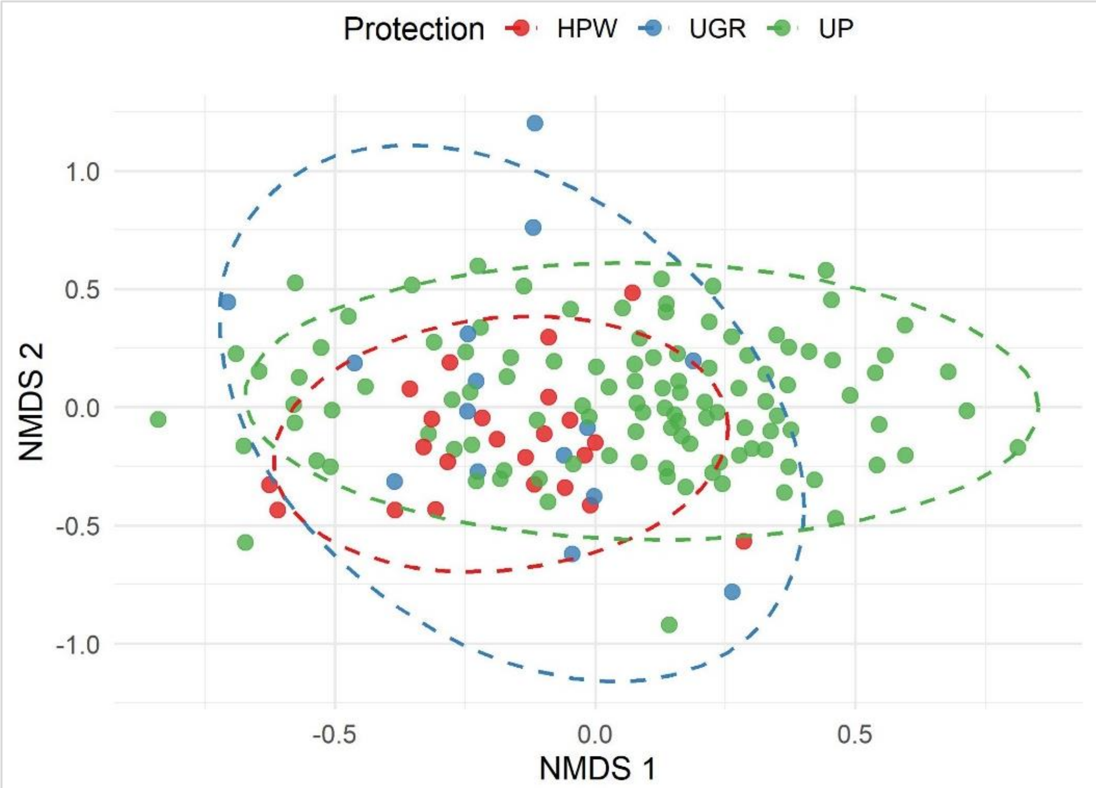

Figure 4.4: NMDS results of post-monsoon for protection level.

4.3.1.3 Influence of Settlement Classes on Waterbird Assemblage Patterns

Permutational multivariate analysis of variance (PERMANOVA) was performed to test for significant differences in waterbird assemblages among the four settlement classes across the pre-monsoon and post-monsoon seasons. During the pre-monsoon season, the analysis revealed that settlement class had a statistically significant effect on waterbird assemblage structure ($F = 2.18$, $p < 0.05$). The variance explained indicated that the settlement class accounted for a moderate proportion of the assemblage variability ($R^2 = 0.11$), representing approximately 11% of the total variation in waterbird assemblage structure during this period. The post-monsoon season demonstrated a similar pattern of assemblage differentiation among settlement classes, with maintained statistical significance ($F = 2.02$; $p < 0.05$). The explanatory power of settlement class remained consistent during this period ($R^2 = 0.10$), indicating that settlement accounted for approximately 10% of community variation.

The validity of the PERMANOVA results was assessed using the permutational analysis of multivariate dispersions (PERMDISP), which tested the critical assumption of homogeneous within-group variability among the settlement classes. During the pre-monsoon season, the analysis confirmed that multivariate dispersions were statistically homogeneous across all four settlement classes ($F = 0.90$, $p > 0.05$), indicating that the PERMANOVA results were not confounded by differences in within-group variability. The post-monsoon season also demonstrated homogeneous dispersions among the settlement classes ($F = 1.05$, $p > 0.05$). The non-significant PERMDISP results in both seasons confirmed that each settlement class exhibited comparable levels of internal assemblage variability, ensuring that the detected differences in PERMANOVA reflected genuine compositional dissimilarity rather than artefacts arising from unequal variance in structures.

Analysis of similarities (ANOSIM) provided independent, rank-based confirmation of the assemblage differences detected through PERMANOVA, using a non-parametric approach that complements the distance-based permutational methods. During the pre-monsoon season, the analysis indicated a weak but detectable separation between the settlement classes ($R = 0.04$, $p > 0.05$). While the R statistic suggests limited separation between settlement classes, the non-significant p-value indicates that this separation may not be statistically reliable during the pre-monsoon. The post-monsoon season demonstrated slightly enhanced assemblage differentiation, with a marginally higher separation statistic ($R = 0.10$, $p > 0.05$). However, the p-value remained non-significant, suggesting that while there may be some degree of assemblage structuring associated with settlement classes, the rank-based approach does not detect a statistically reliable separation between groups in either season.

The SIMPER analysis conducted during the pre-monsoon period revealed distinct avian species assemblages across the Non-polluted Site (NS), Ramsar Site (RS), Sewage-impacted Upper (SU), and Unpolluted Site (US) reaches, highlighting ecological gradients and species-specific habitat preferences. The analysis of NS versus RS indicated a total dissimilarity of 16.36%. The Asian plain martin (cod = 49.42%; ad = 0.08; ava = 35.29; avb = 41.48) emerged as the leading contributor, followed by the Knob-billed duck (cod = 14.78%; ad = 0.02; ava = 0.79; avb = 12.90). The eight species collectively accounted for 99.90% of the dissimilarity. For RS, compared to SU, the overall dissimilarity was 3.36%. The garganey (cod = 95.78%; ad = 0.03; ava = 3.00; avb = 7.78) was the dominant contributor, followed by the western yellow wagtail (cod = 3.42%; ad = 0.00115; ava = 0.05; avb = 0.33). These three species explained 99.90% of the dissimilarity. The SU vs. US comparison showed a total dissimilarity of 8.30%. The Indian pond heron (cod = 37.19%; ad = 0.03086; ava = 7.56; avb = 15.47) was the primary driver, followed by the red-wattled lapwing (cod = 36.42%; ad = 0.03022; ava = 6.44; avb = 15.73). Six species accounted for 99.10% of the dissimilarity.

The NS versus US comparison indicated an overall dissimilarity of 8.63%. The Temminck's stint (cod = 52.32%; ad = 0.04515; ava = 6.36; avb = 75.33) was the primary contributor, followed by the red-wattled lapwing (cod = 30.52%; ad = 0.02634; ava = 5.72; avb = 15.73). Eight species accounted for 99.90% of dissimilarity.

For RS versus US, the overall dissimilarity was 12.78%. The black-winged stilt (cod = 42.71%; ad = 0.05457; ava = 17.75; avb = 79.47) was the top contributor, followed by Temminck's stint (cod = 31.25%; ad = 0.03993; ava = 4.22; avb = 75.33). Six species accounted for 94.60% of the dissimilarity. A comparison between the NS and SU revealed an overall dissimilarity of 13.05%. The river lapwing (cod = 53.75%; ad = 0.07014; ava = 21.30; avb = 22.22) was the foremost contributor, followed by the garganey (cod = 29.39%; ad = 0.03835; ava = 2.94; avb = 7.78). Eight species accounted for 99.80% of dissimilarity. (Table 4.4).

The SIMPER analysis for the post-monsoon period underscored notable seasonal shifts in avian assemblages across the NS, RS, SU, and US reaches, reflecting variations in habitat utilisation and ecological conditions. The NS versus RS comparison showed an overall dissimilarity of 12.10%. The red-naped ibis (cod = 38.54%; ad = 0.04663; ava = 6.22; avb = 23.00) was the leading contributor, followed by the gadwall (cod = 26.23%; ad = 0.03174; ava = 3.93; avb = 17.55). Eleven species accounted for 99.90% of dissimilarity. For RS versus SU, the overall dissimilarity was 18.18%. The Asian plain martin (cod = 62.18%; ad = 0.11304; ava = 38.88; avb = 75.56) was the primary contributor, followed by the pied avocet (cod = 19.20%; ad = 0.03490; ava = 2.00; avb = 34.78). Seven species explained 99.60% of dissimilarity. The SU versus US comparison indicated an overall dissimilarity of 7.02%. The pied avocet (cod = 49.62%; ad = 0.03484; ava = 34.78; avb = 10.70) was the top contributor, followed by the common pochard (cod = 37.30%; ad = 0.02619; ava = 9.44; avb = 0.00). Eight species accounted for 99.70% of dissimilarity.

The comparison of NS and US revealed an overall dissimilarity of 35.45%. The great cormorant (cod = 68.40%; ad = 0.24243; ava = 77.99; avb = 365.60) was the dominant contributor, followed by the river lapwing (cod = 8.79%; ad = 0.03115; ava = 5.84; avb = 18.70). Nine species accounted for 99.60% of the dissimilarity. For RS versus US, the overall dissimilarity was 9.00%. The river lapwing (cod = 33.96%; ad = 0.03057; ava = 7.80; avb = 18.70) was the primary contributor, followed by the Indian spot-billed duck (cod = 31.82%; ad = 0.02864; ava = 9.32; avb = 5.40). Five species accounted for 99.20% of dissimilarity. The NS versus SU comparison showed an overall dissimilarity of 18.68%. The Asian plain martin (cod = 56.78%; ad = 0.10607; ava = 12.81; avb = 75.56) was the primary contributor, followed by the pied avocet (cod = 19.44%; ad = 0.03632; ava = 2.16; avb = 34.78). Nine species explained 99.50% of the dissimilarity (Table 4.4).

SIMPER analysis revealed that waterbird assemblage dissimilarity across the settlement gradient was driven by a relatively small number of species with distinct habitat preferences and settlement class associations. In the pre-monsoon season, the Asian Plain Martin, Asian Openbill, and River Lapwing were the primary drivers of dissimilarity, with each species showing distinct preferences for particular settlement classes. In the post-monsoon season, the Great Cormorant consistently emerged as a major contributor across multiple comparisons, particularly showing strong associations with urban environments. The Asian Plain Martin and Ruddy Shelduck also featured prominently in several comparisons.

These patterns highlight the importance of specific species in structuring waterbird communities along the urbanisation gradient, with different species dominating the seasonal differences in assemblages. The complete species-level results for all group comparisons and seasons are presented in Table 4.4.

Table 4.4: Results of SIMPER analysis for settlement variations across seasons.

Pre-monsoon					
Species	**Average dissimilarity (ad)**	**Contribution % to overall dissimilarity**	**Cumulative % of dissimilarity**	**Mean abundance of species in group A (ava)**	**Mean abundance of species in group B (avb)**
NS (Group A) – RS (Group A)					
Asian Plain Martin	0.08086	49.42	20.80	35.29	41.48
Knob-billed Duck	0.02419	14.78	64.00	0.79	12.90
Little Stint	0.01985	12.13	69.10	3.00	9.65
Eurasian Spoonbill	0.01567	9.58	79.10	1.05	7.47
Indian Spot-billed Duck	0.01385	8.46	82.50	1.98	6.00
Northern Pintail	0.00603	3.69	93.50	0.00	1.55
Blue-tailed Bee-eater	0.00296	1.81	96.90	0.09	3.22
Common Gull-billed Tern	0.00022	0.13	99.90	0.00	0.15
RS (Group A) - SU (Group B)					
Garganey	0.03220	95.78	53.80	3.00	7.78
Western Yellow Wagtail	0.00115	3.42	98.60	0.05	0.33
Common Coot	0.00027	0.80	99.90	0.00	0.11
SU (Group A) - US (Group B)					
Indian Pond-heron	0.03086	37.19	56.20	7.56	15.47
Red-wattled lapwing	0.03022	36.42	59.60	6.44	15.73

Marsh Sandpiper	0.01046	12.61	85.60	3.33	1.33
Black-headed Gull	0.00904	10.89	86.60	0.00	0.93
Greater Painted-snipe	0.00155	1.87	98.70	0.22	0.20
Bronze-winged Jacana	0.00085	1.02	99.10	0.11	0.13
NS (Group A) - US (Group B)					
Temminck's Stint	0.04515	52.32	39.40	6.36	75.33
Red-wattled lapwing	0.02634	30.52	63.60	5.72	15.73
Black-headed Gull	0.00681	7.89	90.60	0.00	0.93
Wood Sandpiper	0.00546	6.33	93.90	0.23	5.00
Greater Painted-snipe	0.00103	1.19	99.00	0.00	0.20
Northern Shoveler	0.00077	0.89	99.20	0.00	0.40
Peregrine Falcon	0.00051	0.59	99.60	0.00	0.07
Curlew Sandpiper	0.00023	0.27	99.90	0.00	0.20
RS (Group A) - US (Group B)					
Black-winged Stilt	0.05457	42.71	22.00	17.75	79.47
Temminck's Stint	0.03993	31.25	48.90	4.22	75.33
Eurasian Spoonbill	0.02117	16.57	67.90	7.47	4.93
Little Grebe	0.00528	4.13	92.80	0.88	3.33
Wood Sandpiper	0.00508	3.98	94.60	0.00	5.00
Red-crested Pochard	0.00173	1.35	98.00	0.42	0.47
NS (Group A) - SU (Group A)					
River Lapwing	0.07014	53.75	16.80	21.30	22.22
Garganey	0.03835	29.39	41.80	2.94	7.78
Marsh Sandpiper	0.01094	8.38	84.70	0.10	3.33
Black-bellied Tern	0.00777	5.95	92.10	1.10	1.22
Western Yellow Wagtail	0.00132	1.01	98.60	0.05	0.33
Bronze-winged Jacana	0.00094	0.72	98.80	0.01	0.11
Eurasian Wigeon	0.00075	0.57	99.20	0.02	0.22
Common Coot	0.00029	0.22	99.80	0.00	0.11

Post-monsoon					
NS (Group A) – RS (Group A)					
Red-naped Ibis	0.04663	38.54	46.90	6.22	23.00
Gadwall	0.03174	26.23	64.10	3.93	17.55
Indian Spot-billed Duck	0.01851	15.30	71.30	1.06	9.32
River Tern	0.00801	6.62	88.30	1.65	4.15
Great Thick-knee	0.00768	6.35	90.10	0.65	3.38
Sarus Crane	0.00424	3.50	92.60	0.86	1.40
Ruff	0.00321	2.65	94.40	0.00	1.25
Citrine Wagtail	0.00034	0.28	99.80	0.02	0.17
Pallas's Fish-eagle	0.00027	0.22	99.80	0.00	0.10
White-breasted Waterhen	0.00026	0.21	99.80	0.01	0.10
Black-tailed Godwit	0.00011	0.09	99.90	0.00	0.07
RS (Group A) - SU (Group B)					
Asian Plain Martin	0.11304	62.18	30.10	38.88	75.56
Pied Avocet	0.03490	19.20	57.40	2.00	34.78
Common Pochard	0.02695	14.82	67.30	2.58	9.44
Common Moorhen	0.00271	1.49	96.00	0.00	0.78
Black-headed Gull	0.00254	1.40	96.60	0.03	1.89
Purple Swamphen	0.00116	0.64	98.40	0.00	0.33
Purple Heron	0.00050	0.28	99.60	0.00	0.22
SU (Group A) - US (Group B)					
Pied Avocet	0.03484	49.62	58.00	34.78	10.70
Common Pochard	0.02619	37.30	64.00	9.44	0.00
Common Moorhen	0.00292	4.16	97.20	0.78	0.00
Black-headed Gull	0.00242	3.45	97.70	1.89	0.00
Barn Swallow	0.00132	1.88	98.60	0.56	0.40
Purple Swamphen	0.00125	1.78	98.90	0.33	0.00
Marsh Sandpiper	0.00074	1.05	99.40	0.22	0.00

Purple Heron	0.00053	0.75	99.70	0.22	0.00
NS (Group A) - US (Group B)					
Great Cormorant	0.24243	68.40	27.90	77.99	365.60
River Lapwing	0.03115	8.79	52.30	5.84	18.70
Spotted Redshank	0.03039	8.57	55.80	0.55	19.30
Grey Heron	0.02231	6.29	67.80	5.59	10.80
Eurasian Wigeon	0.01634	4.61	76.20	0.11	8.30
Common Sandpiper	0.00902	2.54	90.40	1.51	2.10
Barn Swallow	0.00137	0.39	98.40	0.02	0.40
Steppe Eagle	0.00087	0.25	99.10	0.01	0.60
Western Yellow Wagtail	0.00056	0.16	99.60	0.04	0.10
RS (Group A) - US (Group B)					
River Lapwing	0.03057	33.96	53.50	7.80	18.70
Indian Spot-billed Duck	0.02864	31.82	60.40	9.32	5.40
Spotted Redshank	0.02862	31.80	63.70	0.20	19.30
Barn Swallow	0.00122	1.36	98.40	0.00	0.40
Steppe Eagle	0.00096	1.07	99.20	0.07	0.60
NS (Group A) - SU (Group A)					
Asian Plain Martin	0.10607	56.78	31.70	12.81	75.56
Pied Avocet	0.03632	19.44	62.50	2.16	34.78
Common Pochard	0.02691	14.41	69.60	0.05	9.44
Intermediate Egret	0.00477	2.55	92.40	0.81	2.67
Asian Woollyneck	0.00462	2.47	93.00	0.59	2.56
Common Moorhen	0.00295	1.58	96.00	0.00	0.78
Black-headed Gull	0.00258	1.38	97.00	0.00	1.89
Purple Swamphen	0.00127	0.68	98.40	0.00	0.33
Marsh Sandpiper	0.00077	0.41	99.20	0.01	0.22
Purple Heron	0.00054	0.29	99.50	0.01	0.22

Non-metric multidimensional scaling (NMDS) ordinations of waterbird assemblages across settlement classes revealed seasonal differences in community structure. In the pre-monsoon season, NMDS ordination (stress = 0.16) showed that points representing unsettled (NS) and rural (RS) sites formed relatively distinct groups, whereas semi-urban (SU) and urban (US) sites exhibited greater dispersion and partial overlap (Figure 4.5). During the post-monsoon season, NMDS ordination (stress = 0.18) showed increased overlap among all four settlement classes (Figure 4.6). Although NS sites remained loosely clustered near the ordination centre, RS, SU, and US points showed considerable overlap, with their 95% confidence ellipses largely overlapping.

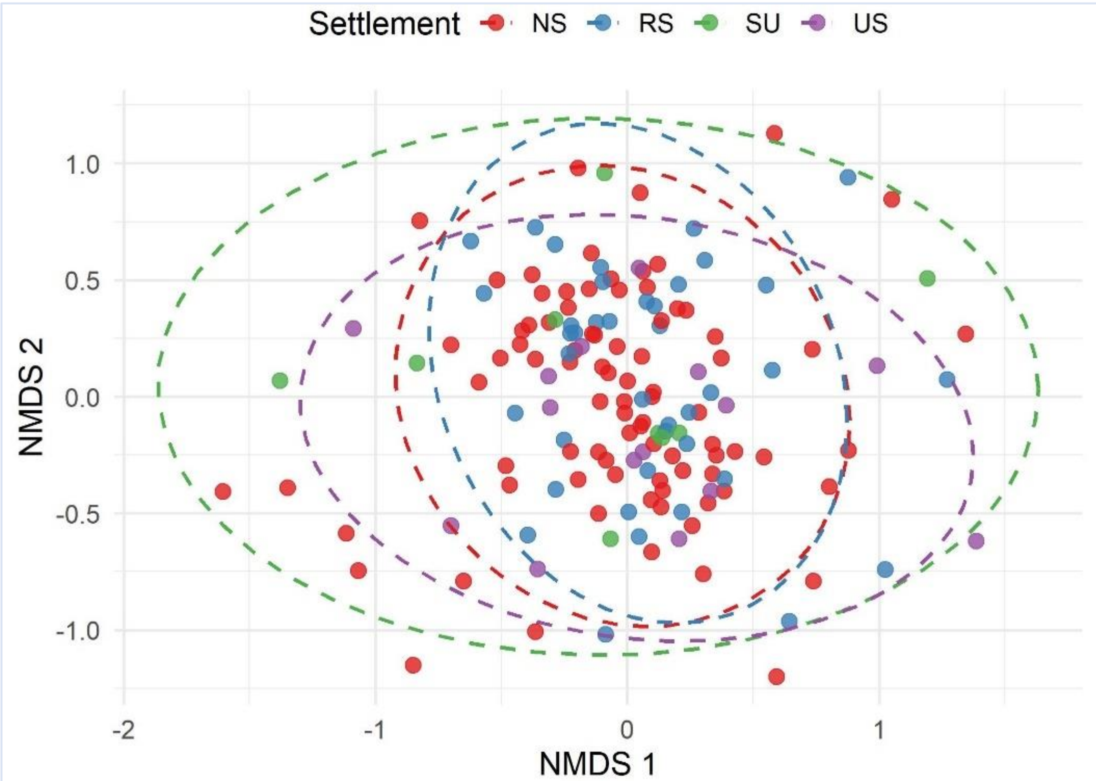

Figure 4.5: NMDS results of pre-monsoon for settlement variations.

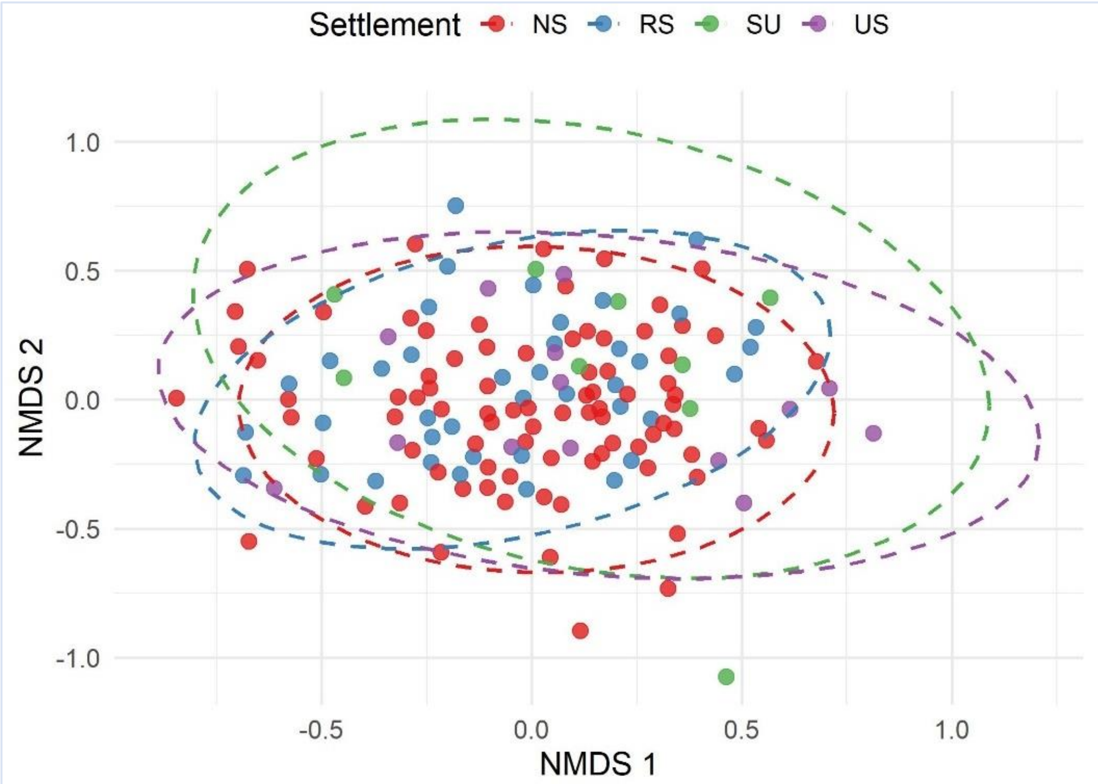

Figure 4.6: NMDS results of post-monsoon for settlement variations.

4.3.2 Beta Diversity Analysis of Waterbird Assemblage Patterns

4.3.2.1 Elevational Variations in Waterbird Beta Diversity

Beta diversity analysis of waterbird assemblages revealed distinct elevation patterns across the river stretch. The analysis employed Baselga's framework, partitioning total beta diversity (βSOR) into turnover (βSIM) and nestedness (βSNE) components.

During the pre-monsoon period, the mean (±SE) total beta diversity was highest in the lower stretch (βSOR = 0.61 ± 0.21), followed by the middle (βSOR = 0.58 ± 0.19) and upper stretches (βSOR = 0.54 ± 0.19). Turnover dominated dissimilarity patterns across all elevation classes, with lower stretches showing the highest species replacement (βSIM = 0.46 ± 0.26), while nestedness remained relatively low (βSNE < 0.17 for all classes). Density distributions revealed that βSNE was strongly left-skewed, with peak densities near zero, indicating minimal nested subset patterns (Figure 4.7).

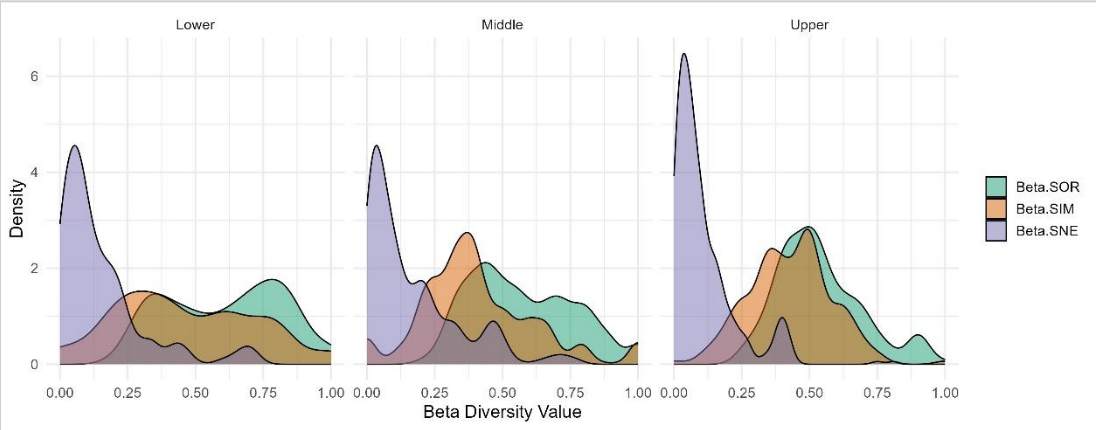

Figure 4.7: Pre-monsoon beta diversity component across different elevational classes.

Post-monsoon patterns showed reduced elevational differentiation, with convergent beta diversity values across the elevation classes (Upper: βSOR = 0.58 ± 0.12; Middle: βSOR = 0.53 ± 0.13; Lower: βSOR = 0.58 ± 0.14). Turnover remained the primary driver of dissimilarity (βSIM values: 0.42–0.47), while nestedness contributions were consistently low (βSNE < 0.12) (Figure 4.8).

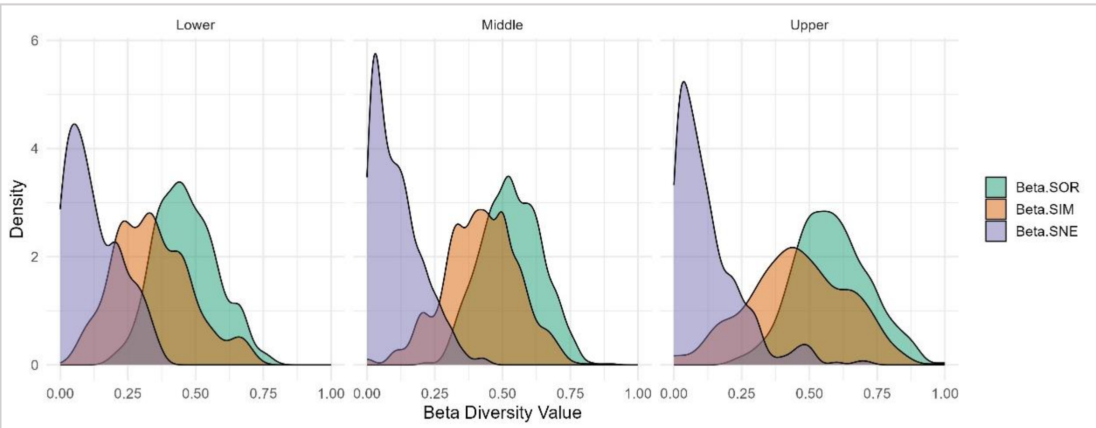

Figure 4.8: Post-monsoon beta diversity component across different elevational classes.

sSeasonal analysis revealed higher overall beta diversity during the pre-monsoon (mean βSOR = 0.57; βSIM = 0.42; βSNE = 0.15) than during the post-monsoon period (mean βSOR = 0.54; βSIM = 0.43; βSNE = 0.11), indicating modest seasonal assemblage restructuring. The upper stretch showed the most pronounced seasonal shift, with the βSNE distributions becoming more concentrated near zero post-monsoon.

Species turnover consistently exceeded nestedness across all elevation classes and seasons, with βSIM contributing 70-85% of the total dissimilarity. The middle stretch exhibited intermediate patterns, whereas the upper stretch showed the most constrained beta diversity range.

4.3.2.2 Waterbird Beta Diversity Patterns Across Protection Classes

Beta diversity patterns of riverine waterbird assemblages varied markedly among protection classes in both the pre-monsoon and post-monsoon seasons. Overall dissimilarity (βSOR) was highest in the Upper Ganga River Ramsar Site (UGR) and lowest in the unprotected stretch (UnP), driven primarily by turnover (βSIM) rather than nestedness (βSNE).

During the pre-monsoon period, the Upper Ganga River Ramsar Site (UGR) exhibited the highest mean total beta diversity (βSOR = 0.66 ± 0.19), followed by the unprotected stretch (UnP; βSOR = 0.57 ± 0.19) and the Hastinapur Wildlife Sanctuary (HPW; βSOR = 0.55 ± 0.17). The turnover component (βSIM) was the dominant driver of dissimilarity in all protection classes, particularly in UGR (βSIM = 0.47 ± 0.25), whereas the nestedness component (βSNE) remained low across all classes. This pattern is visually evident in the density plots, where the βSOR and βSIM distributions for the UGR are shifted towards higher values, indicating greater species replacement along this protected stretch (Figure 4.9).

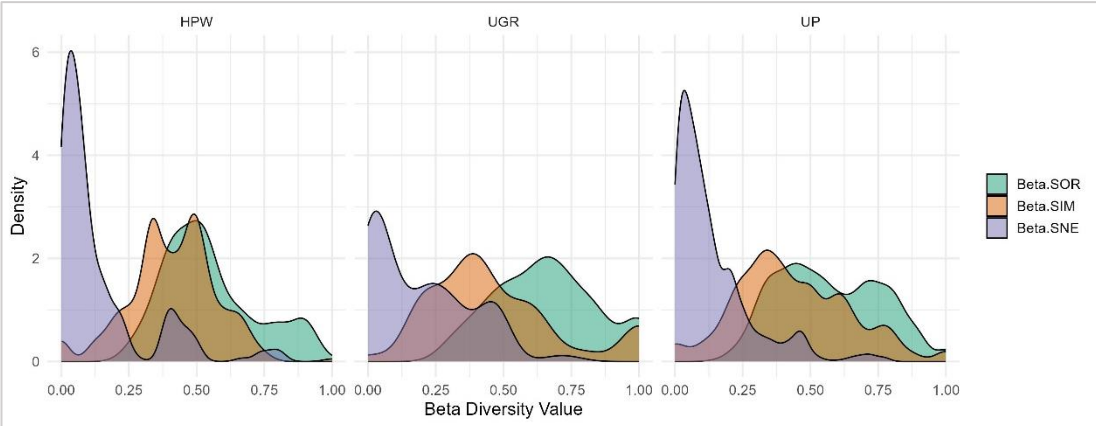

Figure 4.9: Pre-monsoon beta diversity component across different protection levels.

In the post-monsoon period, the mean βSOR values remained highest in UGR (0.58 ± 0.12), with HPW and UnP showing similar, slightly lower values (HPW = 0.58 ± 0.14; UNP = 0.53 ± 0.13). Again, turnover (βSIM) was the primary contributor to total dissimilarity, with all classes showing mean βSIM values between 0.42 and 0.47, and nestedness (βSNE) was low (< 0.12). The density plots for this period confirmed that turnover-driven dissimilarity was consistent across the river, with most βSIM values clustering between 0.30 and 0.60 (Figure 4.10).

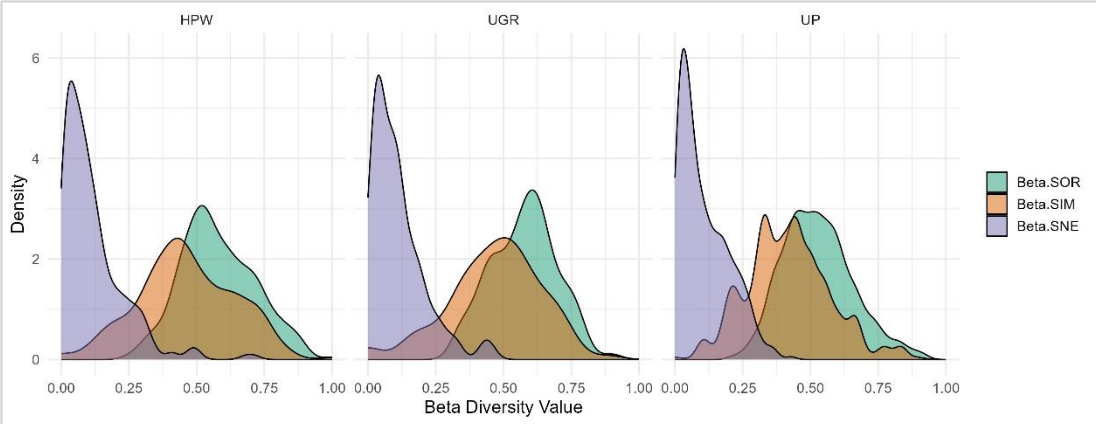

Figure 4.10: Post-monsoon beta diversity component across different protection levels.

Pairwise comparisons within protection classes revealed significantly greater turnover dissimilarity in UGR than UnP in both seasons (pre-monsoon mean ΔβSIM = 0.06; post-monsoon ΔβSIM = 0.05; $p < 0.01$). The nestedness contributions did not differ significantly among the classes ($p > 0.05$). These patterns indicate that species replacement along the river is most pronounced within the Ramsar site, underscoring its high spatial heterogeneity.

When averaged across all protection classes, total beta diversity was slightly higher in the pre-monsoon (mean βSOR = 0.57; βSIM = 0.43; βSNE = 0.14) than in the post-monsoon (mean βSOR = 0.54; βSIM = 0.43; βSNE = 0.11), suggesting modest seasonal homogenisation of waterbird assemblages.

4.3.2.3 Waterbird Beta Diversity Patterns Across Settlement Classes

During the pre-monsoon period, the mean βSOR was highest in urban areas (US; 0.72 ± 0.16), intermediate in semi-urban (SU; 0.58 ± 0.23) and rural areas (RS; 0.57 ± 0.17), and lowest in non-settled areas (NS; 0.60 ± 0.19).

Turnover (βSIM) dominated the total dissimilarity across all classes (70–85% of βSOR). The US again showed the highest mean turnover (0.50 ± 0.31), whereas NS, RS, and SU averaged 0.46 ± 0.20, 0.44 ± 0.20, and 0.52 ± 0.20, respectively. Nestedness (βSNE) remained low in all classes (mean < 0.15) and was strongly left-skewed, indicating that species loss or gain contributed minimally to community dissimilarity.

The analysis of pre-monsoon data revealed distinct patterns of beta diversity across settlement classes, with urban areas (US) showing the highest compositional heterogeneity (βSOR=0.72 ±0.16), while non-settled areas (NS) exhibited more moderate dissimilarity (βSOR=0.60 ± 0.19). Turnover consistently dominated nestedness across all settlement types and seasons, indicating that species replacement, rather than species loss/gain, drives community differences along the urbanisation gradient (Figure 4.11). In the post-monsoon period, overall βSOR decreased modestly in the US (0.56 ± 0.18) and SU (0.68 ± 0.19) but converged across other classes (NS = 0.56 ± 0.12; RS = 0.57 ± 0.15) (Figure 4.12).

Across settlement classes, mean total beta diversity was slightly higher in the pre-monsoon period (mean βSOR = 0.60; βSIM = 0.45; βSNE = 0.15) than in the post-monsoon period (mean βSOR = 0.56; βSIM = 0.45; βSNE = 0.11), indicating modest seasonal community restructuring (Figure 4.11). Overall, species turnover (βSIM) consistently dominated nestedness (βSNE) in driving spatial dissimilarity among waterbird assemblages, with urban stretches exhibiting the highest spatial heterogeneity.

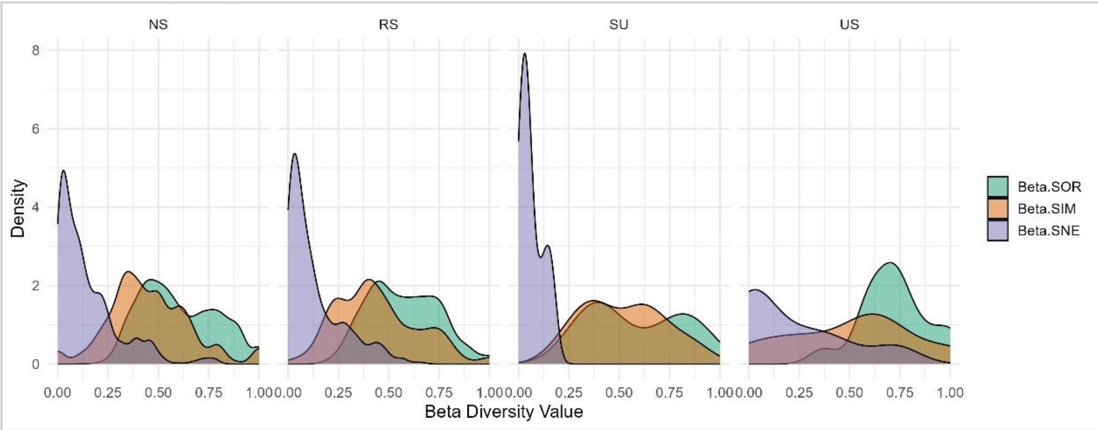

Figure 4.11: Pre-monsoon beta diversity component across different settlement levels.

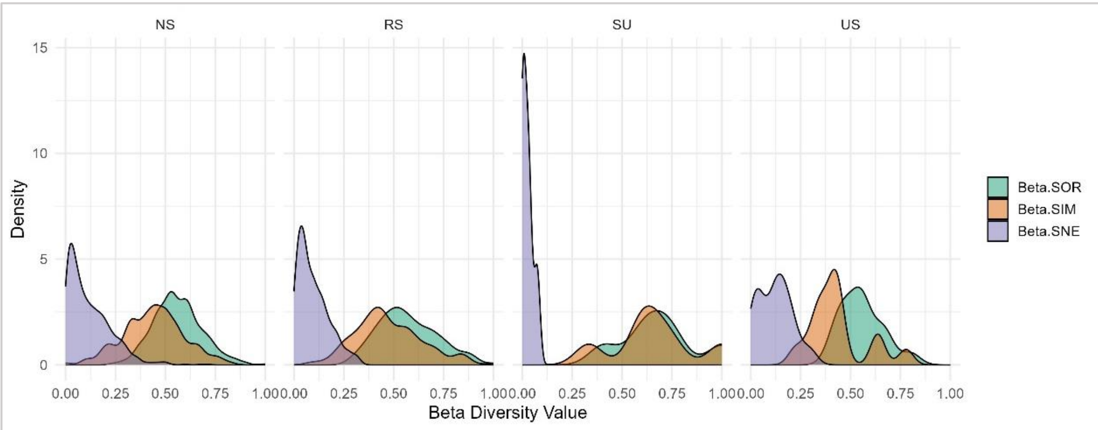

Figure 4.12 Pre-monsoon beta diversity component across different settlement levels

4.3.3 Influence of Habitat Parameters on Waterbird Assemblage Patterns

Multicollinearity assessment revealed no strong linear relationships among the predictor variables, with all pairwise correlations below $|r| < 0.7$ for both post-monsoon and pre-monsoon datasets. Variance Inflation Factor analysis confirmed minimal collinearity, with VIF values ranging from 1.16 to 3.04 (mean = 1.75) for post-monsoon and 1.12 to 3.10 (mean = 1.70) for pre-monsoon, all well below the critical threshold of 10. This filtering process retained 20 environmental and anthropogenic variables from both datasets, ensuring statistical robustness for subsequent ordination analyses.

Based on the DCA results, the gradient lengths of Axis 1 for both the pre-monsoon and post-monsoon datasets exceeded four standard deviation units (4.29 and 4.35, respectively), indicating unimodal rather than linear species responses along the primary environmental gradient. Consequently, Canonical Correspondence Analysis (CCA) was selected as the appropriate ordination method for subsequent analyses (ter Braak, 1986; Legendre & Legendre, 2012). The observed gradient lengths surpassed the 4 SD threshold, justifying the use of unimodal methods to capture the ecological patterns in the data. Prior to ordination, species abundance data were subjected to Hellinger transformation to reduce the influence of double zeros and to ensure compatibility with the selected analytical approach.

4.3.3.1 Canonical Correspondence Analysis (CCA)

Canonical Correspondence Analysis (CCA) was conducted to examine the relationship between the waterbird assemblage structure and environmental gradients. The first canonical axis (CCA1) exhibited a high canonical correlation ($r = 0.95$, $r^2 = 0.90$), and the second axis (CCA2) also showed a strong correlation ($r = 0.92$, $r^2 = 0.85$). Together, these axes explained a cumulative variance of 1.75 in the species-environment relationship, indicating robust community structuring by the measured variables.

Among the environmental variables, the fish abundance index (fishing intensity) had the highest loading magnitude (CCA1 = 0.57, CCA2 = 0.49), followed by channel flow (CCA1 = 0.39, CCA2 = -0.43), built-up area (CCA1 = 0.26, CCA2 = -0.46), solid waste (CCA1 = 0.02, CCA2 = 0.37), and channel width (CCA1 = -0.31, CCA2 = -

0.03). These variables defined the primary environmental gradients that structured the waterbird community (Table 4.5).

Table 4.5: Canonical coefficients (loadings) for environmental and anthropogenic variables.

Variable	CCA1	CCA2
Meander	-0.214	-0.108
Channel Width	-0.311	-0.028
Channel Depth	0.22	-0.055
Channel type	0.174	-0.047
Channel Flow	0.392	-0.427
Built-up	0.261	-0.463
Agri	-0.067	-0.081
Plantation	-0.14	0.05
Forest	0.169	0.05
Degraded Scrub	0.263	-0.045
Grassland	0.163	0.218
Wasteland	0.179	-0.202
Fish Intensity	0.57	0.487
Anthropogenic Influences	-0.102	0.151
Riverbed Agriculture	0.17	0.138
Solid Waste	0.025	0.369
Bank Characteristics	0.088	0.032
Bank Slope	-0.058	0.259

Waterbird species demonstrated distinct responses to the identified environmental gradients. The Pied Avocets (*Recurvirostra avosetta*) showed the strongest overall response (CCA1 = 0.41, CCA2 = -0.13), indicating a strong association with fishing intensity. Little terns (*Sternula albifrons*) also exhibited high loadings (CCA1 = 0.36, CCA2 = 0.17), whereas Indian spot-billed ducks (*Anas poecilorhyncha*) were associated with the negative end of the second axis (CCA1 = 0.16, CCA2 = -0.35). The river lapwing (*Vanellus duvaucelii*) showed negative loadings on both axes (CCA1 = -0.27, CCA2 = -0.26), indicating a preference for wider channels with lower fishing intensity and reduced flow. The great white egret (*Ardea alba*) was primarily associated with the positive end of the second axis (CCA1 = 0.10, CCA2 = 0.35) (Table 4.6).

Table 4.6: Canonical coefficients (loadings) for species.

Species	CCA1	CCA2
Asian Openbill	-0.071	-0.041
Asian Woollyneck	0.148	0.091
Bar-headed Goose	0.015	0.145
Black-bellied Tern	-0.01	0.198
Black-headed Ibis	-0.078	-0.131
Black-necked Stork	-0.136	0.119
Black-winged Stilt	-0.224	0.023
Brown-headed Gull	0.149	0.116
Cattle Egret	0.02	-0.107
Common Sandpiper	-0.062	-0.047
Eurasian Curlew	0.131	-0.315
Eurasian Spoonbill	-0.151	0.075
Great Thick-knee	-0.015	-0.172
Great White Egret	0.1	0.349
Grey Heron	-0.02	-0.161
Indian Cormorant	-0.245	0.048

Indian Pond-heron	0.01	-0.05
Indian Skimmer	0.112	-0.028
Indian Spot-billed Duck	0.162	-0.347
Indian Thick-knee	-0.065	0.028
Intermediate Egret	0.032	0.058
Little Cormorant	-0.017	-0.158
Little Egret	-0.11	0.041
Little Pratincole	-0.159	0.083
Little Ringed Plover	0.257	0.087
Little Tern	0.358	0.169
Marsh Sandpiper	0.321	-0.08
Oriental Darter	0.019	0.026
Painted Stork	-0.067	-0.234
Pied Avocet	0.413	-0.126
Pied Kingfisher	-0.094	0.007
Red-naped Ibis	0.087	0.259
Red-wattled lapwing	-0.205	0.113
River Lapwing	-0.275	-0.259
River Tern	0.093	0.019
Ruddy Shelduck	-0.038	0.25
Sarus Crane	0.236	0.041
White-breasted Waterhen	-0.025	0.279
White-throated Kingfisher	0.076	-0.149

The CCA biplot visually summarises these relationships, with environmental vectors and species scores clearly aligned along the principal axes of the variation. The primary environmental gradient (CCA1) represented a continuum from fishing intensity to channel flow and channel width. The secondary gradient (CCA2) captures anthropogenic influence and habitat modification, with species such as the great white egret and red-naped ibis showing tolerance for areas with solid waste and built-up influence, whereas flow-dependent species such as the Indian spot-billed duck and Eurasian curlew are negatively associated with these conditions (Figure 4.13).

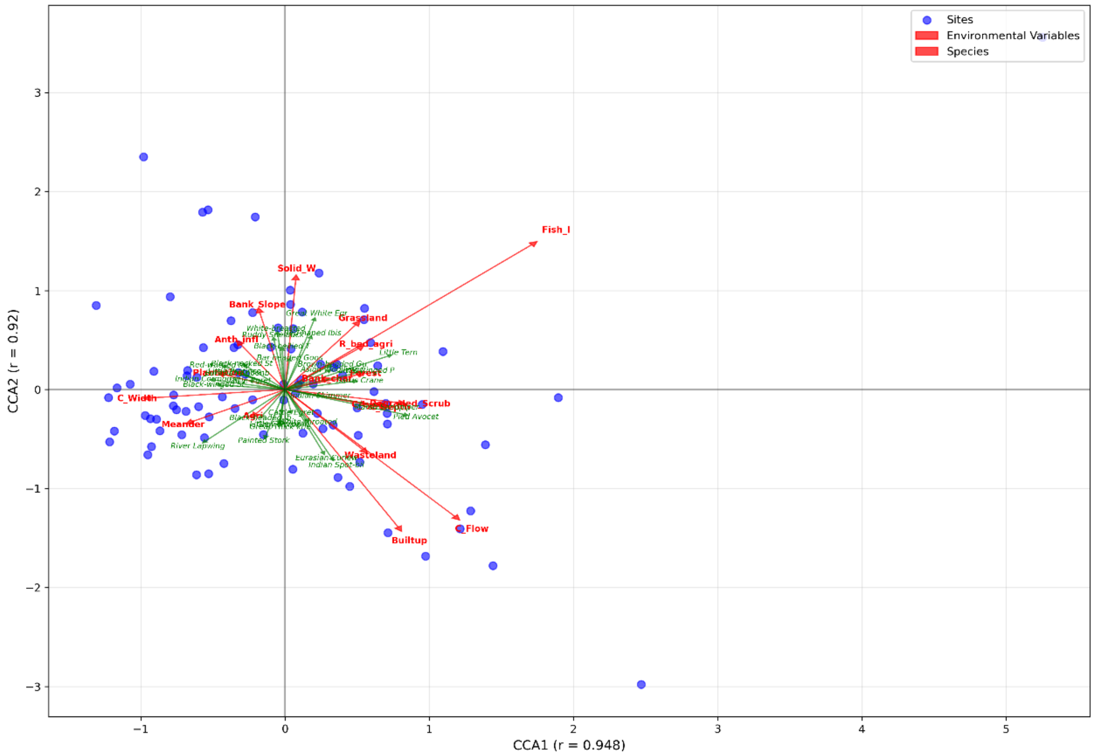

Figure 4.13: Canonical Correspondence Analysis (CCA) ordination plots showing the relationship among waterbirds and various anthropogenic and habitat variables.

The high canonical correlations and explained variance indicate that the measured environmental variables successfully captured the primary drivers of the waterbird community structure. The clear separation of species along environmental gradients demonstrates strong habitat filtering and niche-partitioning.

4.4 Discussion

The pronounced spatial structuring of waterbird assemblages along the elevation gradient confirms the presence of a hierarchical pattern of habitat selection in waterbird assemblages in the middle stretch of the Ganga River (Cody 1981; Weller 1999). The PERMANOVA results demonstrating significant differences among elevation classes ($F = 3.99 – 6.04$, $p < 0.05$) support previous findings that physical habitat characteristics, including water depth, shoreline complexity, and proximity to different habitat types, are key determinants of waterbird distribution (Almeida et al., 2017; Brandolin & Blendinger, 2016; McCain, C. M., 2009). The stronger post-monsoon differentiation ($R^2 = 0.32$) than pre-monsoon ($R^2 = 0.23$) suggests that seasonal hydrological fluctuations enhance habitat specialisation, consistent with studies highlighting the importance of dynamic habitat conditions in riverine ecosystems (Cintra, 2015, 2019; Wen et al., 2016).

The seasonal reorganisation of waterbird assemblages, evidenced by increased overlap and homogenisation during the post-monsoon season, reflects the dynamic nature of riverine ecosystems driven by hydrological cycles (Robinson et al., 2002; Ward et al., 2002). The overlap of communities during the post-monsoon period, particularly evident in the NMDS ordination (stress = 0.17), suggests that monsoon flooding temporarily reduces environmental heterogeneity and facilitates broader species distribution (Liu et al., 2023; Thomaz et al., 2007). Flooding creates uniform habitats, such as open water bodies, reducing niche differentiation and enabling community overlap (Zou et al., 2024).

The influx of migratory species during the post-monsoon period results in increased abundance and changes in species assemblages. Species such as bar-headed geese demonstrate the critical importance of riverine habitats as stopover and wintering sites for migrants (Lehikoinen et al., 2013). The reduced beta diversity during the post-monsoon season and high turnover rates indicate that seasonal variation enhances species exchange between river stretches without eliminating fundamental habitat preferences (Xia et al., 2023).

Significant differences in waterbird assemblages among protection classes (PERMANOVA: $F = 3.03–3.26$, $p < 0.05$) provide evidence of the effectiveness of formal protection in maintaining distinct and specialised avian assemblages. However, the heterogeneous dispersion patterns in protected areas (PERMDISP: $F = 3.46 – 4.46$, $p < 0.05$) suggest that protection classes alone do not guarantee habitat homogeneity. This finding indicates that even within protected areas, local environmental factors continue to drive community differentiation, supporting the need for adaptive management strategies that consider internal habitat variability (Gotelli and Colwell, 2001). This pattern suggests that comprehensive conservation strategies must extend beyond formally protected areas to include landscape-level approaches that maintain habitat connectivity and quality across the entire river system.

The moderate but significant effects of settlement classes on waterbird assemblages (PERMANOVA: $F = 2.02 – 2.18$, $p < 0.05$) reflect the complex relationship between urbanisation and waterbird assemblage structure. However, the overall trend towards community homogenisation along the urban gradient indicates that anthropogenic pressures erode distinct habitat boundaries and reduce beta diversity. This finding aligns with the established patterns of biotic homogenisation in human-modified landscapes (Villamagna et al., 2012) and supports concerns regarding the cumulative effects of multiple anthropogenic stressors on waterbird populations (Gan et al., 2007; Quan et al., 2002).

The dominance of species turnover over nestedness across all spatial and protection gradients (βSIM > βNES in all elevation, protection, and settlement classes) provides crucial insights into the mechanisms driving community assembly in riverine systems. This pattern indicates that local extinctions and colonisation, rather than simple species loss, shape assemblage differences along environmental gradients (White et al., 2019).

The highest beta diversity in the lower river stretch and urban areas reflects the dynamic nature of these habitats, where fluctuating environmental conditions and disturbance regimes promote high species replacement rates. This finding supports the theoretical predictions that intermediate disturbance levels maximise diversity through enhanced turnover (Grant, 1999; Grant and Grant, 2006).

The low nestedness values (< 0.17) across all elevation, protection, and settlement classes contradict simple models of community disassembly and instead support metacommunity theories emphasising dispersal limitation and environmental segregation (Ghosh-Harihar & Price, 2014; Price et al., 2015). This pattern has important conservation implications, suggesting that maintaining habitat heterogeneity and connectivity is more critical than simply preserving large and homogeneous areas (Hansen & Hoffman, 2011; Hodgson et al., 2009).

SIMPER analysis revealed that relatively few species accounted for the majority of dissimilarity between assemblages, with the Asian plain martin, little pratincole, ruddy shelduck, and bar-headed goose emerging as key contributors. This pattern reflects the importance of habitat specialists and seasonal migrants in driving community differentiation, consistent with studies that emphasise the disproportionate influence of indicator species on assemblage structure (Tak et al., 2010).

The seasonal shift in key contributing species from the Asian plain martin and little pratincole in the pre-monsoon to cormorants and bar-headed geese in the post-monsoon possibly reflects changes in resource availability and habitat conditions following monsoon flooding. This temporal variation in species contributions highlights the dynamic nature of riverine food webs and the importance of maintaining diverse foraging habitats throughout the annual cycle (Lorenzón et al. 2019).

Canonical Correspondence Analysis (CCA) revealed that habitat parameters, particularly fishing intensity, channel flow, and channel width, are key drivers of waterbird assemblage patterns in the studied riverine system, with distinct seasonal variations between the pre-monsoon and post-monsoon seasons. The high canonical correlations (CCA1: $r = 0.95$, CCA2: $r = 0.92$) and substantial explained variance (1.75 cumulative) underscore the robust structuring of waterbird communities by these environmental gradients.

Species-specific responses to environmental gradients highlight the ecological diversity within waterbird assemblages. For instance, species such as the pied avocet and little tern, which exhibited strong positive loadings on CCA1, were closely associated with fishing intensity and channel flow, reflecting their dependence on dynamic riverine conditions. In contrast, species such as the river lapwing, with negative loadings on both axes, prefer wider, slower-flowing channels. This contrast illustrates niche partitioning driven by habitat heterogeneity, where distinct environmental conditions support specialised ecological roles. These patterns align with previous research emphasising the critical role of resource availability and hydrological conditions in shaping waterbird distributions (Nilsson & Nilsson, 1978; Kingsford & Norman, 2002).

Anthropogenic influences, such as built-up areas and solid waste, emerged as significant secondary gradients along CCA2, shaping waterbird assemblages in the study area. Species such as the great white egret and red-naped ibis demonstrate tolerance for modified habitats, thriving in areas with human-induced changes. Conversely, species such as the Indian spot-billed duck and Eurasian curlew, show negative associations with anthropogenic conditions, preferring less disturbed natural riverine environments. This dichotomy underscores the complex interplay between natural habitat features and human-induced modifications, particularly during the post-monsoon period, when hydrological connectivity may facilitate species exchange, whereas habitat preferences maintain community distinctiveness.

The clear separation of species along environmental and anthropogenic gradients in the CCA biplot suggests strong habitat filtering, where environmental heterogeneity fosters diverse ecological niches. The distinct clustering of species in the biplot reflects how habitat characteristics, such as flow velocity and fishing intensity, act as filters that determine the species that can thrive under specific conditions. During post-monsoon, the observed reduction in beta diversity indicates increased species exchange across habitats; however, fundamental habitat preferences continue to maintain community distinctiveness. This balance between connectivity and niche specialisation highlights the importance of maintaining diverse habitat conditions to support various waterbird assemblages.

These findings have significant implications for conservation, emphasising the need to preserve natural riverine features, such as fishing intensity and flow velocity, while mitigating anthropogenic impacts, such as solid waste. Maintaining habitat heterogeneity is critical for sustaining diverse waterbird communities, as it supports the ecological niches on which different species rely. Future management strategies should prioritise the restoration of natural flow regimes and minimisation of habitat degradation to enhance the ecological integrity of riverine systems. Such efforts align with the broader conservation goals for wetland-dependent species, ensuring the long-term sustainability of these ecosystems (Strayer & Dudgeon, 2010).

The clear stratification of waterbird communities by elevation, protection, and settlement class demonstrates that riverine ecosystems function as complex habitat mosaics that support distinct assemblages at multiple spatial scales. This finding supports the concept of riverine landscapes as linear habitats with complex land-water interactions that generate high turnover and biodiversity (He et al., 2018; Ormerod and Tyler, 1993).

The maintenance of environmental heterogeneity has emerged as a critical management priority, as evidenced by the strong relationship between habitat complexity and community differentiation. Management strategies should focus on preserving natural flow regimes, maintaining riparian vegetation structure, and controlling anthropogenic disturbances that homogenise habitat conditions (Buckton and Ormerod, 2002; Sullivan et al., 2007).

The seasonal dynamics revealed in this study emphasise the need for adaptive management approaches that account for temporal variations in habitat requirements and species distributions. Conservation planning must consider the needs of both resident and migratory species, ensuring that critical habitats remain available throughout their annual cycle (Buckton and Ormerod, 2008).

CHAPTER 5
PRIORITY AREAS FOR CONSERVATION OF WATERBIRDS

5.1 Introductions

The conservation of waterbirds and their habitats have emerged as a critical global priority, particularly in the context of accelerated wetland degradation, climate change, and biodiversity loss (Brooks et al., 2002; Myers, 2003; Olson and Dinerstein, 1998; Stattersfield et al., 1998). Waterbirds, encompassing a diverse group of species adapted to aquatic environments, are widely recognised as indicators of aquatic ecosystems. Their population trends, distribution patterns, and community compositions provide valuable insights into the ecological integrity of these habitats, making them central to conservation research (Gill & Donsker, 2021; Kingsford et al., 2017; Rodrigues et al., 2004).

Globally, identifying and protecting priority areas for biodiversity conservation has been foundational to efforts aimed at halting species extinction and safeguarding critical habitats. The concept of biodiversity hotspots, for instance, has drawn attention to regions with exceptional concentrations of endemic and threatened species that are experiencing rapid habitat loss (Brooks et al. 2002; Myers 2003). National and International frameworks, such as the Ramsar Convention on Wetlands and the Convention on Biological Diversity (CBD), have further emphasised the need for targeted conservation action in wetlands and riverine systems, recognising their vital role in supporting both biodiversity and human well-being (CBD, 2020; Ramsar Convention Secretariat, 2016). In Europe, the Natura 2000 network and the African-Eurasian Migratory Waterbird Agreement (AEWA) have provided models for identifying and managing key sites for waterbird conservation at continental scales (AEWA, 2022; BirdLife International, 2019).

Despite these advances, waterbirds and their habitats continue to face mounting threats from habitat loss, hydrological alterations, pollution, invasive species, and climate change (Amano et al., 2018; Davidson, 2014; Kingsford et al., 2017). Wetland loss and degradation have led to significant declines in waterbird populations globally, with migratory species being particularly vulnerable because of their reliance on networks of sites across vast geographic ranges (Amano et al., 2018; Murray et al., 2014). The need for spatially explicit conservation prioritisation, informed by robust ecological data and an understanding of local and regional dynamics, has never been more urgent.

The Gangetic plains are among the most ecologically and socioeconomically significant landscapes in India. The Ganga River supports a rich diversity of waterbirds, including migratory and resident species, many of which are globally threatened (Khan et al. 2013). The middle stretch of the Ganga River, extending from Balawali in the Bijnor district to the confluence with the Yamuna at Prayagraj, traverses a complex mosaic of protected areas, wetlands, agricultural lands, and densely populated urban centres and also holds rich avifauna diversity (Rodgers et al. 2000). Key conservation sites, such as the State Wildlife Barasingha Sanctuary, Haiderpur Wetland Ramsar Site, Upper Ganga River Ramsar Site, and Important Bird Areas (IBAs), play a vital role in sustaining waterbird populations, yet face increasing pressure from human-induced stressors, such as habitat alteration and water regulation (Figarski & Kajtoch, 2015; Kingsford, 2000; Ramsar Convention Secretariat, 2016). Consequently, these challenges suggest that protected areas alone are often insufficient to protect biodiversity, particularly waterbirds, in aquatic habitats (Gavioli et al., 2023).

The dynamic interplay of natural and anthropogenic factors in the Middle Ganga underscores the need for integrated landscape-scale approaches to conservation prioritisation (Hamza et al. 2024; Zhang et al. 2020).

Thus, identifying priority areas for waterbird conservation in the Middle Ganga is both scientifically and practically imperative. By systematically assessing the distribution and abundance of waterbirds, targeted conservation actions that maximise ecological benefits can be implemented. Such efforts are also critical for sustaining the livelihoods and well-being of millions of people who depend on the Ganga River for water, food, and cultural identity (CBD, 2020; Ramsar Convention Secretariat, 2016).

This chapter aims to delineate priority areas for the conservation of waterbirds along the middle stretch of the Ganga River by drawing on comprehensive field surveys. By identifying key habitats and threats, this study seeks to inform science-based conservation planning and policy interventions, contributing to the long-term sustainability of one of India's most important riverine ecosystems. The findings presented here are intended to support the development of integrated management strategies that balance the needs of biodiversity conservation with those of human communities, ensuring the continued vitality of the Ganga River and its waterbird populations for future generations.

5.2 Data Analysis

BEU 61 to 210 were selected for the analysis. Bird species richness and abundance data for each BEU were used as the primary data. Conservation values were assigned to each BEU to identify conservation-important locations in the study area. Three species attributes were selected to determine the conservation value of each BEU (Anoop, 2024).

1. Presence of species of conservation concern: The IUCN status of bird species reported in each BEU was identified and ranked. The BEU-wise rank average was estimated for further analysis based on the ranks shown in Table 5.1.

Table 5.1: Values assigned for the IUCN status of birds.

Sr. No.	IUCN Status	Rank
1.	Endangered	5
2.	Vulnerable	4
3.	Near Threatened	3
4.	Least concern	2
5.	Not evaluated	1

2. Occurrence of island-nesting species: Species richness of island-nesting birds was analysed.

3. Species diversity: BEU-wise, the Shannon-Weiner diversity index was calculated using the *diversity* () function in the Vegan R package.

All values of the abovementioned criteria were normalised to 0-1 using a formula in MS Excel.

$$Zi = (Xi - minimum\ value) / (maximum\ value - minimum\ value)$$

Where Zi = criteria value, Xi = ith number in the dataset.

The normalised data of the three criteria were used to estimate the conservation value of the sampling locations.

$$Conservation\ value = (CR1 + CR2 + CR3) / total\ number\ of\ criteria$$

Where CR1 = normalised value of criteria 1; CR2 = normalised value of criteria 2; CR3 = normalised value of criteria 3.

The conservation values were summarised by computing the 25th percentile, median, and 75th percentile. Segments with conservation values above the 75th percentile were classified as high-priority zones to identify priority areas.

5.3 Results

5.3.1 Species of conservation concern

In total, 107 species were recorded during the study and classified into four IUCN Red List categories, reflecting their global conservation status: endangered (EN), vulnerable (VU), near-threatened (NT), and least concern (LC). Four species were recorded under the endangered (EN) category: the Black-bellied tern (*Sterna acuticauda*), Indian skimmer (*Rynchops albicollis*), Pallas's fish-eagle (*Haliaeetus leucoryphus)*, and Steppe eagle (*Aquila nipalensis*). These species face a high risk of extinction in the wild, and their presence highlights the importance of conservation at the surveyed sites. Three species, viz. The common pochard (*Aythya ferina*), river tern (*Sterna aurantia*), and sarus crane (*Grus antigone)* were listed as vulnerable (VU), indicating a high risk of extinction and the need for targeted habitat protection measures.

A total of 14 species, including black-headed ibis (*Threskiornis melanocephalus*), painted stork (*Mycteria leucocephala*), oriental darter (*Anhinga melanogaster*), and great thick-knee (*Esacus recurvirostris*), were classified as near threatened (NT). These species are near threatened, therefore, necessitating monitoring and precautionary conservation efforts. The majority of species (75) belonged to the least concern category (LC). While these species are not currently threatened globally, several, such as the Indian spot-billed duck (*Anas poecilorhyncha*) and grey heron (*Ardea cinerea*), are known to be sensitive to habitat degradation and may serve as indicators of ecosystem health. The presence of 21 species (21.9%) belonging to the globally threatened or near-threatened categories underscores the ecological significance of the surveyed riverine habitats for waterbird conservation.

The upper stretch supported the occurrence of 90 species (93.8%), including all four endangered (EN), three vulnerable (VU), 13 near threatened (NT), and 70 least concern (LC) species. The middle stretch exhibited the highest richness, with 92 species (95.8%), including four endangered (EN), three vulnerable (VU), 12 near threatened (NT), and 73 least concern (LC) species. The lower stretch hosted 88 species (91.7%), including four endangered (EN), two vulnerable (VU), 13 near threatened (NT), and 69 least concern (LC) species.

5.3.2 Island Nesting Birds

The study revealed significant variations in species richness and diversity across the upper, middle, and lower stretches of the study area. The middle stretch exhibited the highest diversity (1.22 ± 0.04), followed by the upper (0.99 ± 0.08) and lower stretches showed the lowest diversity (0.50 ± 0.05). Among the species, the black-bellied tern was most abundant in the middle stretch (27.5%), followed by the lower (13.5%) and upper stretches (6.0%). The great thick-knee showed the highest proportion in the middle stretch (21.7%), followed by the lower (13.4%) and upper stretches (5.9%). Indian skimmers dominated the lower stretch (58.4% of 3885), with 38.0% in the middle and 3.8% in the upper stretch. Little pratincoles were most abundant in the lower stretch (74.6%), followed by the middle (20.5%) and upper stretches (6.3%). Little Terns showed the highest proportion in the lower stretch (78.9% of 4299), with 16.9% in the middle stretch and 6.6% in the upper stretch. River Lapwing was most prevalent in the middle stretch (49.4% of 1471), followed by the upper (23.5%) and lower stretch (2.6%). The River Tern had the highest proportion in the middle stretch (89.6% of 531), with 7.2% in the upper stretch and 3.2% in the lower stretch.

The species richness of island-nesting birds across different BEUs ranged from 0 to 7 species across the BEUs. Maximum richness (7 species) was recorded at BEUs 78, 80, 92, 106, 129, and 130, indicating areas with a greater diversity of island-nesting bird species. In contrast, BEUs such as 149, 154, and 160 reported the lowest richness, with a presence of only 0 to 1 species. The majority of BEUs demonstrated moderate species richness, with values ranging from 2 to 6.

5.3.3 Species Diversity

The normalised Shannon diversity values ranged from 0.0 to 1.0, with a mean value of approximately 0.65. The distribution of normalised diversity values indicated moderate to high diversity across most BEUs, with the 25th percentile at 0.51, the median at 0.68, and the 75th percentile at 0.80.

5.3.4 Conservation Importance Locations

The conservation values of the 750 km stretch of the river were analysed to assess the conservation importance of the different river stretches in the study area. These values, ranging from 0.14 to 0.86, reflect the ecological significance of each segment based on the waterbird abundance and associated environmental factors.

The conservation values across the study area exhibited considerable variation, indicating heterogeneous ecological conditions along the river. The mean conservation value was 0.49 (SD ± 0.17), suggesting moderate overall conservation importance. However, specific BEUs stand out because of exceptionally high or low values falling within various elevation categories, such as Upper, Middle, and Lower. These BEUs also fall into different protection classes, namely Hastinapur Wildlife Sanctuary (HPW), Upper Ganga River Ramsar Site (UGR), and Unprotected (UnP). Additionally, they are categorised into settlement classes like Urban (US), Semi-urban (SU), Rural (RS), and Unsettled (NS). The highest conservation value was observed for BEU 196 (0.86, UnP, NS). Other high-value segments included BEU 162 (0.80, UnP, RS), BEU 165 (0.84, UnP, US), BEU 169 (0.83, UnP, NS), BEU 191 (0.80, UnP, NS), and BEU 194 (0.82, UnP, RS), all of which spanned 30 km in the lower stretch and exceeded 0.79, marking them as critical areas for conservation. Conversely, the lowest values were observed in BEU 119 (0.14, UnP, NS), BEU 128 (0.14, UnP, NS), and BEU 129 (0.14, UnP, RS), covering 15 km in the middle stretch, indicating potential habitat degradation or anthropogenic pressures (Figure 5.1; Table 5.2).

To identify priority areas, segments with conservation values above the 75th percentile (0.63) were classified as high-priority zones. These included 35 BEUs (175 km), predominantly in the lower stretches. Notable clusters occurred between BEUs 142 and 200, including BEUs 142 (0.65, UnP, NS), 145 (0.68, UnP, NS), 153–156 (0.69–0.72, UnP, NS), and 160–165 (0.67–0.84, UnP, SU/US) (Figure 5.1; Table 5.2).

Segments below the 25th percentile (0.33) were considered low-priority, comprising 33 BEUs (165 km) mainly clustered in the upper stretch (for example, BEUs 61, 63, 78, 80–81, UnP/HPW, NS/RS) and middle stretches (for example, BEUs 92, 95, 98, 102-107, 111, 115-116, 128–132, 139; UGR/UnP, RS/NS/US) (Figure 5.1; Table 5.2).

The upper stretch, spanning 135 km (27 BEUs), had the lowest mean conservation value of 0.46 (SD ± 0.14). The values ranged from 0.25 (BEU 80, HPW, NS) to 0.68 (BEU 86, HPW, RS), indicating moderate variability. High-value segments include BEU 67 (0.66, HPW, NS), BEU 69 (0.67, HPW, RS), BEU 70 (0.64, HPW, US), 76 (0.66, HPW, US), and BEU 86 (0.68, HPW, RS), covering 25 km, primarily under the Hastinapur Wildlife Sanctuary with non-settled or rural settlements. Low-value segments, such as BEU 78, 80, and 81 (0.25, HPW, NS), span 15 km and are also under HPW, but may face habitat degradation, possibly due to upstream pressures, despite their non-settled status (Figure 5.1; Table 5.2).

The middle stretch, covering 225 km (45 BEUs), had the lowest mean conservation value of 0.24 (SD ± 0.06). The values ranged from 0.14 (BEU 119, UnP, NS) to 0.34 (BEU 100, UGR, US). Low-value segments (19 BEUs), including BEU 119 (0.14, UnP, NS), BEU 111 (0.16, UnP, NS), and BEU 128–129 (0.14, UnP, NS/RS), covered a total of 95 km area, primarily characterised as unprotected with non-settled or rural settlements, indicating potential habitat limitations or disturbances (Figure 5.1; Table 5.2).

The lower stretch, spanning 390 km (78 BEUs), had the highest mean conservation value of 0.68 (SD ± 0.12). The values ranged from 0.27 (BEU 134, UnP, NS) to 0.86 (BEU 196, UnP, NS). High-priority segments (30 BEUs, 150 km) exceeded the 75th percentile (0.63), including BEU 196 (0.86, UnP, NS), BEU 165 (0.84, UnP, US), BEU 169 (0.83, UnP, NS), and BEU 194 (0.82, UnP, RS). These segments are mostly unprotected with unsettled, rural, or urban settlements. Low-value segments, such as BEU 134 (0.27, UnP, NS) and BEU 139 (0.32, UnP, US), span 10 km and are outliers in this high-value stretch (Figure 5.1; Table 5.2).

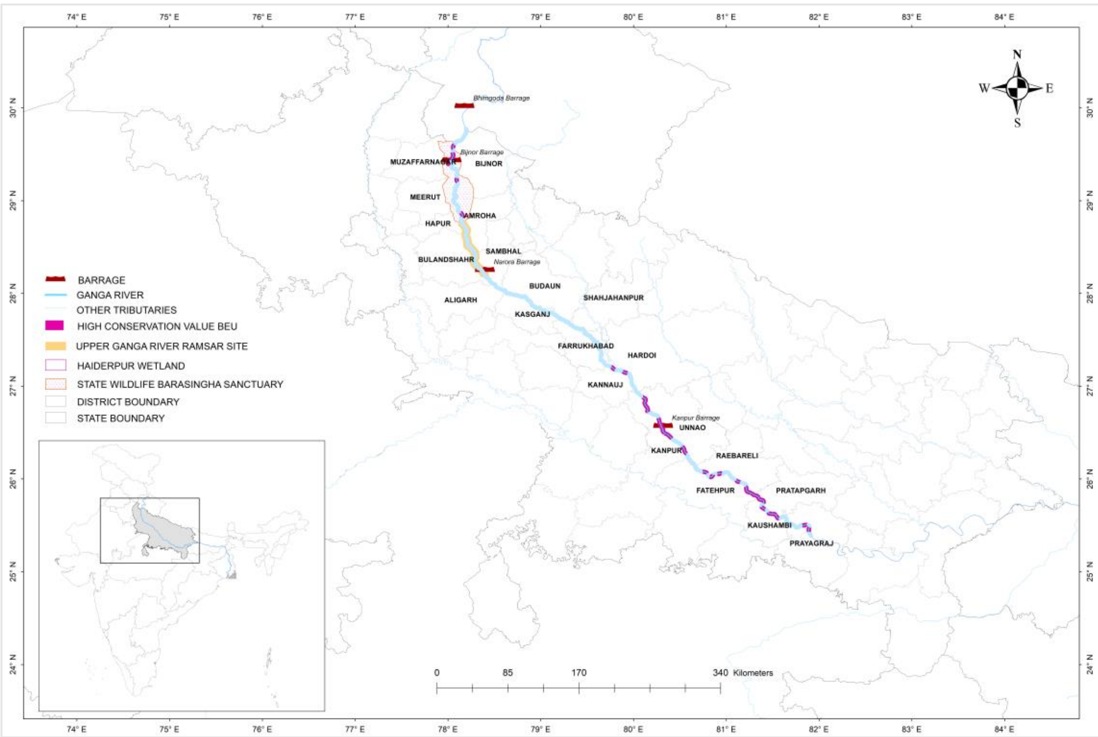

Figure 5.1: High conservation river segments in the study area.

Table 5.2: High and low conservation value river segments.

BEU	Priority	Elevation Class	Protection Status	Settlement Class	Conservation value
196	High	Lower	UnP	Unsettled	0.86
165	High	Lower	UnP	Urban	0.84
169	High	Lower	UnP	Unsettled	0.83
194	High	Lower	UnP	Rural	0.82
162	High	Lower	UnP	Rural	0.8
191	High	Lower	UnP	Unsettled	0.8
163	High	Lower	UnP	Urban	0.76
189	High	Lower	UnP	Rural	0.74
155	High	Lower	UnP	Unsettled	0.72
190	High	Lower	UnP	Unsettled	0.72
181	High	Lower	UnP	Rural	0.71
198	High	Lower	UnP	Unsettled	0.7
210	High	Lower	UnP	Urban	0.7
153	High	Lower	UnP	Unsettled	0.69
199	High	Lower	UnP	Unsettled	0.69
200	High	Lower	UnP	Unsettled	0.69
161	High	Lower	UnP	Rural	0.68
145	High	Lower	UnP	Unsettled	0.68
156	High	Lower	UnP	Unsettled	0.68
186	High	Lower	UnP	Unsettled	0.68
86	High	Upper	HPW	Rural	0.68
179	High	Lower	UnP	Rural	0.67
160	High	Lower	UnP	Semi Urban	0.67
192	High	Lower	UnP	Unsettled	0.67
69	High	Upper	HPW	Rural	0.67
177	High	Lower	UnP	Unsettled	0.66

67	High	Upper	HPW	Unsettled	0.66
76	High	Upper	HPW	Unsettled	0.66
142	High	Lower	UnP	Unsettled	0.65
154	High	Lower	UnP	Unsettled	0.65
193	High	Lower	UnP	Rural	0.64
164	High	Lower	UnP	Urban	0.64
70	High	Upper	HPW	Urban	0.64
170	High	Lower	UnP	Unsettled	0.63
208	High	Lower	UnP	Urban	0.63
100	Low	Middle	UGR	Unsettled	0.34
122	Low	Middle	UnP	Unsettled	0.34
96	Low	Middle	UGR	Rural	0.33
98	Low	Middle	UGR	Urban	0.33
107	Low	Middle	UnP	Rural	0.33
105	Low	Middle	UnP	Unsettled	0.33
109	Low	Middle	UnP	Unsettled	0.33
61	Low	Upper	UnP	Unsettled	0.33
139	Low	Lower	UnP	Unsettled	0.32
92	Low	Middle	UGR	Rural	0.32
102	Low	Middle	UGR	Rural	0.32
132	Low	Middle	UnP	Unsettled	0.31
104	Low	Middle	UnP	Rural	0.3
95	Low	Middle	UGR	Rural	0.29
126	Low	Middle	UnP	Rural	0.28
116	Low	Middle	UnP	Unsettled	0.28
134	Low	Lower	UnP	Unsettled	0.27
103	Low	Middle	UGR	Semi Urban	0.26
114	Low	Middle	UnP	Rural	0.26
121	Low	Middle	UnP	Unsettled	0.25

131	Low	Middle	UnP	Unsettled	0.25
78	Low	Upper	HPW	Unsettled	0.25
81	Low	Upper	HPW	Unsettled	0.25
80	Low	Upper	HPW	Unsettled	0.25
63	Low	Upper	UnP	Rural	0.25
115	Low	Middle	UnP	Urban	0.24
118	Low	Middle	UnP	Unsettled	0.23
130	Low	Middle	UnP	Rural	0.22
106	Low	Middle	UnP	Unsettled	0.22
111	Low	Middle	UnP	Unsettled	0.16
129	Low	Middle	UnP	Rural	0.14
119	Low	Middle	UnP	Unsettled	0.14
128	Low	Middle	UnP	Unsettled	0.14

5.4 Discussion

Conservation values, ranging from 0.14 to 0.86, with a mean of 0.49 (SD ± 0.17), highlight the complex interaction between protection status and settlement patterns. The Upper, Middle, and Lower stretches provide a framework for ecological implications, conservation priorities, and management strategies, contextualised within global and regional riverine ecology literature.

The upper stretch (0.46 ± 0.14) displayed moderate conservation value, with few high-value segments, namely, BEU 67, 69, 70, 76, and 86, covering 25 km under the Hastinapur Wildlife Sanctuary. However, low-value segments, such as BEU 78, 80, and 81, suggest that protection status does not ensure ecological health, possibly due to upstream pollution or hydrological alterations (Allan et al., 2013; Palmer et al., 2008). This variability within protected areas underscores the need for active management to mitigate external stressors (Gaston et al. 2008).

In contrast, the middle stretch (mean = 0.24, SD ± 0.06) exhibited the lowest conservation values with no high-value segments. Segments with the lowest conservation values, such as BEU 119 and BEUs 128 and 129, spanning 20 km, indicate degraded habitats, likely owing to anthropogenic pressures, such as agricultural intensification. The low value segments in the Upper Ganga Ramsar Site, such as BEUs 92, 95, 96, 98, 100, 102, and 103, showed low values, suggesting that its international designation does not guarantee high ecological integrity, a pattern observed in other Ramsar sites facing external pressures such as agricultural runoff or inadequate management (Davidson, 2014; Finlayson et al., 2011; Sundar & Kittur, 2012).

The lower stretch BEUs (133 – 210 BEU; mean = 0.68; SD ± 0.12) emerged as the most ecologically significant, hosting 30 high-priority BEUs (150 km) with conservation values above the 75th percentile (0.62). In these segments, BEU 196, 194, 165, and 169 indicated exceptional habitat suitability, likely supporting diverse waterbird assemblages owing to favourable hydrological conditions or availability of food resources (Kingsford & Norman, 2002; Roshier et al., 2002; Sundar & Kittur, 2012). These findings align with studies emphasising lower river stretches as biodiversity hotspots, where comparatively slower flows and wide channels enhance foraging and breeding opportunities for waterbirds (Bunn & Arthington, 2002; Nilsson et al., 2005; Sundar & Kittur, 2012). The prevalence of unsettled segments in high-value areas (e.g. BEU 196) supports the evidence that minimal human disturbance fosters higher avian diversity (Sodhi et al., 2011; Strayer & Dudgeon, 2010).

Protection status significantly shapes conservation outcomes; however, its efficacy varies. The Hastinapur Wildlife Sanctuary spans 115 km of the upper and middle stretches, but its segments exhibit a wide value range (0.25 – 0.68), indicating that legal protection alone is insufficient without robust management (Bruner et al., 2001; Gaston et al., 2008). The Upper Ganga Ramsar Site showed moderate values (0.26 – 0.32), suggesting the potential for enhanced conservation through habitat restoration, as advocated by Ramsar sites globally (Finlayson et al., 2011; Zedler & Kercher, 2005). Unprotected segments in the lower stretch dominated the high-value areas (0.63 – 0.86), reflecting natural resilience, possibly because of intact floodplain habitats. This highlights the urgency of the formal protection of these segments to prevent future degradation (Margules & Pressey, 2000).

The results advocate the need for having a spatially explicit conservation strategy. The 145km of high-priority segments in the lower stretch require immediate protection, potentially through designation as wildlife sanctuaries or Ramsar sites, given their unprotected status and high ecological value (CBD, 2020; Margules & Pressey, 2000). BEUs exhibiting high conservation values should be prioritised to secure critical waterbird habitats. BEUs (67, 69,70, 76, 78, 80, 81, 86) falling within the Hastinapur Wildlife Sanctuary in the upper stretch benefit from existing protection but require enhanced management to address low-value segments (BEUs 78, 80, 81) through measures such as habitat restoration, maintaining natural hydrological cycles (Sutherland et al., 2004; Zedler, 2000). The middle stretch, with the overall lowest conservation values (mean = 0.24, SD ± 0.06), demands urgent restoration, particularly in the Unprotected (BEUs 106, 111, 114, 115, 116, 118, 119, 121, 126, 128, 129, 130, 132) and Upper Ganga River Ramsar Site (BEUs 92, 95, 102, 103) (Finlayson et al., 2011; Sundar & Kittur, 2012; Vörösmarty et al., 2010).

This study has identified the lower stretch as the primary conservation priority, with high-value unprotected segments requiring urgent protection. The segments within the Hastinapur Wildlife Sanctuary of the Upper stretch require enhanced management to address low-value areas, whereas the Upper Ganga Ramsar Site and unprotected zones in the middle stretch demand restoration to improve ecological value. These findings provide a robust, evidence-based framework for prioritising conservation actions, contributing to the sustainable management of riverine ecosystems and the preservation of waterbird biodiversity in the Gangetic floodplains.

CHAPTER 6
SYNTHESIS AND CONSERVATION IMPLICATIONS

6.1 Synthesis

The study was conducted over 750 km of the middle stretch of the Ganga River between 29°38'15" N; 78° 6' 22" E and 25°25'49" N; 81°53'19.01" E, which revealed rich avifaunal diversity, with 2,34,468 waterbirds from 107 species belonging to 25 families and 11 orders. The study area supports a diverse array of resident (43.9%), winter migrant (28.9%), and resident with winter migration (27.1%) species of waterbirds. Seasonal fluctuations in waterbird abundance and species richness were evident, with the highest waterbird abundance and species richness recorded in the post-monsoon season of 2018 (51,264 individuals, 88 species) and the lowest in the post-monsoon season of 2019 (32,225 individuals, 74 species). The order Charadriiformes dominated across seasons, whereas Anseriformes exhibited significant post-monsoon peaks, reflecting a seasonal winter influx. The presence of three vulnerable (VU), 11 near threatened (NT), and five endangered (EN) species, along with 15 species protected under Schedule I of the Wild Life (Protection) Act, 1972, underscores the conservation significance of the study area. Furthermore, species accumulation curves and non-parametric estimators (Chao 2, Jackknife 1, and Jackknife 2) indicated that the observed species richness closely approximated true diversity. However, some seasons, such as pre-monsoon 2017 and 2018, required additional sampling effort to reach full species detection.

Shannon-Weiner diversity ranged from 2.97 (post-monsoon 2018–19) to 3.97 (pre-monsoon 2017), indicating seasonal variations in species abundance and evenness.

Margalef's richness index showed moderate fluctuations (6.64–7.95), suggesting stable species richness. Pielou's evenness was lowest in post-monsoon 2019–20 (0.16) and highest in pre-monsoon 2019 (0.35). The relative diversity index (RDi) highlighted the dominance of Anatidae (RDi = 18.69), with seasonal increases in the post-monsoon period, whereas families such as Scolopacidae and Ardeidae showed consistent species composition. Of the 107 waterbird species recorded, the top 20 species comprised 82% of the population in the pre-monsoon season and 86% in the post-monsoon season. In the pre-monsoon season, the most abundant species were the little cormorant (20.30%), river lapwing (6.34%), Asian openbill (5.41%), and little pratincole (5.28%). In the post-monsoon, black-headed gull (14.76%) and great cormorant (14.23%) were most abundant.

Spatial and temporal analyses revealed distinct patterns in the waterbird assemblage structure. Species richness during the pre-monsoon period ranged from 42 (S15) to 66 (S5) across all 15 study sites. In the post-monsoon period, species richness varied between 46 (S14) and 70 (S5) species. The overall species richness ranged from 64 to 86 species, with Site S5 showing the highest overall richness (86 species) and Site S14 the lowest (64 species).

Beta diversity analyses highlighted moderate compositional dissimilarity ($\beta = 0.61$), driven primarily by species turnover (80.20%) rather than nestedness (19.80%), indicating that site-to-site differences were largely due to species replacement. Seasonal variations were further supported by multivariate analyses, with PERMANOVA ($F = 21.70$, $p < 0.05$) and ANOSIM ($R = 0.33$, $p < 0.05$) confirming significant differences between the pre-monsoon and post-monsoon assemblages. The

NMDS plot (stress = 0.27) also corroborated these seasonal variations, while SIMPER analysis identified key species, such as the great cormorant and ruddy shelduck, as dominant in the post-monsoon season, and little pratincole and river lapwing in the pre-monsoon season, contributing to 25.5% of seasonal dissimilarity. Strong positive correlations ($r > 0.7$) were observed between the Asian openbill and Asian woollyneck, indicating their frequent co-occurrence in shared habitats during the pre-monsoon season. During post-monsoon, a distinct cluster comprising black-headed ibis, oriental darter, and painted stork exhibited moderate to strong positive associations ($r = 0.45$–0.70), suggesting similar habitat preferences and resource utilisation.

A comprehensive analysis of waterbird assemblages along a riverine gradient revealed a complex interplay of ecological and anthropogenic factors shaping community structure across seasons, elevations, protection statuses, and settlement classes. Multivariate analyses (PERMANOVA, ANOSIM, and NMDS) confirmed significant differences in assemblages across elevation, protection, and settlement classes. Stronger differentiation was observed across elevation classes during both the pre-monsoon (PERMANOVA: $F=3.99$, $R^2=0.23$, $p < 0.05$) and post-monsoon (PERMANOVA: $F=6.037$, $R^2=0.32$, $p > 0.05$) seasons. Significant differences were also found in the protection classes during the pre-monsoon ($F=3.03$, $R^2=0.04$, $p < 0.05$) and post-monsoon ($F=3.27$, $R^2=0.04$, $p < 0.05$) seasons. Additionally, significant variations were noted among settlement classes in both the pre-monsoon ($F=2.18$, $R^2=0.11$, $p < 0.05$) and post-monsoon ($F=2.02$, $R^2=0.10$, $p < 0.05$) seasons. These differences may be attributed to the greater abundance of habitat-specialised birds or their preferences for specific habitat conditions, which fluctuate seasonally, influencing their distribution and abundance across the study area. Beta diversity analyses further underscore that species turnover, rather than nestedness, drives community dissimilarity, particularly in the lower stretch (βSOR=0.61) and urban areas (βSOR=0.72) during the pre-monsoon period, highlighting dynamic habitat heterogeneity and high species replacement.

Canonical Correspondence Analysis (CCA) reveals that fishing intensity, channel flow, and anthropogenic factors like built-up areas and solid waste are primary drivers of community structure, with species such as pied avocet and little tern thriving in intensive fishing areas and flowing channels, while great white egret and red-naped ibis tolerate modified environments.

Seasonal dynamics highlight the critical role of hydrological cycles in shaping waterbird communities, with post-monsoon homogenisation reducing beta diversity (βSOR=0.54 vs. 0.57 pre-monsoon) due to a shift in species composition, possibly driven by monsoon flooding. This temporal variability, coupled with high turnover rates (βSIM=70–85%), emphasises the importance of maintaining habitat connectivity and heterogeneity to support both resident and migratory species. The dominance of turnover over nestedness across all gradients suggests that local extinctions and colonisations, rather than species loss, drive community assembly, aligning with metacommunity theories of dispersal limitation and environmental filtering. These findings collectively demonstrate that riverine ecosystems function as complex habitat mosaics, where spatial and temporal environmental gradients, modulated by protection status and human influence, shape diverse and dynamic waterbird assemblages.

Spatial prioritisation analyses identified river stretches that collectively capture the majority of waterbird diversity. These stretches underscore the feasibility of establishing a representative and resilient network of protected river stretches that can sustain waterbird populations under current and future environmental scenarios.

The spatial analysis of the Middle Ganga River reveals pronounced heterogeneity in waterbird conservation value along its course, with the lower stretch (133–210 BEUs) emerging as the most critical region. This area, characterised by an extensive unprotected river stretch with minimal human disturbance, supports the highest number of high-priority conservation segments (32 BEUs,160 km). Notably, BEUs 196, 165, 169, 194, 191, 162, and 163 exhibited high conservation values, each exceeding 0.76, and provided suitable habitats for globally threatened species, including the black-bellied tern, Indian skimmer, Pallas's fish-eagle, and steppe eagle. The ecological integrity of these stretches is underpinned by their habitat diversity and relative isolation from intensive human activity, making them indispensable for sustaining waterbird populations and the overall riverine biodiversity.

In contrast, the middle stretch (88–132 BEUs) presents a more complex conservation scenario. While it does not contain any high conservation value segments, the overall conservation value was lowest among the three river stretches, with a mean of 0.24. This stretch is characterised by a mosaic of habitats and settlement types, including urban, rural, and unsettled. Despite the presence of the Upper Ganga Ramsar Site, many segments suffer from anthropogenic pressures such as riverbed agriculture and fishing, which could lead to low species richness and compromise ecological integrity.

These findings highlight that formal protection alone does not guarantee ecological health, underscoring the need for targeted restoration and adaptive management.

The Upper stretch (61–87 BEUs), encompassing Balawali (29°38'15" N; 78° 6'22" E) and the Brijghat (28°44'42" N, 78° 9'42" E), demonstrated moderate conservation value (mean = 0.46) with notable variability. High-value segments were primarily located within protected areas, whereas several low-value segments indicated ongoing habitat degradation and disturbance.

6.2 Conservation Implications

The primary threat to waterbird assemblages along the studied river stretch is habitat loss and fragmentation, driven by agriculture and sand mining. Infrastructure developments, such as embankments, dams, and barrages, have also disrupted natural hydrological regimes and diminished the extent and quality of riverine habitats. These alterations have led to a significant reduction in habitat availability, resulting in a decline in waterbird diversity and abundance. The conversion of riparian forests to agricultural land has further exacerbated habitat loss, whereas intensive fishing, dumping of solid waste, and unregulated riverbed agriculture have degraded habitat quality, reduced food availability, and increased disturbances to foraging and roosting birds. Large-scale water extraction for irrigation and domestic use has altered hydrological regimes, leading to reduced water levels and loss of foraging areas.

The presence of 30% migratory species underscores the importance of the study stretch as a critical stopover and wintering ground, highlighting its global conservation significance. This necessitates the integration of the conservation priority stretches of the study area, such as the lower stretch, into international conservation frameworks, such as the Ramsar Convention. Immediate conservation actions are essential to protect and restore high-diversity sites by establishing or expanding existing protected areas, such as the State Wildlife Barasingha Sanctuary, to counter anthropogenic pressures, including sand mining, riverbed agriculture, overfishing, and riverbank agriculture.

Human-induced factors impact waterbird populations through direct habitat degradation and indirect disruption of food webs. Therefore, management interventions must prioritise preserving and restoring diverse riverine habitats, including open water, riparian zones, sandbars, riverine islands, and foraging areas. Hydrological management, such as regulating water levels and restoring natural flow regimes, is critical for maintaining the dynamic processes that support habitat heterogeneity and ecosystem resilience.

Pronounced seasonal variations in waterbird assemblages, driven by high species turnover, necessitate adaptive, season-specific management strategies tailored to the ecological needs of diverse feeding guilds. The dominance of Charadriiformes across seasons and post-monsoon peaks in Anseriformes highlights the need to maintain varied microhabitats, such as shallow mudflats for wading birds, such as little pratincole and river lapwing, during the pre-monsoon season, and deeper water bodies for species, such as great cormorant and ruddy shelduck, in the post-monsoon period. Strong co-occurrence patterns among wading birds, such as Asian openbill and Asian woollyneck, suggest that protecting key aggregation sites could benefit associated species clusters. Management efforts should focus on preserving natural flow regimes, maintaining riparian vegetation, and regulating water levels to support diverse foraging habitats while mitigating stressors, such as solid waste from religious and urban activities and hydrological alterations due to agricultural demands.

Continuous monitoring and research are vital for tracking temporal trends and assessing conservation effectiveness amidst ongoing environmental and climatic changes. Long-term monitoring programs should be established to detect shifts in species richness, abundance, and community structure, particularly given the correlation between temperature gradients and nestedness patterns, which indicate the impact of climate change on community assembly. Site-specific conservation plans are critical for areas with unique species compositions, particularly in the lower stretches of the river, which are identified as biodiversity hotspots. Bringing these stretches under the Wild Life (Protection) Act, 1972, with science-based management plans, is essential to counter threats from over-exploitation, pollution, and hydrological alterations. Enhancing the management effectiveness of existing protected areas, such as Hastinapur Wildlife Sanctuary, through habitat restoration and mitigation of rural and urban impacts is equally critical.

Effective conservation requires mitigating major anthropogenic pressures, including regulating fishing activities, sand mining, and unsustainable water abstraction. Strengthening community-based resource management and fostering active participation by local stakeholders can significantly improve regulatory compliance and promote long-term sustainability. Moreover, adopting water-efficient agricultural practices offers a viable strategy to reduce irrigation demand, thereby lowering dependency on water withdrawals from barrages. Applying integrated pest management approaches can also help minimise pesticide runoff into aquatic ecosystems, contributing to the preservation of ecological health.

Integrating river restoration and conservation objectives into regional land-use planning, agricultural policies, and water management frameworks is essential for long-term sustainability. Strengthening legal protections and improving enforcement will enhance conservation outcomes. Standardised monitoring protocols, remote sensing, and citizen science initiatives can enhance data collection and support evidence-based decision-making, fostering public engagement in wetland conservation.

This study advances the understanding of waterbird conservation by highlighting the critical role of habitat heterogeneity, the dominant influence of anthropogenic pressures, and the importance of spatial prioritisation. Integrating functional diversity metrics, multivariate analyses, and spatial planning tools provides a robust framework for assessing conservation needs and designing effective interventions. By addressing ecological, habitat, and socio-economic considerations, this research offers a foundation for evidence-based conservation planning and management to ensure the long-term viability of waterbird populations and wetland ecosystems.

6.3 Conclusion

The conservation of waterbirds in the study area depends on maintaining habitat heterogeneity, mitigating anthropogenic pressures, and strategically protecting key areas. Through coordinated, multi-level actions, including habitat protection, restoration, and community engagement, it is possible to secure the ecological health of the river, preserve its role as a critical habitat for waterbirds, and contribute to global biodiversity conservation goals amidst significant socio-economic challenges.

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Appendix I. List of birds from the middle stretch of the Ganga River. IUCN: International Union for Conservation of Nature, LC: Least Concern, NT: Near Threatened, VU: Vulnerable, EN: Endangered, WPA: Wild Life (Protection) Act, 1972, II Part-B: Schedule II Part B, I Part-B: Schedule I Part-B, R/LM: Resident/Local Migrant, R/WM: Resident/Winter Migrant, WM: Winter Migrant, R: Resident

Taxon	Common name	IUCN	WPA	Status
	ANSERIFORMES **Anatidae**			
Dendrocygna javanica	Lesser Whistling-duck	LC	II Part-B	R/LM
Anser indicus	Bar-headed Goose	LC	II Part-B	R/WM
Anser anser	Greylag Goose	LC	II Part-B	WM
Anser albifrons	Greater White-fronted Goose	LC	II Part-B	WM
Mergus merganser	Goosander	LC	II Part-B	R/WM
Tadorna tadorna	Common Shelduck	LC	II Part-B	WM
Tadorna ferruginea	Ruddy Shelduck	LC	II Part-B	R/WM
Sarkidiornis melanotos	Knob-billed Duck	LC	II Part-B	R/LM
Netta rufina	Red-crested Pochard	LC	II Part-B	WM
Aythya ferina	Common Pochard	VU	I Part-B	WM
Aythya nyroca	Ferruginous Duck	NT	II Part-B	R/WM

Aythya fuligula	Tufted Duck	LC	II Part-B	WM
Spatula querquedula	Garganey	LC	II Part-B	WM
Spatula clypeata	Northern Shoveler	LC	II Part-B	WM
Mareca strepera	Gadwall	LC	II Part-B	WM
Mareca penelope	Eurasian Wigeon	LC	II Part-B	WM
Anas poecilorhyncha	Indian Spot-billed Duck	LC	II Part-B	R/LM
Anas platyrhynchos	Mallard	LC	II Part-B	R/WM
Anas acuta	Northern Pintail	LC	II Part-B	WM
Anas crecca	Common Teal	LC	II Part-B	WM
		PODICIPEDIFORMES **Podicipedidae**		
Tachybaptus ruficollis	Little Grebe	LC	II Part-B	R/LM
Podiceps cristatus	Great Crested Grebe	LC	II Part-B	R/WM
		GRUIFORMES **Rallidae**		
Zapornia akool	Brown Crake	LC	II Part-B	R/LM
Amaurornis phoenicurus	White-breasted Waterhen	LC	II Part-B	R
Porphyrio porphyrio	Purple Swamphen	LC	II Part-B	R/LM
Gallinula chloropus	Common Moorhen	LC	II Part-B	R/WM

Fulica atra	Common Coot	LC	II Part-B	R/WM
GRUIFORMES **Gruidae**				
Anthropoides virgo	Demoiselle Crane	LC	I Part-B	WM
Grus antigone	Sarus Crane	VU	I Part-B	R/LM
Grus grus	Common Crane	LC	I Part-B	WM
CICONIIFORMES **Ciconiidae**				
Mycteria leucocephala	Painted Stork	LC	II Part-B	R/LM
Anastomus oscitans	Asian Openbill	LC	II Part-B	R/LM
Ciconia nigra	Black Stork	LC	II Part-B	WM
Ciconia episcopus	Asian Woollyneck	NT	II Part-B	R
Ephippiorhynchus asiaticus	Black-necked Stork	NT	II Part-B	R
PELECANIFORMES **Threskiornithidae**				
Platalea leucorodia	Eurasian Spoonbill	LC	I Part-B	R
Threskiornis melanocephalus	Black-headed Ibis	NT	II Part-B	R/LM
Pseudibis papillosa	Red-naped Ibis	LC	II Part-B	R

		PELECANIFORMES **Ardeidae**		
Nycticorax nycticorax	Black-crowned Night-heron	LC	II Part-B	R/LM
Butorides striata	Green-backed Heron	LC	II Part-B	R
Ardeola grayii	Indian Pond-heron	LC	II Part-B	R/LM
Bubulcus ibis	Cattle Egret	LC	II Part-B	R/LM
Ardea cinerea	Grey Heron	LC	II Part-B	R/WM
Ardea purpurea	Purple Heron	LC	II Part-B	R/LM
Ardea alba	Great White Egret	LC	II Part-B	R/LM
Ardea intermedia	Intermediate Egret	LC	II Part-B	R/LM
Egretta garzetta	Little Egret	LC	II Part-B	R/LM
		PELECANIFORMES **Pelecanidae**		
Pelecanus crispus	Dalmatian Pelican	NT	II Part-B	WM
Pelecanus onocrotalus	Great White Pelican	LC	II Part-B	R/WM
		SULIFORMES **Phalacrocoracidae**		
Microcarbo niger	Little Cormorant	LC	II Part-B	R/LM
Phalacrocorax carbo	Great Cormorant	LC	II Part-B	R/WM

Phalacrocorax fuscicollis	Indian Cormorant	LC	II Part-B	R/LM
		SULIFORMES **Anhingidae**		
Anhinga melanogaster	Oriental Darter	NT	II Part-B	R/LM
		CHARADRIIFORMES **Burhinidae**		
Burhinus indicus	Indian Thick-knee	LC	II Part-B	R
Esacus recurvirostris	Great Thick-knee	NT	II Part-B	R/LM
		CHARADRIIFORMES **Recurvirostridae**		
Recurvirostra avosetta	Pied Avocet	LC	II Part-B	R/WM
Himantopus himantopus	Black-winged Stilt	LC	II Part-B	R/LM
		CHARADRIIFORMES **Charadriidae**		
Charadrius dubius	Little Ringed Plover	LC	II Part-B	R/WM
Charadrius alexandrinus	Kentish Plover	LC	II Part-B	R/WM
Charadrius mongolus	Siberian Sandplover	EN	II Part-B	R/WM
Vanellus duvaucelii	River Lapwing	NT	II Part-B	R/LM
Vanellus cinereus	Grey-headed Lapwing	LC	II Part-B	WM

Vanellus indicus	Red-wattled Lapwing	LC	II Part-B	R/LM
Vanellus leucurus	White-tailed Lapwing	LC	II Part-B	WM
		CHARADRIIFORMES Rostratulidae		
Rostratula benghalensis	Greater Painted-snipe	LC	II Part-B	R/LM
		CHARADRIIFORMES Jacanidae		
Hydrophasianus chirurgus	Pheasant-tailed Jacana	LC	II Part-B	R/LM
Metopidius indicus	Bronze-winged Jacana	LC	II Part-B	R
		CHARADRIIFORMES Scolopacidae		
Numenius phaeopus	Whimbrel	LC	II Part-B	WM
Numenius arquata	Eurasian Curlew	NT	II Part-B	WM
Limosa limosa	Black-tailed Godwit	NT	II Part-B	WM
Calidris pugnax	Ruff	LC	II Part-B	WM
Calidris ferruginea	Curlew Sandpiper	NT	II Part-B	WM
Calidris temminckii	Temminck's Stint	LC	II Part-B	WM
Calidris minuta	Little Stint	LC	II Part-B	WM
Actitis hypoleucos	Common Sandpiper	LC	II Part-B	R/WM

Tringa ochropus	Green Sandpiper	LC	II Part-B	R/WM
Tringa erythropus	Spotted Redshank	LC	II Part-B	WM
Tringa nebularia	Common Greenshank	LC	I Part-B	WM
Tringa totanus	Common Redshank	LC	II Part-B	R/WM
Tringa glareola	Wood Sandpiper	LC	II Part-B	WM
Tringa stagnatilis	Marsh Sandpiper	LC	II Part-B	WM
		CHARADRIIFORMES **Glareolidae**		
Glareola lactea	Little Pratincole	LC	II Part-B	R/LM
		CHARADRIIFORMES **Laridae**		
Rynchops albicollis	Indian Skimmer	EN	I Part-B	R/LM
Larus brunnicephalus	Brown-headed Gull	LC	II Part-B	R/WM
Larus ridibundus	Black-headed Gull	LC	II Part-B	R/WM
Larus ichthyaetus	Pallas's Gull	LC	II Part-B	R
Sternula albifrons	Little Tern	LC	II Part-B	R/WM
Gelochelidon nilotica	Common Gull-billed Tern	LC	I Part-B	R
Chlidonias hybrida	Whiskered Tern	LC	II Part-B	R
Sterna aurantia	River Tern	VU	I Part-B	R

Sterna acuticauda	Black-bellied Tern	EN	I Part-B	R
		ACCIPITRIFORMES **Pandionidae**		
Pandion haliaetus	Osprey	LC	I Part-B	R
		ACCIPITRIFORMES **Accipitridae**		
Aquila nipalensis	Steppe Eagle	EN	I Part-B	WM
Circus aeruginosus	Western Marsh-harrier	LC	I Part-B	WM
Haliaeetus leucoryphus	Pallas's Fish-eagle	EN	I Part-B	R/WM
		CORACIIFORMES **Meropidae**		
Merops philippinus	Blue-tailed Bee-eater	LC	II Part-B	R/WM
		CORACIIFORMES **Alcedinidae**		
Alcedo atthis	Common Kingfisher	LC	II Part-B	R/WM
Ceryle rudis	Pied Kingfisher	LC	II Part-B	R
Halcyon smyrnensis	White-throated Kingfisher	LC	II Part-B	R/LM
		FALCONIFORMES **Falconidae**		
Falco peregrinus	Peregrine Falcon	LC	I Part-B	R/WM

PASSERIFORMES Hirundinidae				
Hirundo smithii	Wire-tailed Swallow	LC	II Part-B	R
Hirundo rustica	Barn Swallow	LC	II Part-B	R/WM
Riparia chinensis	Asian Plain Martin	LC	II Part-B	R/LM
PASSERIFORMES Motacillidae				
Motacilla flava	Western Yellow Wagtail	LC	II Part-B	R/WM
Motacilla citreola	Citrine Wagtail	LC	II Part-B	R/WM
Motacilla maderaspatensis	White-browed Wagtail	LC	II Part-B	R
Motacilla alba	White Wagtail	LC	II Part-B	R/WM

Appendix II. Bird Species and their distribution across sites along the river stretch

Taxon	Common Name	Site ID
	ANSERIFORMES **Anatidae**	
Dendrocygna javanica	Lesser Whistling-duck	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S15
Anser indicus	Bar-headed Goose	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S15
Anser anser	Greylag Goose	S1,S2,S3,S4,S5,S7,S8,S10,S12
Anser albifrons	Greater White-fronted Goose	S2
Mergus merganser	Goosander	S1,S2,S6,S7,S8
Tadorna tadorna	Common Shelduck	S1,S3,S5,S6,S8,S9,S10,S12,S13,S15
Tadorna ferruginea	Ruddy Shelduck	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Sarkidiornis melanotos	Knob-billed Duck	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S15
Netta rufina	Red-crested Pochard	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Aythya ferina	Common Pochard	S3,S5,S7
Aythya nyroca	Ferruginous Duck	S5,S9
Aythya fuligula	Tufted Duck	S5,S11

Spatula querquedula	Garganey	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11
Spatula clypeata	Northern Shoveler	S1,S2,S3,S4,S5,S6,S10,S12,S14,S15
Mareca strepera	Gadwall	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Mareca penelope	Eurasian Wigeon	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S12,S13
Anas poecilorhyncha	Indian Spot-billed Duck	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11
Anas platyrhynchos	Mallard	S1,S2,S3,S4,S6,S7,S8,S9,S10,S12
Anas acuta	Northern Pintail	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Anas crecca	Common Teal	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
	PODICIPEDIFORMES Podicipedidae	
Tachybaptus ruficollis	Little Grebe	S1,S2,S5,S6,S7,S9,S10,S11,S13,S14,S15
Podiceps cristatus	Great Crested Grebe	S1,S5,S7,S10
GRUIFORMES Rallidae		
Zapornia akool	Brown Crake	S5
Amaurornis phoenicurus	White-breasted Waterhen	S3,S4,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Porphyrio porphyrio	Purple Swamphen	S5

Gallinula chloropus	Common Moorhen	S5
Fulica atra	Common Coot	S2,S5,S10,S11,S12
GRUIFORMES **Gruidae**		
Anthropoides virgo	Demoiselle Crane	S4,S6
Grus antigone	Sarus Crane	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14
Grus grus	Common Crane	S1,S2,S4,S5,S6,S9,S10,S12,S13,S15
CICONIIFORMES **Ciconiidae**		
Mycteria leucocephala	Painted Stork	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Anastomus oscitans	Asian Openbill	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Ciconia nigra	Black Stork	S1,S2,S3,S6,S7,S8,S11,S14
Ciconia episcopus	Asian Woollyneck	S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Ephippiorhynchus asiaticus	Black-necked Stork	S1,S2,S3,S4,S5,S6,S7,S8,S9,S12
PELECANIFORMES **Threskiornithidae**		
Platalea leucorodia	Eurasian Spoonbill	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S12,S13,S15

Threskiornis melanocephalus	Black-headed Ibis	S1,S5,S7,S8,S9,S10,S11,S12,S13,S14,S15
Pseudibis papillosa	Red-naped Ibis	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
	PELECANIFORMES **Ardeidae**	
Nycticorax nycticorax	Black-crowned Night-heron	S1,S2,S4,S6,S9,S10,S12,S13,S14,S15
Butorides striata	Green-backed Heron	S1,S4,S5,S6,S9,S10,S11,S12,S13,S14
Ardeola grayii	Indian Pond-heron	S1,S2,S3,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Bubulcus ibis	Cattle Egret	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Ardea cinerea	Grey Heron	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Ardea purpurea	Purple Heron	S1,S2,S4,S5,S7,S9,S10,S11,S12,S13,S14
Ardea alba	Great White Egret	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Ardea intermedia	Intermediate Egret	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Egretta garzetta	Little Egret	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
	PELECANIFORMES **Pelecanidae**	
Pelecanus crispus	Dalmatian Pelican	S1,S11
Pelecanus onocrotalus	Great White Pelican	S11,S12,S13,S14

	SULIFORMES **Phalacrocoracidae**	
Microcarbo niger	Little Cormorant	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Phalacrocorax carbo	Great Cormorant	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Phalacrocorax fuscicollis	Indian Cormorant	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
	SULIFORMES **Anhingidae**	
Anhinga melanogaster	Oriental Darter	S1,S2,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
	CHARADRIIFORMES **Burhinidae**	
Burhinus indicus	Indian Thick-knee	S4,S5,S6,S7,S8,S9
Esacus recurvirostris	Great Thick-knee	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S12,S14
	CHARADRIIFORMES **Recurvirostridae**	
Recurvirostra avosetta	Pied Avocet	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Himantopus himantopus	Black-winged Stilt	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15

CHARADRIIFORMES **Charadriidae**		
Charadrius dubius	Little Ringed Plover	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Charadrius alexandrinus	Kentish Plover	S1,S2,S3,S5,S6,S7,S8,S9,S10,S12,S13,S15
Charadrius mongolus	Siberian Sandplover	S3,S6,S7,S10,S11,S12,S13,S15
Vanellus duvaucelii	River Lapwing	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Vanellus cinereus	Grey-headed Lapwing	S11
Vanellus indicus	Red-wattled Lapwing	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Vanellus leucurus	White-tailed Lapwing	S5
CHARADRIIFORMES **Rostratulidae**		
Rostratula benghalensis	Greater Painted-snipe	S13,S15
CHARADRIIFORMES **Jacanidae**		
Hydrophasianus chirurgus	Pheasant-tailed Jacana	S1,S6,S11
Metopidius indicus	Bronze-winged Jacana	S6,S9,S10,S11,S13

	CHARADRIIFORMES **Scolopacidae**	
Numenius phaeopus	Whimbrel	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Numenius arquata	Eurasian Curlew	S1,S3,S4,S5,S6,S7,S8,S9,S10,S12,S14
Limosa limosa	Black-tailed Godwit	S1,S2,S4,S5,S6,S7,S8,S9,S10,S11
Calidris pugnax	Ruff	S2,S6,S11,S12,S14,S15
Calidris ferruginea	Curlew Sandpiper	S9,S11,S12
Calidris temminckii	Temminck's Stint	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Calidris minuta	Little Stint	S1,S2,S3,S4,S5,S6,S8,S9,S10,S11,S12,S13,S14,S15
Actitis hypoleucos	Common Sandpiper	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Tringa ochropus	Green Sandpiper	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Tringa erythropus	Spotted Redshank	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Tringa nebularia	Common Greenshank	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Tringa totanus	Common Redshank	S2,S3,S4,S5,S6,S7,S8,S9,S10,S12,S13,S14,S15
Tringa glareola	Wood Sandpiper	S1,S2,S4,S5,S6,S7,S8,S9,S11,S13
Tringa stagnatilis	Marsh Sandpiper	S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S13
	CHARADRIIFORMES **Glareolidae**	
Glareola lactea	Little Pratincole	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15

CHARADRIIFORMES **Laridae**		
Rynchops albicollis	Indian Skimmer	S1,S2,S3,S4,S5,S6,S7,S8,S9,S11,S13,S14,S15
Larus brunnicephalus	Brown-headed Gull	S2,S3,S4,S5,S7,S8,S10,S11,S12,S13,S14,S15
Larus ridibundus	Black-headed Gull	S1,S2,S3,S5,S6,S8,S10,S11,S12,S14,S15
Larus ichthyaetus	Pallas's Gull	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Sternula albifrons	Little Tern	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Gelochelidon nilotica	Common Gull-billed Tern	S4,S5,S8
Chlidonias hybrida	Whiskered Tern	S1,S2,S3,S4,S5,S6,S7,S9,S10,S12,S14,S15
Sterna aurantia	River Tern	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S14,S15
Sterna acuticauda	Black-bellied Tern	S1,S2,S3,S4,S5,S6,S7,S8,S9
ACCIPITRIFORMES **Pandionidae**		
Pandion haliaetus	Osprey	S1,S2,S3,S4,S5,S7,S8,S9,S10,S11,S12,S13,S14,S15
ACCIPITRIFORMES **Accipitridae**		
Aquila nipalensis	Steppe Eagle	S1,S3,S4,S6,S8,S9,S10,S12,S13,S14,S15
Circus aeruginosus	Western Marsh-harrier	S7,S12

Haliaeetus leucoryphus	Pallas's Fish-eagle	S1,S12,S14
	CORACIIFORMES **Meropidae**	
Merops philippinus	Blue-tailed Bee-eater	S2,S4,S5,S6,S7,S9,S10,S11,S12,S13,S14,S15
	CORACIIFORMES **Alcedinidae**	
Alcedo atthis	Common Kingfisher	S2,S4,S5
Ceryle rudis	Pied Kingfisher	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Halcyon smyrnensis	White-throated Kingfisher	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
	FALCONIFORMES **Falconidae**	
Falco peregrinus	Peregrine Falcon	S1,S3,S4,S5,S6,S8,S9,S11,S12,S13,S14,S15
	PASSERIFORMES **Hirundinidae**	
Hirundo smithii	Wire-tailed Swallow	S2
Hirundo rustica	Barn Swallow	S1,S2,S3,S4,S11,S12,S13,S15
Riparia chinensis	Asian Plain Martin	S1,S2,S3,S4,S5,S7,S8,S9,S10,S11,S12,S13,S14,S15
	PASSERIFORMES	

	Motacillidae	
Motacilla flava	Western Yellow Wagtail	S1,S2,S3,S5,S11,S12,S13,S14
Motacilla citreola	Citrine Wagtail	S1,S2,S3,S4,S5,S6
Motacilla maderaspatensis	White-browed Wagtail	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15
Motacilla alba	White Wagtail	S1,S2,S3,S4,S5,S6,S7,S8,S9,S10,S11,S12,S13,S14,S15

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ANNOTATED LIST OF SPECIES

An annotated checklist of aquatic avifauna in the human-dominated middle stretch of the Ganga River

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Abstract. The Ganga River is a vital riverine habitat for several endangered species of flora and fauna, including waterbirds. The river flows through densely populated cities such as Kanpur, Prayagraj, and Varanasi. Major threats to the ecological integrity and hydrology of the river include flow alteration, water abstraction at barrages and dams, riverbed agriculture, unsustainable resource extraction such as fishing and sand mining, and discharge of untreated industrial and domestic effluents. Between 2018 and 2021, we conducted avifaunal surveys of the 750 km stretch of the Middle Ganga River and documented 107 aquatic avifaunal species belonging to 11 orders and 25 families. Among the observed species, three are Vulnerable and 11 are Near Threatened. Our study documents the rich diversity of aquatic avifauna despite human-induced habitat degradation and unsustainable resource extraction. We highlight the need for more focused conservation efforts supported by firm policy and legislation.

Key words. Conservation, Ramsar Site, richness, threatened, waterbirds, wildlife sanctuary

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INTRODUCTION

India harbours a rich biodiversity owing to its diverse ecosystems, which include alpine forests, deciduous forests, tropical rainforests, grasslands, deserts, mangroves, freshwaters, and coral reefs (Mittermeier et al. 2011; Rodgers and Panwar 1988). The Indian landmass is categorised into 10 biogeographic zones based on altitude, moisture, topography, and rainfall, and the Gangetic Plains is one of these biogeographic zones. It encompasses the vast floodplain formed by the Ganges River and its tributaries, supports rich aquatic biodiversity, and serves as crucial habitat for numerous species (Rodgers et al. 2000; Kumar et al. 2005). The Gangetic Plains is home to unique and magnificent species such as *Platanista gangetica* (Roxburgh 1801), *Gavialis gangeticus* (Gmelin 1789), *Crocodylus palustris* (Lesson 1831), *Lutrogale perspicillata* (Geoffroy 1826), along with several species of freshwater turtles, fishes, and birds (Rodgers and Panwar 1988; Dudgeon 2000; Das et al. 2022). The Gangetic Plains serve as critical habitats and provide abundant food resources and nesting sites for more than 200 species of waterbird, including ground-nesting birds such as *Grus antigone* (Linnaeus, 1758) and *Rynchops albicollis* (Swainson, 1838) (Kumar 2022). The Gangetic Plains lie within the Central Asian Flyway, a vital and globally significant migratory route for several bird species (Mundkur 2005).

Waterbirds serve as indicators in riverine ecosystems (Rajpar et al. 2022). Their presence, abundance, and diversity reflect the availability of food resources, water quality, and integrity of the habitat. Waterbirds occupy various trophic levels and utilise a wide range of habitats within the ecosystem. They are sensitive to changes in environmental conditions, making them reliable indicators of ecosystem stability and health (Rajpar et al. 2022). As a result, assessing and monitoring the status of waterbirds in riverine ecosystems is essential (Colloff et al. 2018). Moreover, changes in waterbird populations can indicate broader ecological shifts, such as changes in hydrological regimes, pollution, or climate, underscoring their importance as indicators of ecosystem dynamics.

Attempts have been made in the past to document the status of waterbirds in the Ganga River (Rao 2001; Bashir et al. 2012; Khan et al. 2013; Dey et al. 2014; Arya et al. 2020; Joshi et al. 2021). However, systematic surveys have not been conducted across the middle segment of the river, and most of the

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studies were limited to the smaller segments of the river. Previous studies were mostly conducted in the State Wildlife Barasingha Sanctuary (formerly known as Hastinapur Wildlife Sanctuary), Haiderpur Wetland Ramsar Site, and Upper Ganga River Ramsar Site (Rao 2001; Bashir et al. 2012; Khan et al. 2013; Dey et al. 2014; Arya et al. 2020; Joshi et al. 2021), and so there is lack of a comprehensive assessment of the status of the waterbirds in the middle stretch of the Ganga River.

Systematic monitoring is useful in the assessment of the status of threatened species at the regional level and can help in the formulation of conservation strategies (Hussain 1987; Dudgeon 2000). The main objective of our study is to produce a detailed checklist of waterbirds of the middle stretch of the Ganga River.

STUDY AREA

The Ganga River, originating from the Gangotri Glacier of the Himalayas and flowing to the Ganga Sagar in the Bay of Bengal, spans over 2,200 km and passes through the states of Uttarakhand, Uttar Pradesh, Bihar, Jharkhand, and West Bengal (Singh et al. 2007). The river is divided into three major stretches: Upper (from the origin to Haridwar), Middle (Haridwar to Varanasi), and Lower (Varanasi to Ganga Sagar) (WII-GACMC 2018). We conducted our study along the 750 km stretch of the Middle Ganga from Balawali, Bijnor (29.8125°N, 078.1762°E) to Sangam, Prayagraj (25.4303°N, 081.8888°E) in Uttar Pradesh, India (Figure 1). This stretch passes through the densely populated cities of Bijnor, Farrukhabad, Kannauj, Kanpur, and Prayagraj. The majority of the stretch studied is outside of protected areas. Only about 15% (110 km) is protected as the State Wildlife Barasingha Sanctuary, of which a 10 km stretch (1.3%) constitutes the Haiderpur

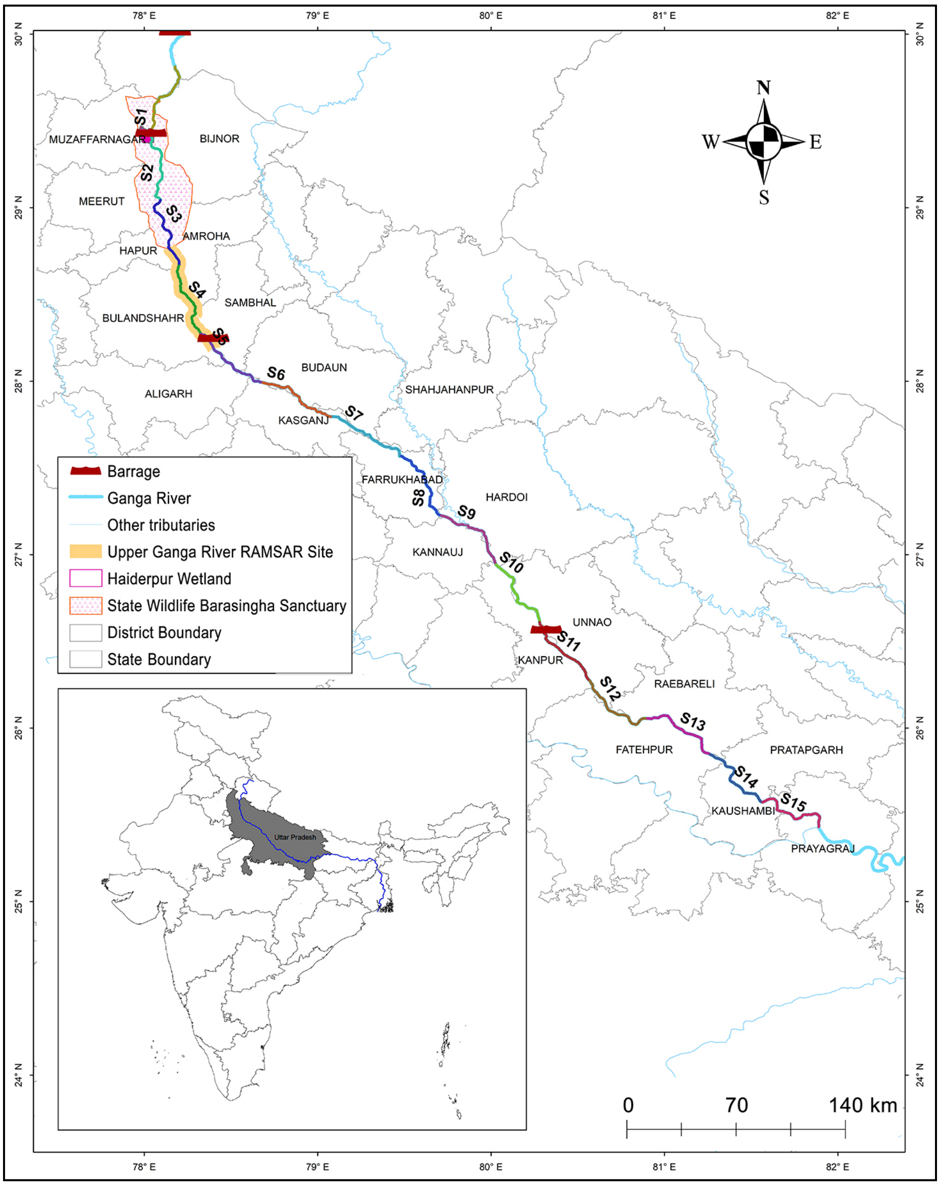

Figure 1. Map of the Middle stretch of the Ganga River in Uttar Pradesh, India.

Wetland Ramsar Site. Additionally, 11% (82 km) is in the Upper Ganga River Ramsar Site, and 3.3% (25 km) is in the Narora Important Birds Area (IBA site code IN-UP-10) (Rahmani et al. 2016). The main geomorphological features of the mainstem Ganga River include channels ranging from narrow to wide with intermittent meanders, alluvial islands, and broad sandbars (Singh et al. 2007). These diverse habitats provide food sources and nesting sites, attracting various resident and migratory bird species throughout the year (Rao 2001).

The middle stretch of the Ganga River supports one of the most densely populated areas in the world, with a population density of 634–1,452 individuals/km^2, significantly higher than the average population density of India (382 individuals/km^2) (GUP 2021). The region faces unsustainable water demand for agriculture, industry, and electricity generation. Additionally, the habitat and water quality have been substantially degraded because of sand mining, unplanned development, and pollution. These factors are responsible for degrading riverine habitats and pose serious challenges for sustainability and environmental health in the region (Hussain et al. 2020; Dagar et al. 2021).

METHODS

Our study area was divided into 15 equal river segments of 50 km each (Sites S1–S15; Table 1). Each year two boat-based continuous river surveys were conducted: post-monsoon/winter (November–February), during 0800–1200 h and 1500–1700 h, and pre-monsoon/summer (April–June), during 0600–0900 h and 1600–1800 h. The surveys were conducted between April 2018 and December 2021 using an inflatable boat powered by a 25 hp outboard motor (OBM) at a constant speed of 6–8 km/h. All observations were made using Nikon Aculon 10×50 binoculars. Photographs and detailed notes were also taken when possible.

Standard field guides were used to confirm the identity of the species (Ali 2002; Kazmierczak and van Perlo 2003; Grimmett et al. 2019). The boat was stopped for species identifications and individual counts when large congregations were sighted. Opportunistic bird observations along the river were also included in the checklist. The common names and taxonomic positions of birds were adopted from the Handbook of the Birds of the World and the BirdLife International Digital Checklist of the Birds of the World (HBW and BirdLife International 2024). Species were categorised as resident, winter visitor, and summer visitor (Ali and Ripley 1995; Kumar et al. 2005). Only bird species that are ecologically dependent on the wetland for at least a part of their annual cycle (Ramsar Convention 1994) were considered in our study. The species were also categorised by the number of sites occupied following MacKinnon and Phillipps (1993). The species occupied >81% of the sites are categorized as common (C), 61–80% of the sites as fairly common (FC), 21–60% as uncommon (Uc), and ≤20% of the sites are considered rare. The conservation status of the species was adopted from the IUCN Red List of threatened species (IUCN 2024). The national protection status was taken from the *Indian Wild Life (Protection) Act, 1972* (WPA), as amended in 2022.

Table 1. Geographical locations of the surveyed sites in the middle stretch of the Ganga River.

Site	Start		End		Average elevation a.s.l. (m)	Species richness
	Latitude (°N)	Longitude (°E)	Latitude (°N)	Longitude (°E)		
S1	29.8127	078.1764	29.4344	078.0330	220	79
S2	29.4344	078.0330	29.0427	078.0931	200	79
S3	29.0427	078.0931	28.6648	078.1987	180	72
S4	28.6648	078.1987	28.2714	078.3268	170	76
S5	28.2714	078.3268	27.9924	078.6817	160	86
S6	27.9924	078.6817	27.7955	079.0871	140	79
S7	27.7955	079.0871	27.5675	079.4823	130	74
S8	27.5675	079.4823	27.2244	079.7126	120	72
S9	27.2244	079.7126	26.9419	080.0284	110	76
S10	26.9419	080.0284	26.6105	080.2791	100	75
S11	26.6105	080.2791	26.2722	080.5689	90	73
S12	26.2722	080.5689	26.0553	080.9028	90	77
S13	26.0553	080.9028	25.8474	081.2644	80	69
S14	25.8474	081.2644	25.5733	081.5651	70	64
S15	25.5733	081.5651	25.4302	081.8886	70	65

RESULTS

We recorded 107 species of waterbirds in the study area. These belong to 11 orders and 25 families (Table 2). The Anatidae family (20 species) was most abundant, followed by Scolopacidae (14 species), Ardeidae and Laridae (nine species each), Charadriidae (seven species), Ciconiidae and Rallidae (five species each), Motacillidae (four species), Accipitridae, Alcedinidae, Gruidae, Hirundinidae, Phalacrocoracidae,

Table 2. Annotated list of birds from the middle stretch of the Ganga River. IUCN: International Union for Conservation of Nature, LC: Least Concern, NT: Near Threatened, VU: Vulnerable, EN: Endangered, WPA: Wild Life (Protection) Act, 1972, II Part-B: Schedule II Part B, I Part-B: Schedule I Part-B, R/LM: Resident/Local Migrant, R/WM: Resident/Winter Migrant, WM: Winter Migrant, R: Resident, C: Common, FC: Fairly Common, UC: Uncommon, Ra: Rare.

Taxon	Common name	Site	IUCN	WPA	Status	Abundance
ANSERIFORMES Anatidae						
Dendrocygna javanica	Lesser Whistling-duck	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15	LC	II Part-B	R/LM	C
Anser indicus	Bar-headed Goose	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15	LC	II Part-B	R/WM	C
Anser anser	Greylag Goose	1, 2, 3, 4, 5, 7, 8, 10, 12	LC	II Part-B	WM	UC
Anser albifrons	Greater White-fronted Goose	2	LC	II Part-B	WM	Ra
Mergus merganser	Goosander	1, 2, 6, 7, 8	LC	II Part-B	R/WM	UC
Tadorna tadorna	Common Shelduck	1, 3, 5, 6, 8, 9, 10, 12, 13, 15	LC	II Part-B	WM	FC
Tadorna ferruginea	Ruddy Shelduck	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/WM	C
Sarkidiornis melanotos	Knob-billed Duck	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15	LC	II Part-B	R/LM	C
Netta rufina	Red-crested Pochard	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	WM	C
Aythya ferina	Common Pochard	3, 5, 7	VU	I Part-B	WM	Ra
Aythya nyroca	Ferruginous Duck	5, 9	NT	II Part-B	R/WM	Ra
Aythya fuligula	Tufted Duck	5, 11	LC	II Part-B	WM	Ra
Spatula querquedula	Garganey	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11	LC	II Part-B	WM	FC
Spatula clypeata	Northern Shoveler	1, 2, 3, 4, 5, 6, 10, 12, 14, 15	LC	II Part-B	WM	FC
Mareca strepera	Gadwall	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	WM	C
Mareca penelope	Eurasian Wigeon	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13	LC	II Part-B	WM	FC
Anas poecilorhyncha	Indian Spot-billed Duck	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11	LC	II Part-B	R/LM	FC
Anas platyrhynchos	Mallard	1, 2, 3, 4, 6, 7, 8, 9, 10, 12	LC	II Part-B	R/WM	FC
Anas acuta	Northern Pintail	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	WM	C
Anas crecca	Common Teal	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	WM	C
PODICIPEDIFORMES Podicipedidae						
Tachybaptus ruficollis	Little Grebe	1, 2, 5, 6, 7, 9, 10, 11, 13, 14, 15	LC	II Part-B	R/LM	FC
Podiceps cristatus	Great Crested Grebe	1, 5, 7, 10	LC	II Part-B	R/WM	UC
GRUIFORMES Rallidae						
Zapornia akool	Brown Crake	5	LC	II Part-B	R/LM	Ra
Amaurornis phoenicurus	White-breasted Waterhen	3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R	FC
Porphyrio porphyrio	Purple Swamphen	5	LC	II Part-B	R/LM	Ra
Gallinula chloropus	Common Moorhen	5	LC	II Part-B	R/WM	Ra
Fulica atra	Common Coot	2, 5, 10, 11, 12	LC	II Part-B	R/WM	UC
GRUIFORMES Gruidae						
Anthropoides virgo	Demoiselle Crane	4, 6	LC	I Part-B	WM	Ra
Grus antigone	Sarus Crane	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14	VU	I Part-B	R/LM	C
Grus grus	Common Crane	1, 2, 4, 5, 6, 9, 10, 12, 13, 15	LC	I Part-B	WM	FC
CICONIIFORMES Ciconiidae						
Mycteria leucocephala	Painted Stork	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/LM	C
Anastomus oscitans	Asian Openbill	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/LM	C
Ciconia nigra	Black Stork	1, 2, 3, 6, 7, 8, 11, 14	LC	II Part-B	WM	UC
Ciconia episcopus	Asian Woollyneck	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	NT	II Part-B	R	C
Ephippiorhynchus asiaticus	Black-necked Stork	1, 2, 3, 4, 5, 6, 7, 8, 9, 12	NT	II Part-B	R	FC

Taxon	Common name	Site	IUCN	WPA	Status	Abundance
PELECANIFORMES Threskiornithidae						
Platalea leucorodia	Eurasian Spoonbill	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 15	LC	I Part-B	R	C
Threskiornis melanocephalus	Black-headed Ibis	1, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15	NT	II Part-B	R/LM	FC
Pseudibis papillosa	Red-naped Ibis	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R	C
PELECANIFORMES Ardeidae						
Nycticorax nycticorax	Black-crowned Night-heron	1, 2, 4, 6, 9, 10, 12, 13, 14, 15	LC	II Part-B	R/LM	FC
Butorides striata	Green-backed Heron	1, 4, 5, 6, 9, 10, 11, 12, 13, 14	LC	II Part-B	R	FC
Ardeola grayii	Indian Pond-heron	1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/LM	C
Bubulcus ibis	Cattle Egret	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/LM	C
Ardea cinerea	Grey Heron	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/WM	C
Ardea purpurea	Purple Heron	1, 2, 4, 5, 7, 9, 10, 11, 12, 13, 14	LC	II Part-B	R/LM	FC
Ardea alba	Great White Egret	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/LM	C
Ardea intermedia	Intermediate Egret	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/LM	C
Egretta garzetta	Little Egret	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/LM	C
PELECANIFORMES Pelecanidae						
Pelecanus crispus	Dalmatian Pelican	1, 11	NT	II Part-B	WM	Ra
Pelecanus onocrotalus	Great White Pelican	11, 12, 13, 14	LC	II Part-B	R/WM	UC
SULIFORMES *Phalacrocoracidae*						
Microcarbo niger	Little Cormorant	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/LM	C
Phalacrocorax carbo	Great Cormorant	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/WM	C
Phalacrocorax fuscicollis	Indian Cormorant	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/LM	C
SULIFORMES Anhingidae						
Anhinga melanogaster	Oriental Darter	1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	NT	II Part-B	R/LM	C
CHARADRIIFORMES Burhinidae						
Burhinus indicus	Indian Thick-knee	4, 5, 6, 7, 8, 9	LC	II Part-B	R	UC
Esacus recurvirostris	Great Thick-knee	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14	NT	II Part-B	R/LM	FC
CHARADRIIFORMES Recurvirostridae						
Recurvirostra avosetta	Pied Avocet	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/WM	C
Himantopus himantopus	Black-winged Stilt	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/LM	C
CHARADRIIFORMES Charadriidae						
Charadrius dubius	Little Ringed Plover	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/WM	C
Charadrius alexandrinus	Kentish Plover	1, 2, 3, 5, 6, 7, 8, 9, 10, 12, 13, 15	LC	II Part-B	R/WM	FC
Charadrius mongolus	Siberian Sandplover	3, 6, 7, 10, 11, 12, 13, 15	EN	II Part-B	R/WM	UC
Vanellus duvaucelii	River Lapwing	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	NT	II Part-B	R/LM	C
Vanellus cinereus	Grey-headed Lapwing	11	LC	II Part-B	WM	Ra
Vanellus indicus	Red-wattled Lapwing	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/LM	C
Vanellus leucurus	White-tailed Lapwing	5	LC	II Part-B	WM	Ra
CHARADRIIFORMES Rostratulidae						
Rostratula benghalensis	Greater Painted-snipe	13, 15	LC	II Part-B	R/LM	Ra
CHARADRIIFORMES Jacanidae						
Hydrophasianus chirurgus	Pheasant-tailed Jacana	1, 6, 11	LC	II Part-B	R/LM	Ra
Metopidius indicus	Bronze-winged Jacana	6, 9, 10, 11, 13	LC	II Part-B	R	UC
CHARADRIIFORMES Scolopacidae						
Numenius phaeopus	Whimbrel	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	WM	C

Taxon	Common name	Site	IUCN	WPA	Status	Abundance
Numenius arquata	Eurasian Curlew	1, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14	NT	II Part-B	WM	FC
Limosa limosa	Black-tailed Godwit	1, 2, 4, 5, 6, 7, 8, 9, 10, 11	NT	II Part-B	WM	FC
Calidris pugnax	Ruff	2, 6, 11, 12, 14, 15	LC	II Part-B	WM	UC
Calidris ferruginea	Curlew Sandpiper	9, 11, 12	NT	II Part-B	WM	Ra
Calidris temminckii	Temminck's Stint	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	WM	C
Calidris minuta	Little Stint	1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	WM	C
Actitis hypoleucos	Common Sandpiper	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/WM	C
Tringa ochropus	Green Sandpiper	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/WM	C
Tringa erythropus	Spotted Redshank	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	WM	C
Tringa nebularia	Common Greenshank	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	I Part-B	WM	C
Tringa totanus	Common Redshank	2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14, 15	LC	II Part-B	R/WM	C
Tringa glareola	Wood Sandpiper	1, 2, 4, 5, 6, 7, 8, 9, 11, 13	LC	II Part-B	WM	FC
Tringa stagnatilis	Marsh Sandpiper	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13	LC	II Part-B	WM	FC
CHARADRIIFORMES Glareolidae						
Glareola lactea	Little Pratincole	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/LM	C
CHARADRIIFORMES Laridae						
Rynchops albicollis	Indian Skimmer	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 14, 15	EN	I Part-B	R/LM	C
Larus brunnicephalus	Brown-headed Gull	2, 3, 4, 5, 7, 8, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/WM	FC
Larus ridibundus	Black-headed Gull	1, 2, 3, 5, 6, 8, 10, 11, 12, 14, 15	LC	II Part-B	R/WM	FC
Larus ichthyaetus	Pallas's Gull	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R	C
Sternula albifrons	Little Tern	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/WM	C
Gelochelidon nilotica	Common Gull-billed Tern	4, 5, 8	LC	I Part-B	R	Ra
Chlidonias hybrida	Whiskered Tern	1, 2, 3, 4, 5, 6, 7, 9, 10, 12, 14, 15	LC	II Part-B	R	FC
Sterna aurantia	River Tern	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 15	VU	I Part-B	R	C
Sterna acuticauda	Black-bellied Tern	1, 2, 3, 4, 5, 6, 7, 8, 9	EN	I Part-B	R	UC
ACCIPITRIFORMES Pandionidae						
Pandion haliaetus	Osprey	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	I Part-B	R	C
ACCIPITRIFORMES Accipitridae						
Aquila nipalensis	Steppe Eagle	1, 3, 4, 6, 8, 9, 10, 12, 13, 14, 15	EN	I Part-B	WM	FC
Circus aeruginosus	Western Marsh-harrier	7, 12	LC	I Part-B	WM	Ra
Haliaeetus leucoryphus	Pallas's Fish-eagle	1, 12, 14	EN	I Part-B	R/WM	Ra
CORACIIFORMES Meropidae						
Merops philippinus	Blue-tailed Bee-eater	2, 4, 5, 6, 7, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/WM	FC
CORACIIFORMES Alcedinidae						
Alcedo atthis	Common Kingfisher	2, 4, 5	LC	II Part-B	R/WM	Ra
Ceryle rudis	Pied Kingfisher	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R	C
Halcyon smyrnensis	White-throated Kingfisher	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/LM	C
FALCONIFORMES Falconidae						
Falco peregrinus	Peregrine Falcon	1, 3, 4, 5, 6, 8, 9, 11, 12, 13, 14, 15	LC	I Part-B	R/WM	FC
PASSERIFORMES Hirundinidae						
Hirundo smithii	Wire-tailed Swallow	2	LC	II Part-B	R	Ra
Hirundo rustica	Barn Swallow	1, 2, 3, 4, 11, 12, 13, 15	LC	II Part-B	R/WM	UC
Riparia chinensis	Asian Plain Martin	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/LM	C
PASSERIFORMES Motacillidae						
Motacilla flava	Western Yellow Wagtail	1, 2, 3, 5, 11, 12, 13, 14	LC	II Part-B	R/WM	UC

Taxon	Common name	Site	IUCN	WPA	Status	Abundance
Motacilla citreola	Citrine Wagtail	1, 2, 3, 4, 5, 6	LC	II Part-B	R/WM	UC
Motacilla maderaspatensis	White-browed Wagtail	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R	C
Motacilla alba	White Wagtail	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	LC	II Part-B	R/WM	C

Threskiornithidae (three species each), and Burhinidae, Jacanidae, Pelecanidae, Podicipedidae, Recurvirostridae (two species each). Anhingidae, Falconidae, Glareolidae, Meropidae, Pandionidae, Rostratulidae were poorly represented by only a single species (Table 2). The area supports three Vulnerable species, 11 Near Threatened, and five Endangered species (IUCN 2024) (Table 2). Of all species observed, 15 are protected under Schedule I of the WPA (Table 2). Among the avian species observed in the study area, 47 species (43.9%) were resident, 31 species (28.9%) were winter migrants, and 29 species (27.1%) were resident with winter migration (Table 2). Thirty-four species were observed at all sites. In contrast, seven species—*Anser albifrons* (Scopoli, 1769), *Zapornia akool* (Sykes, 1832), *Porphyrio porphyrio* (Linnaeus, 1758), *Gallinula chloropus* (Linnaeus, 1758), *Vanellus cinereus* (Blyth, 1842), *Vanellus leucurus* (Lichtenstein, 1823), and *Hirundo smithii* (Leach, 1818)—were observed from a single site and presumably localised. The maximum species richness (86 species) was observed from Site 5, and the minimum (64 species) was observed from Site 14.

Observations of selected species recorded from the middle stretch of the Ganga River

Family Anatidae

***Dendrocygna javanica* (Horsfield, 1821)**
Lesser Whistling-duck
Figure 2A

Observations. INDIA – Uttar Pradesh • Amroha; Site 4; 28.5560°N, 078.2110°E; 180 m a.s.l.; 25.IV.2018, A.A. Usmani obs. • Budaun; Site 6; 27.9614°N, 078.8034°E; 150 m a.s.l.; 14.XII.2019, A.A. Usmani obs. • Raebareli; Site 12; 26.1020°N, 080.6797°E; 90 m a.s.l.; 6.V.2019, A.A. Usmani obs.

Identification. A small duck with brown and chestnut body; bill slaty-grey and legs plumbeous-blue. Forehead and crown brown, and rest of head and neck fulvous grey. A noisy bird, whistles repeatedly.

***Anser indicus* (Latham, 1790)**
Bar-headed Goose
Figure 2B

Observations. INDIA – Uttar Pradesh • Muzaffarnagar; Site 2; 29.2648°N, 078.0926°E; 200 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Kasganj; Site 6; 27.8826°N, 078.8994°E; 140 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Unnao; Site 10; 26.9262°N, 080.0469°E; 100 m a.s.l.; 27.II.2021, A.A. Usmani obs.

Identification. An ashy-grey, white and brown goose, with two characteristic, black bars on the white head. Bill yellow with a black tip.

***Anser anser* (Linnaeus, 1758)**
Greylag Goose
Figure 2C

Observations. INDIA – Uttar Pradesh • Bijnor; Site 1; 29.6431°N, 078.1195°E; 220 m a.s.l.; 7.II.2021, A.A. Usmani obs. • Sambhal; Site 4; 28.2918°N, 078.3149°E; 170 m a.s.l.; 12.II.2021, A.A. Usmani obs. • Fatehpur; S12; 26.2116°N, 080.5978°E; 90 m a.s.l.; 28.II.2021, A.A. Usmani obs.

Identification. A large grey-brown goose with bill and legs pink. Base of bill with a very narrow white feather rim. Head and neck ashy-brown; back and rump pale.

***Mergus merganser* (Linnaeus, 1758)**
Goosander
Figure 2D

Observations. INDIA – Uttar Pradesh • Bijnor; Site 1; 29.7102°N, 078.1828°E; 220 m a.s.l.; 7.II.2021, A.A. Usmani obs. • Farrukhabad; Site 8; 27.4740°N, 079.6084°E; 120 m a.s.l.; 26.II.2021, A.A. Usmani obs.

Identification. Neck, narrow, slender; bill pointed, red; legs red. Male with dark-green head and white breast. Female with white chin and throat and grey-brown upperparts.

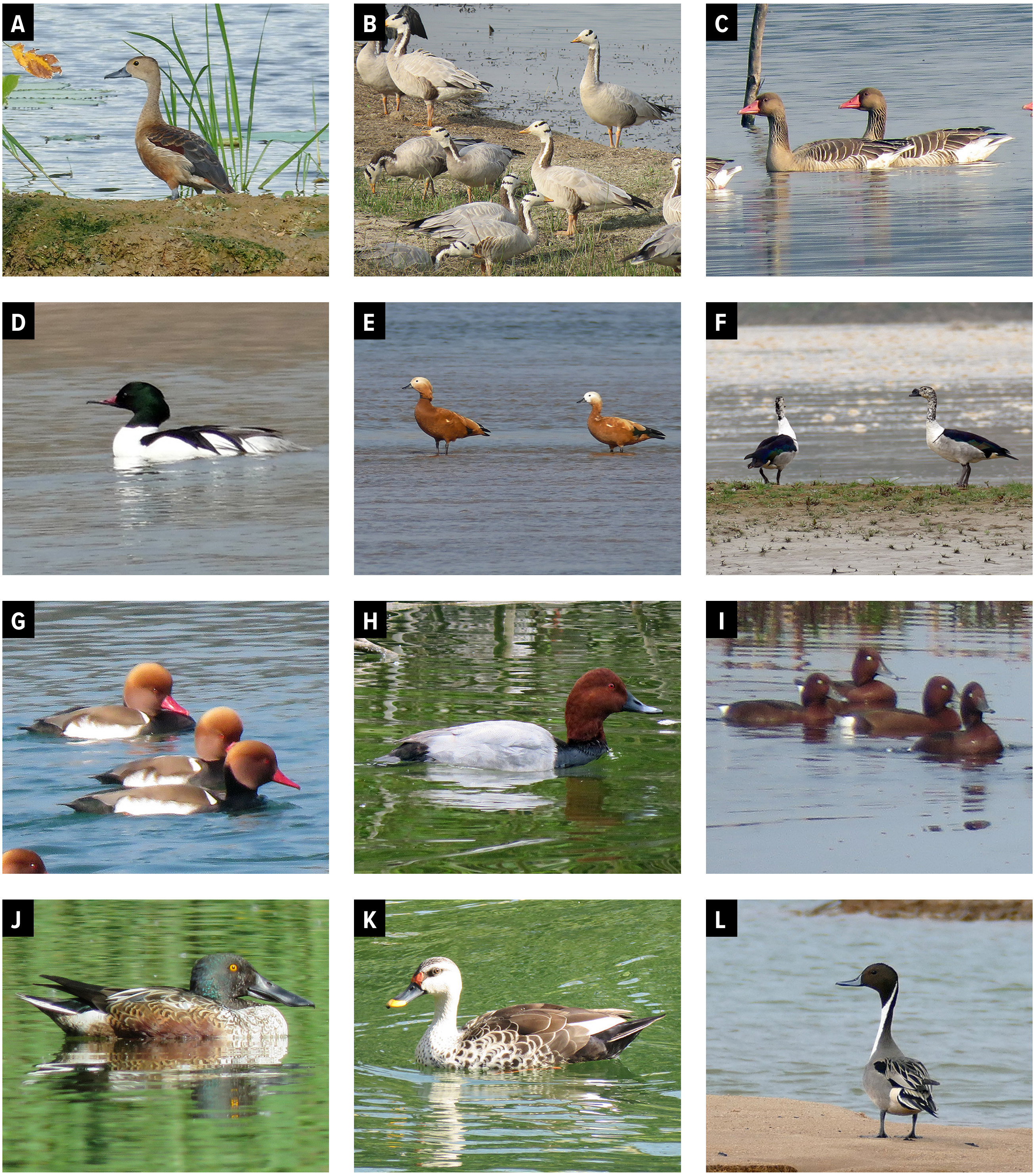

Figure 2. Birds of the middle stretch of the Ganga River **A.** *Dendrocygna javanica*. **B.** *Anser indicus*. **C.** *Anser anser*. **D.** *Mergus merganser*. **E.** *Tadorna ferruginea*. **F.** *Sarkidiornis melanotos*. **G.** *Netta rufina*. **H.** *Aythya ferina*. **I.** *Aythya nyroca*. **J.** *Spatula clypeata*. **K.** *Anas poecilorhynchav* **L.** *Anas acuta*.

Tadorna ferruginea **(Pallas, 1764)**
Ruddy Shelduck
Figure 2E

Observations. INDIA – Uttar Pradesh • Amroha; Site 3; 28.9174°N, 078.1116°E; 180 m a.s.l.; 4.II.2019, A.A. Usmani obs. • Aligarh; Site 5; 28.0416°N, 078.5805°E; 150 m a.s.l.; 13.XII.2019, A.A. Usmani obs. • Pratapgarh; Site 14; 25.6857°N, 081.3971°E; 70 m a.s.l.; 17.II.2019, A.A. Usmani obs.

Identification. A large, orange-brown duck with a pale head and neck; beak black. Wing-coverts white, and speculum prominent and metallic green.

Sarkidiornis melanotos **(Pennant, 1769)**
Knob-billed Duck
Figure 2F

Observations. INDIA – Uttar Pradesh • Meerut; Site 2; 29.0950, 078.0745°E; 200 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Kannauj; Site 9; 27.0435°N, 079.9784°E; 100 m a.s.l.; 27.II.2021, A.A. Usmani obs. • Fatehpur; Site 12; 26.0813°N, 080.7241°E; 90 m a.s.l.; 28.II.2021, A.A. Usmani obs.

Identification. A large, glossy, blue-black and white duck. Males with a swollen, fleshy knob (comb) on bill. Females smaller, dull-coloured, and without a comb.

Netta rufina **(Pallas, 1773)**
Red-crested Pochard
Figure 2G

Observations. INDIA – Uttar Pradesh • Sambhal; Site 5; 28.2259°N, 078.3791°E; 160 m a.s.l.; 12.II.2021, A.A. Usmani obs. • Hardoi; Site 9; 27.1460°N, 079.9101°E; 110 m a.s.l.; 27.II.2021, A.A. Usmani obs. • Kanpur Nagar; Site 11; 26.5101°N, 080.3188°E; 90 m a.s.l.; 27.II.2021, A.A. Usmani obs. • Pratapgarh; Site 14; 25.6857, 081.3971°E; 70 m a.s.l.; 28.II.2021, A.A. Usmani obs.

Identification. Males with golden-orange head, a silky chestnut crest, bright crimson bill, and fleshy, dull-red legs and feet. Females with pale, dull wings, dark crown, and dusky-black bill.

Aythya ferina **(Linnaeus, 1758)**
Common Pochard
Figure 2H

Observations. INDIA – Uttar Pradesh • Bulandshahr; Site 5; 28.2641°N, 078.3500°E; 180 m a.s.l.; 12.II.2021, A.A. Usmani obs. • Sambhal; Site 5; 28.2259°N, 078.3791°E; 160 m a.s.l.; 12.XII.2019, A.A. Usmani obs.

Identification. Male with deep-chestnut head and neck; black bill with a pale-grey band near tip. Female with rufous-brown head, neck, upper back, and breast.

Aythya nyroca **(Güldenstädt, 1770)**
Ferruginous Duck
Figure 2I

Observations. INDIA – Uttar Pradesh • Sambhal; Site 5; 28.1845°N, 078.4005°E; 160 m a.s.l.; 12.II.2021, A.A. Usmani obs. • Hardoi; Site 9; 27.1314°N, 079.9556°E; 110 m a.s.l.; 27.II.2021, A.A. Usmani obs.

Identification. Male with deep-chestnut head, neck, and breast; bill bluish black; iris white. Female with iris dark, brownish; legs dark, slaty. Female with duller colour a less contrasting off-white belly.

Spatula clypeata **(Linnaeus, 1758)**
Northern Shoveler
Figure 2J

Observations. INDIA – Uttar Pradesh • Bulandshahr; Site 4; 28.3703°N, 078.2745°E; 170 m a.s.l.; 12.II.2021, A.A. Usmani obs. • Sambhal; Site 5; 28.0958°N, 078.5045°E; 150 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Kanpur Nagar; Site 10; 26.8261°N, 080.1200°E; 100 m a.s.l.; 27.II.2021, A.A. Usmani obs.

Identification. Bill large, spatulate (shovel-shaped). Males with glossy, green head and neck; eyes yellow and breast white. Females with greyish-blue shoulder patch.

Anas poecilorhyncha **(Forster, 1781)**
Indian Spot-billed Duck
Figure 2K

Observations. INDIA – Uttar Pradesh • Bijnor; Site 2; 29.3097°N, 078.0996°E; 200 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Budaun; Site 6; 27.9528°N, 078.8442°E; 140 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Farrukhabad; Site 8; 27.5290°N, 079.5406°E; 120 m a.s.l.; 26.II.2021, A.A. Usmani obs.

Identification. Bill black, with yellow tip; eye-stripe yellow. Speculum white and green. Plumage brown, with scaly patterns.

Anas acuta **(Linnaeus, 1758)**
Northern Pintail
Figure 2L

Observations. INDIA – Uttar Pradesh • Amroha; Site 3; 28.9174°N, 078.1116°E; 180 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Budaun; Site 6; 27.8537°N, 078.9337°E; 140 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Prayagraj; Site 15; 25.4757°E, 081.7562°E; 70 m a.s.l.; 13.I.2021, A.A. Usmani obs.

Identification. Males with chocolate-brown head, a white stripe down side of neck, and a long, pointed, pin-like tail. Females mottled brown and buff; tail pointed but pin-less.

Family Podicipedidae

Tachybaptus ruficollis **(Pallas, 1764)**
Little Grebe
Figure 3A

Observations. INDIA – Uttar Pradesh • Muzaffarnagar; Site 2; 29.2648°N, 078.0926°E; 200 m a.s.l.; 1.II.2020, A.A. Usmani obs. • Bulandshahr; Site 5; 28.1845°N, 078.4005°E; 160 m a.s.l.; 12.II.2021, A.A. Usmani obs. • Unnao; Site 10; 26.8951°N, 080.0844°E; 100 m a.s.l.; 20.XII.2019, A.A. Usmani obs.

Identification. A small, tailless aquatic bird with short, pointed bill. Breeding individuals with blackish-brown nape, crown, and forehead.

Podiceps cristatus **(Linnaeus, 1758)**
Great Crested Grebe
Figure 3B

Observations. INDIA – Uttar Pradesh • Bijnor; Site 1; 29.7498°N, 078.2027°E; 230 m a.s.l.; 7.II.2021, A.A. Usmani obs. • Sambhal; Site 5; 28.2259°N, 078.3791°E; 160 m a.s.l.; 3.II.2020, A.A. Usmani obs. • Farrukhabad; Site 7; 27.6418°N, 079.3528°E; 130 m a.s.l.; 15.XII.2019, A.A. Usmani obs. • Kanpur Nagar; Site 10; 26.8951°N, 080.0844°E; 100 m a.s.l.; 8.II.2020, A.A. Usmani obs.

Identification. A tailless aquatic bird, with a slender, white neck; bill straight, pointed; body comparatively larger than the *Tachybaptus ruficollis*. Head with two backwardly directed ear tufts.

Family Rallidae

Porphyrio porphyrio **(Linnaeus, 1758)**
Purple Swamphen
Figure 3C

Observations. INDIA – Uttar Pradesh • Bulandshahr; Site 5; 28.1845°N, 078.4005°E; 160 m a.s.l.; 12.II.2021, A.A. Usmani obs.

Identification. Body purple-blue; Easily identified by its characteristic red forehead, bill, and legs.

Gallinula chloropus **(Linnaeus, 1758)**
Common Moorhen
Figure 3D

Observations. INDIA – Uttar Pradesh • Sambhal; Site 5; 28.2259°N, 078.3791°E; 160 m a.s.l.; 12.II.2021, A.A. Usmani obs.

Identification. Head and neck dark grey. Underparts brown. Iris, base of bill, and frontal shield red.

Fulica atra **(Linnaeus, 1758)**
Common Coot
Figure 3E

Observations. INDIA – Uttar Pradesh • Sambhal; Site 5; 28.2259°N, 078.3791°E; 160 m a.s.l.; 12.II.2021, A.A. Usmani obs. • Unnao; Site 10; 26.8951°N, 080.0844°E; 100 m a.s.l.; 08.II.2020, A.A. Usmani obs. • Kanpur Nagar; Site 11; 26.5480°N, 080.3059°E; 100 m a.s.l.; 27.II.2021, A.A. Usmani obs.

Identification. Body slaty-black, easily identified by its white, pointed bill and white frontal shield.

Family Gruidae

Grus antigone **(Linnaeus, 1758)**
Sarus Crane
Figure 3F

Observations. INDIA – Uttar Pradesh • Amroha; Site 3; 28.7621°N, 078.1450°E; 180 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Farrukhabad; Site 8; 27.4740°N, 079.6084°E; 120 m a.s.l.; 26.II.2021, A.A. Usmani obs. • Unnao; Site 11; 26.3694°N, 080.5108°E; 90 m a.s.l.; 27.II.2021, A.A. Usmani obs. • Raebareli; Site 13; 26.0675°N, 081.0215°E; 80 m a.s.l.; 28.II.2021, A.A. Usmani obs.

Identification. The largest Indian crane; plumage grey; head and upper neck red.

Figure 3. Birds of the middle stretch of the Ganga River **A.** *Tachybaptus ruficollis*. **B.** *Podiceps cristatus*. **C.** *Porphyrio porphyrio*. **D.** *Gallinula chloropus*. **E.** *Fulica atra* **F.** *Grus antigone* **G.** *Mycteria leucocephala*. **H.** *Anastomus oscitans*. **I.** *Ciconia nigra*. **J.** *Ciconia episcopus*. **K.** *Ephippiorhynchus asiaticus*. **L.** *Platalea leucorodia*.

Family Ciconiidae

Mycteria leucocephala **(Pennant, 1769)**
Painted Stork
Figure 3G

Observations. INDIA – UTTAR PRADESH • Meerut; Site 2; 29.0950°N, 078.0745°E; 200 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Hapur; Site 3; 28.8758°N, 078.1182°E; 180 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Farrukhabad; Site 7; 27.6118°N, 079.4444v; 130 m a.s.l.; 26.II.2021, A.A. Usmani obs. • Kannauj; Site

9; 26.9633°N, 080.0203°E; 100 m a.s.l.; 27.II.2021, A.A. Usmani obs. • Fatehpur; Site 13; 26.0283°N, 081.0490°E; 80 m a.s.l.; 28.II.2021, A.A. Usmani obs.

Identification. A large black and white bird with long, pink legs and a yellowish bill and face. Wing coverts characteristically rosy-pink.

Anastomus oscitans **(Boddaert, 1783)**
Asian Openbill
Figure 3H

Observations. INDIA – Uttar Pradesh • Amroha; Site 3; 28.9174°N, 078.1116°E; 180 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Budaun; Site 6; 27.9203°N, 078.8755°E; 140 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Kaushambi; Site 14; 25.7792°N, 081.3572°E; 80 m a.s.l.; 28.II.2021, A.A. Usmani obs. • Prayagraj; Site 15; 25.4952°N, 081.8882°E; 70 m a.s.l.; 13.I.2021, A.A. Usmani obs.

Identification. A comparatively small, white stork with a black tail. Bill peculiar, with arching mandibles leaving a narrow gap between.

Ciconia nigra **(Linnaeus, 1758)**
Black Stork
Figure 3I

Observations. INDIA – Uttar Pradesh • Bijnor; Site 2; 29.4134°N, 078.0411°E; 210 m a.s.l.; 8.II.2021, A.A. Usmani obs. • Kaushambi; Site 14; 25.7627°N, 081.4004°E; 80 m a.s.l.; 28.II.2021, A.A. Usmani obs.

Identification. A black stork with white underparts and a reddish bill and legs.

Ciconia episcopus **(Boddaert, 1783)**
Asian Woollyneck
Figure 3J

Observations. INDIA – Uttar Pradesh • Meerut; Site 2; 29.0950°N, 078.0745°E; 200 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Unnao; Site 10; 26.9262°N, 080.0469°E; 100 m a.s.l.; 27.II.2021, A.A. Usmani obs. • Raebareli; Site 12; 26.0234°N, 080.8423°E; 90 m a.s.l.; 28.II.2021, A.A. Usmani obs. • Prayagraj; Site 15; 25.4757°N, 081.7562°E; 70 m a.s.l.; 13.I.2021, A.A. Usmani obs.

Identification. A large black and white stork, with a conspicuously white, woolly neck. Head with black cap; legs red.

Ephippiorhynchus asiaticus **(Latham, 1790)**
Black-necked Stork
Figure 3K

Observations. INDIA – Uttar Pradesh • Bijnor; Site 1; 29.7498°N, 078.2027°E; 230 m a.s.l.; 7.II.2021, A.A. Usmani obs. • Sambhal; Site 5; 28.0958°N, 078.5045°E; 150 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Farrukhabad; Site 8; 27.5536°N, 079.5026°E; 120 m a.s.l.; 26.II.2021, A.A. Usmani obs. • Hardoi; Site 9; 27.1649°N, 079.8673°E; 110 m a.s.l.; 26.II.2021, A.A. Usmani obs.

Identification. Black and white stork with black bill and large legs. Neck black, with varying sheen. Males characteristically brown; females with yellow iris.

Family Threskiornithidae

Platalea leucorodia **(Linnaeus, 1758)**
Eurasian Spoonbill
Figure 3L

Observations. INDIA – Uttar Pradesh • Meerut; Site 2; 29.1761°N, 078.1033°E; 200 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Kannauj; Site 9; 27.1460°N, 079.9101°E; 110 m a.s.l.; 27.II.2021, A.A. Usmani obs. • Fatehpur; Site 12; 26.2116°N, 080.5978°E; 90 m a.s.l.; 28.II.2021, A.A. Usmani obs.

Identification. A white bird with a characteristic long, flat, spatula-shaped black bill with a yellowish tip. Sexes alike, but with females slightly smaller.

Threskiornis melanocephalus **(Latham, 1790)**
Black-headed Ibis
Figure 4A

Observations. INDIA – Uttar Pradesh • Sambhal; Site 5; 28.1845°N, 078.4005°E; 160 m a.s.l.; 12.II.2021, A.A. Usmani obs. • Hardoi; Site 9; 27.1460°N, 079.9101°E; 110 m a.s.l.; 27.II.2021, A.A. Usmani obs. • Fatehpur; Site 13; 25.9586°N, 081.1719°E; 80 m a.s.l.; 28.II.2021, A.A. Usmani obs.

Identification. White bird with black neck, head, and downcurved bill.

Figure 4. Birds of the middle stretch of the Ganga River. **A.** *Threskiornis melanocephalus*. **B.** *Pseudibis papillosa*. **C.** *Nycticorax nycticorax*. **D.** *Ardeola grayii*. **E.** *Bubulcus ibis*. **F.** *Ardea cinerea*. **G.** *Ardea purpurea*. **H.** *Egretta garzetta*. **I.** *Anhinga melanogaster*. **J.** *Esacus recurvirostris*. **K.** *Recurvirostra avosetta*. **L.** *Himantopus himantopus*.

Pseudibis papillosa **(Temminck, 1824)**
Red-naped Ibis
Figure 4B

Observations. INDIA – Uttar Pradesh • Amroha; Site 3; 29.0237°N, 078.0797°E; 190 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Sambhal; Site 5; 28.1845°N, 078.4005°E; 160 m a.s.l.; 12.II.2021, A.A. Usmani obs. • Kasganj; Site 7; 27.7932°N, 079.1122°E; 140 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Unnao; Site 12; 26.1443°N, 080.6600°E; 90 m a.s.l.; 28.II.2021, A.A. Usmani obs. • Fatehpur; Site 13; 25.9367°N, 081.2140°E; 80 m a.s.l.; 28.II.2021, A.A. Usmani obs. • Kaushambi; Site 15; 25.5893°N, 081.6341°E; 70 m a.s.l.; 13.I.2021, A.A. Usmani obs.

Identification. A blackish-brown bird with a down-curved, curlew-like bill. Legs brick-red. Head with a triangular red cap.

Family Ardeidae

***Nycticorax nycticorax* (Linnaeus, 1758)**
Black-crowned Night-heron
Figure 4C

Observations. INDIA – Uttar Pradesh • Muzaffarnagar; Site 2; 29.3413°N, 078.0684°E; 200 m a.s.l.; 1.II.2020, A.A. Usmani obs. • Hapur; Site 4; 28.6432°N, 078.1924°E; 190 m a.s.l.; 3.II.2020, A.A. Usmani obs. • Pratapgarh; Site 14; 25.7224°N, 081.3827°E; 70 m a.s.l.; 7.V.2019, A.A. Usmani obs. • Kaushambi; Site 15; 25.5893°N, 081.6341°E; 70 m a.s.l.; 8.V.2019, A.A. Usmani obs.

Identification. Grey and black heron, with crest, crown, and nape black. Legs pale green in breeding season, pinkish in non-breeding season.

***Ardeola grayii* (Sykes, 1832)**
Indian Pond-heron
Figure 4D

Observations. INDIA – Uttar Pradesh • Farrukhabad; Site 8; 27.5290°N, 079.5406°E; 120 m a.s.l.; 26.II.2021, A.A. Usmani obs. • Kannauj; Site 9; 27.0019°N, 079.9964°E; 100 m a.s.l.; 27.II.2021, A.A. Usmani obs. • Raebareli; Site 13; 25.9979°N, 081.0843°E; 80 m a.s.l.; 28.II.2021, A.A. Usmani obs. • Prayagraj; Site 15; 25.5893°N, 081.6341°E; 70 m a.s.l.; 13.I.2021, A.A. Usmani obs.

Identification. A earthy-brown heron at rest, but snow-white in flight. Bill yellow, with a black tip and bluish base. Chin, throat, and fore-neck white.

***Bubulcus ibis* (Linnaeus, 1758)**
Cattle Egret
Figure 4E

Observations. INDIA – Uttar Pradesh • Bijnor; Site 1; 29.5841°N, 078.0561°E; 210 m a.s.l.; 8.II.2021, A.A. Usmani obs. • Fatehpur; Site 12; 26.2116°N, 080.5978°E; 90 m a.s.l.; 28.II.2021, A.A. Usmani obs.• Pratapgarh; Site 15; 25.5829°N, 081.5876°E; 70 m a.s.l.; 28.II.2021, A.A. Usmani obs.

Identification. Bill short, yellow; legs dark. All white in non-breeding individuals, but head, neck and mantle orange in breeding birds.

***Ardea cinerea* (Linnaeus, 1758)**
Grey Heron
Figure 4F

Observations. INDIA – Uttar Pradesh • Meerut; Site 3; 28.9886°N, 078.0588°E; 190 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Amroha; Site 4; 28.5560°N, 078.2110°E; 180 m a.s.l.; 12.II.2021, A.A. Usmani obs. • Aligarh; Site 5; 28.0416°N, 078.5805°E; 150 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Kasganj; Site 7; 27.7682°N, 079.1538°E; 130 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Hardoi; Site 9; 27.0891°N, 079.9725°E; 110 m a.s.l.; 27.II.2021, A.A. Usmani obs. • Raebareli; Site 13; 25.9709°N, 081.1237°E; 80 m a.s.l.; 28.II.2021, A.A. Usmani obs. • Prayagraj; Site 15; 25.5477°N, 081.6500°E; 70 m a.s.l.; 13.I.2021, A.A. Usmani obs.

Identification. A large, yellow-billed, ashy-grey heron, with a long neck and legs. Neck white and crown with a black crest.

***Ardea purpurea* (Linnaeus, 1766)**
Purple Heron
Figure 4G

Observations. INDIA – Uttar Pradesh • Bijnor; Site 1; 29.7102°N, 078.1828°E; 220 m a.s.l.; 12.VI.2018, A.A. Usmani obs. • Muzaffarnagar; Site 2; 29.3413°N, 078.0684°E; 200 m a.s.l.; 11.II.2021, A.A. Usmani obs.

Identification. A purple heron with a slaty bill. Chin, cheeks, and throat white. Legs and feet dark slaty-black. Sexes alike.

***Egretta garzetta* (Linnaeus, 1766)**
Little Egret
Figure 4H

Observations. INDIA – Uttar Pradesh • Bijnor; Site 2; 29.3413°N, 078.0684°E; 200 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Bulandshahr; Site 4; 28.4492°N, 078.2831°E; 170 m a.s.l.; 12.II.2021, A.A. Usmani obs. • Aligarh; Site 5; 28.0416°N, 078.5805°E; 150 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Unnao; Site 10; 26.7430°N, 080.1551°E; 100 m a.s.l.; 27.II.2021, A.A. Usmani obs. • Kaushambi; Site 14; 25.6213°N, 081.5168°E; 70 m a.s.l.; 28.II.2021, A.A. Usmani obs.

Identification. A small egret with black bill and legs; feet yellow. Lores yellowish.

Family Anhingidae

***Anhinga melanogaster* (Pennant, 1769)**
Oriental Darter
Figure 4I

Observations. INDIA – Uttar Pradesh • Bijnor; Site 2; 29.4134°N, 078.0411°E; 210 m a.s.l.; 8.II.2021, A.A. Usmani obs. • Sambhal; Site 5; 28.0605°N, 078.5348°E; 160 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Farrukhabad; Site 8; 27.5536°N, 079.5026°E; 120 m a.s.l.; 26.II.2021, A.A. Usmani obs. • Kaushambi; Site 14; 25.6213°N, 081.5168°E; 70 m a.s.l.; 28.II.2021, A.A. Usmani obs.

Identification. Neck long, slender, snake-like; head narrow. Bill dagger-shaped, and tail fan-like.

Family Burhinidae

***Esacus recurvirostris* (Cuvier, 1829)**
Great Thick-knee
Figure 4J

Observations. INDIA – Uttar Pradesh • Bijnor; Site 2; 29.3097°N, 078.0996°E; 200 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Bulandshahr; Site 4; 28.5989°N, 078.1983°E; 180 m a.s.l.; 12.II.2021, A.A. Usmani obs. • Sambhal; Site 5; 28.0958°N, 078.5045°E; 150 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Farrukhabad; Site 7; 27.6118°N, 079.4444°E; 130 m a.s.l.; 26.II.2021, A.A. Usmani obs.

Identification. A brown plover with yellow legs. Bill massive and distinctly upturned, with a yellow base. Eyes large, yellow, with two blackish bands.

Family Recurvirostridae

***Recurvirostra avosetta* (Linnaeus, 1758)**
Pied Avocet
Figure 4K

Observations. INDIA – Uttar Pradesh • Bijnor; Site 2; 29.3413°N, 078.0684°E; 200 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Kasganj; Site 7; 27.7682°N, 079.1538°E; 130 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Kanpur Nagar; Site 10; 26.8261°N, 080.1200°E; 100 m a.s.l.; 27.II.2021, A.A. Usmani obs. • Prayagraj; Site 15; 25.4952°N, 081.8882°E; 70 m a.s.l.; 13.I.2021, A.A. Usmani obs.

Identification. An unmistakable bird with an upcurved, black bill. Body white, with a black head and hind neck.

***Himantopus himantopus* (Linnaeus, 1758)**
Black-winged Stilt
Figure 4L

Observations. INDIA – Uttar Pradesh • Bijnor; Site 2; 29.3097°N, 078.0996°E; 200 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Amroha; Site 3; 28.7273°N, 078.1765°E; 190 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Fatehpur; Site 13; 25.9367°N, 081.2140°E; 80 m a.s.l.; 28.II.2021, A.A. Usmani obs. • Prayagraj; Site 15; 25.4996°N, 081.8450°E; 70 m a.s.l.; 13.I.2021, A.A. Usmani obs.

Identification. A peculiar, long-legged wader with black and white wings. Bill black and legs crimson-red.

Family Charadriidae

***Charadrius dubius* (Scopoli, 1786)**
Little Ringed Plover
Figure 5A

Observations. INDIA – Uttar Pradesh • Bijnor; Site 1; 29.7102°N, 078.1828°E; 220 m a.s.l.; 4.XII.2019, A.A. Usmani obs. • Kasganj; Site 5; 28.0217°N, 078.6218°E; 150 m a.s.l.; 13.XII.2019, A.A. Usmani obs. • Fatehpur; Site 14; 25.8160°N, 081.3298°E; 80 m a.s.l.; 24.XII.2019, A.A. Usmani obs.

Identification. A ringed plover with a unique, nearly black frontal bar and a narrow, black breast band. Bill small, dark; legs yellowish or pinkish. Eye ring and legs yellow.

***Vanellus duvaucelii* (Lesson, 1826)**
River Lapwing
Figure 5B

Observations. INDIA – Uttar Pradesh • Bijnor; Site 1; 29.7102°N, 078.1828°E; 220 m a.s.l.; 7.II.2021,

Figure 5. Birds of the middle stretch of the Ganga River. **A.** *Charadrius dubius*. **B.** *Vanellus duvaucelii*. **C.** *Vanellus cinereus*. **D.** *Vanellus indicus*. **E.** *Rostratula benghalensis*. **F.** *Hydrophasianus chirurgus*. **G.** *Numenius arquata*. **H.** *Tringa erythropus*. **I.** *Glareola lactea*. **J.** *Rynchops albicollis*. **K.** *Larus ichthyaetus*. **L.** *Sternula albifrons*.

A.A. Usmani obs. • Bulandshahr; Site 4; 28.4834°N, 078.2501°E; 170 m a.s.l.; 12.II.2021, A.A. Usmani obs. • Kasganj; Site 6; 27.8826°N, 078.8994°E; 140 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Hardoi; Site 9; 27.0891°N, 079.9725°E; 110 m a.s.l.; 27.II.2021, A.A. Usmani obs. • Fatehpur; Site 12; 26.0739°N, 080.7723°E; 90 m a.s.l.; 28.II.2021, A.A. Usmani obs. • Kaushambi; Site 15; 25.5206°N, 081.6753°E; 70 m a.s.l.; 13.I.2021, A.A. Usmani obs.

Identification. Head, bill, and occipital crest black. Upper tail coverts and tail white. Legs and feet black.

***Vanellus cinereus* (Blyth, 1842)**
Grey-headed Lapwing
Figure 5C

Observations. INDIA – Uttar Pradesh • Kanpur Nagar; Site 11; 26.2900°N, 080.5538°E; 90 m a.s.l.; 22.XII.2019, A.A. Usmani obs. • Unnao; Site 11; 26.2900°N, 080.5538°E; 90 m a.s.l.; 22.XII.2019, A.A. Usmani obs.

Identification. A comparatively large lapwing, with red iris and yellow eyelids. Bill yellow; head and neck grey, with a black subterminal band.

***Vanellus indicus* (Boddaert, 1783)**
Red-wattled lapwing
Figure 5D

Observations. INDIA – Uttar Pradesh • Bijnor; Site 2; 29.3701°N, 078.0385°E; 210 m a.s.l.; 8.II.2021, A.A. Usmani obs. • Sambhal; Site 5; 28.1845°N, 078.4005°E; 160 m a.s.l.; 12.II.2021, A.A. Usmani obs. • Farrukhabad; Site 8; 27.3083°N, 079.6466°E; 120 m a.s.l.; 26.II.2021, A.A. Usmani obs. • Unnao; Site 12; 26.1772°N, 080.6291°E; 90 m a.s.l.; 28.II.2021, A.A. Usmani obs. • Pratapgarh; Site 14; 25.6257°N, 081.4681°E; 70 m a.s.l.; 28.II.2021, A.A. Usmani obs.

Identification. A plover with a unique red wattle, bill, and eyelids. Head, neck, and breast black. Legs yellow.

Family Rostratulidae

***Rostratula benghalensis* (Linnaeus, 1758)**
Greater Painted-snipe
Figure 5E

Observations. INDIA – Uttar Pradesh • Fatehpur; Site 13; 26.0675°N, 081.0215°E; 80 m a.s.l.; 14.V.2018, A.A. Usmani obs. • Prayagraj; Site 15; 25.4979°N, 081.7971°E; 70 m a.s.l.; 16.V.2018, A.A. Usmani obs.

Identification. Bill downcurved, pinkish. Females have head chestnut-brown with comma-like, white mark around eye. Males dull-coloured and smaller.

Family Jacanidae

***Hydrophasianus chirurgus* (Scopoli, 1786)**
Pheasant-tailed Jacana
Figure 5F

Observations. INDIA – Uttar Pradesh • Bijnor; Site 1; 29.7102°N, 078.1828°E; 220 m a.s.l.; 12.VI.2018, A.A. Usmani obs. • Budaun; Site 6; 27.8537°N, 078.9337°E; 140 m a.s.l.; 1.V.2018, A.A. Usmani obs. • Unnao; Site 11; 26.3694°N, 080.5108°E; 90 m a.s.l.; 12.V.2018, A.A. Usmani obs.

Identification. Face and large fore-neck white. Side of neck with a yellowish patch. Tail sickle-shaped.

Family Scolopacidae

***Numenius arquata* (Linnaeus, 1758)**
Eurasian Curlew
Figure 5G

Observations. INDIA – Uttar Pradesh • Bijnor; Site 1; 29.6218°N, 078.0825°E; 210 m a.s.l.; 4.XII.2019, A.A. Usmani obs. • Amroha; Site 3; 28.6874°N, 078.2005°E; 180 m a.s.l.; 7.XII.2019, A.A. Usmani obs. • Farrukhabad; Site 8; 27.5536°N, 079.5026°E; 120 m a.s.l.; 16.XII.2019, A.A. Usmani obs. • Fatehpur; Site 12; 26.0739°N, 080.7723°E; 90 m a.s.l.; 23.XII.2019, A.A. Usmani obs.

Identification. A wader with a unique, long, downward-curved, brown bill. Legs and feet bluish. Bill longer and head pattern more uniform than in *Numenius phaeopus*.

***Tringa erythropus* (Pallas, 1764)**
Spotted Redshank
Figure 5H

Observations. INDIA – Uttar Pradesh • Budaun; Site 7; 27.7401°N, 079.1944°E; 130 m a.s.l.; 5.II.2020, A.A. Usmani obs. • Unnao; Site 12; 26.2538°N, 080.5823°E; 90 m a.s.l.; 10.II.2020, A.A. Usmani obs. • Pratapgarh; Site 14; 25.6590°N, 081.4366°E; 80 m a.s.l.; 28.II.2021, A.A. Usmani obs.

Identification. Bill red and black. Legs red; head, hind neck, and back ashy brown. Breeding adults with black spots and a sooty appearance. Legs and bill longer than in *Tringa tetanus*.

Family Glareolidae

Glareola lactea **(Temminck, 1820)**
Little Pratincole
Figure 5I

Observations. INDIA – Uttar Pradesh • Bijnor; Site 1; 29.7921°N, 078.1844°E; 230 m a.s.l.; 7.II.2021, A.A. Usmani obs. • Kasganj; Site 7; 27.7932°N, 079.1122°E; 140 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Unnao; Site 11; 26.3694°N, 080.5108°E; 90 m a.s.l.; 27.II.2021, A.A. Usmani obs. • Pratapgarh; Site 15; 25.5829°N, 081.5876°E; 70 m a.s.l.; 28.II.2021, A.A. Usmani obs.

Identification. A sandy-grey small bird with a brown forehead. Wings long and pointed. Legs short and dark brown.

Family Laridae

Rynchops albicollis **(Swainson, 1838)**
Indian Skimmer
Figure 5J

Observations. INDIA – Uttar Pradesh • Budaun; Site 6; 27.9855°N, 078.7063°E; 150 m a.s.l.; 14.XII.2019, A.A. Usmani obs. • Farrukhabad; Site 8; 27.5290°N, 079.5406°E; 120 m a.s.l.; 26.II.2021, A.A. Usmani obs. • Prayagraj; Site 15; 25.4952°N, 081.8882°E; 70 m a.s.l.; 8.V.2019, A.A. Usmani obs.

Identification. Bill orange-red with lower mandible longer. Contrasting pied plumage, with cap black, legs and feet red. Sexes alike, but with female slightly smaller.

Larus ichthyaetus **(Pallas, 1773)**
Pallas's Gull
Figure 5K

Observations. INDIA – Uttar Pradesh • Bijnor; Site 2; 29.3413°N, 078.0684°E; 200 m a.s.l.; 22.IV.2018, A.A. Usmani obs. • Hardoi; Site 9; 27.0891°N, 079.9725°E; 110 m a.s.l.; 7.V.2018, A.A. Usmani obs. • Kanpur Nagar; Site 11; 26.3965°N, 080.4711°E; 90 m a.s.l.; 12.V.2018, A.A. Usmani obs.

Identification. The largest gull in India. Bill yellow with an orange and black tip. Eyes dark, with two crescent-shaped white patches in adults.

Sternula albifrons **(Pallas, 1764)**
Little Tern
Figure 5L

Observations. INDIA – Uttar Pradesh • Meerut; Site 2; 29.1761°N, 078.1033°E; 200 m a.s.l.; 21.IV.2019, A.A. Usmani obs. • Amroha; Site 3; 28.7273°N, 078.1765°E; 190 m a.s.l.; 23.IV.2019, A.A. Usmani obs. • Kasganj; Site 7; 27.7682°N, 079.1538°E; 130 m a.s.l.; 1.V.2019, A.A. Usmani obs. • Kannauj; Site 9; 27.0435°N, 079.9784°E; 100 m a.s.l.; 4.V.2019, A.A. Usmani obs. • Kaushambi; Site 15; 25.5206°N, 081.6753°E; 70 m a.s.l.; 8.V.2019, A.A. Usmani obs.

Identification. A small tern with a white forehead, black lores, a black-tipped, yellow bill, and orange legs in breeding adults. Bill blackish, legs dark, and with nape band in non-breeding individuals.

Sterna aurantia **(J.E. Gray, 1831)**
River Tern
Figure 6A

Observations. INDIA – Uttar Pradesh • Meerut; Site 2; 29.1389°N, 078.0769°E; 200 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Bulandshahr; Site 5; 28.2641°N, 078.3500°E; 180 m a.s.l.; 12.II.2021, A.A. Usmani obs. • Kasganj; Site 6; 27.8195°N, 079.0202°E; 140 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Farrukhabad; Site 8; 27.3514°N, 079.6572°E; 110 m a.s.l.; 26.II.2021, A.A. Usmani obs.

Identification. A pale-grey and white bird with a deeply forked tail, bright-yellow bill, and short red legs. Bill orange-yellow; cap black; underparts greyish-white in breeding adults.

Sterna acuticauda **(J.E. Gray, 1832)**
Black-bellied Tern
Figure 6B

Observations. INDIA – Uttar Pradesh • Amroha; Site 3; 29.0237°N, 078.0797°E; 190 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Sambhal; Site 4; 28.3703°N, 078.2745°E; 170 m a.s.l.; 12.II.2021, A.A. Usmani obs. • Budaun; Site 7; 27.7151°N, 079.2367°E; 130 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Hardoi; Site 9; 27.0891°N, 079.9725°E; 110 m a.s.l.; 27.II.2021, A.A. Usmani obs.

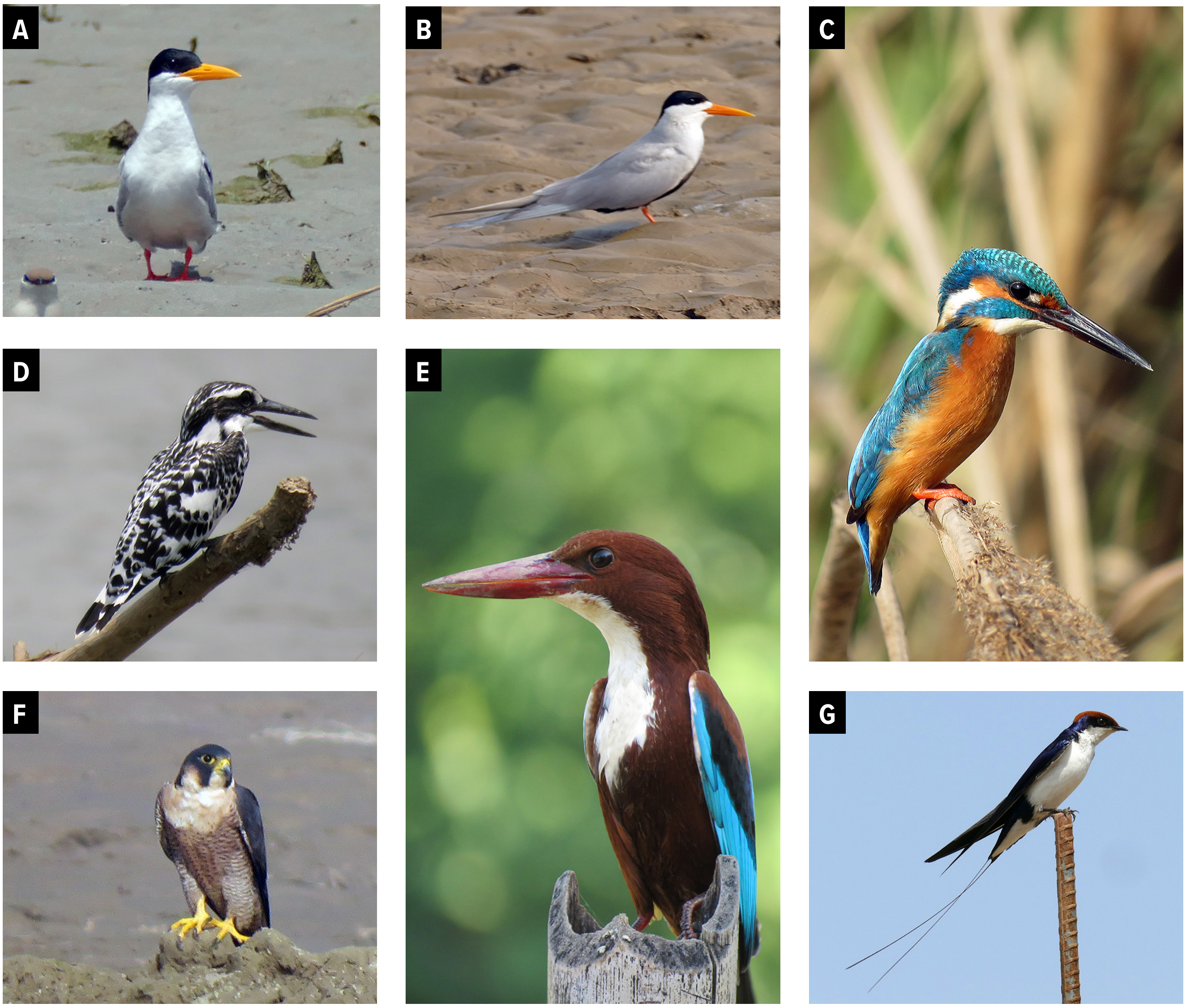

Figure 6. Birds of the middle stretch of the Ganga River **A.** *Sterna aurantia*. **B.** *Sterna acuticauda*. **C.** *Alcedo atthis*. **D.** *Ceryle rudis*. **E.** *Halcyon smyrnensis*. **F.** *Falco peregrinus* **G.** *Hirundo smithii*.

Identification. Bill orange, with a dusky tip. Tail deeply forked; legs orange. Sexes alike.

Family Alcedinidae

***Alcedo atthis* (Linnaeus, 1758)**
Common Kingfisher
Figure 6C

Observations. INDIA – Uttar Pradesh • Sambhal; Site 4; 28.2918°N, 078.3149°E; 170 m a.s.l.; 11.XII.2019, A.A. Usmani obs. • Aligarh; Site 5; 28.0416°N, 078.5805°E; 150 m a.s.l.; 4.II.2020, A.A. Usmani obs.

Identification. A small, blue-green kingfisher (from above), with a long, pointed, black bill and deep-rust-coloured underparts. Chin and throat white.

***Ceryle rudis* (Linnaeus, 1758)**
Pied Kingfisher
Figure 6D

Observations. INDIA – Uttar Pradesh • Meerut; Site 2; 29.1761°N, 078.1033°E; 200 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Bulandshahr; Site 4; 28.4063°N, 078.2912°E; 170 m a.s.l.; 12.II.2021, A.A. Usmani obs. • Budaun; Site 6; 27.9528°N, 078.8442°E; 140 m a.s.l.; 25.II.2021, A.A. Usmani obs. • Unnao; Site 10; 26.9262°N, 080.0469°E; 100 m a.s.l.; 27.II.2021, A.A. Usmani obs. • Fatehpur; Site 13; 25.9367°N, 081.2140°E; 80 m a.s.l.; 28.II.2021, A.A. Usmani obs.

Identification. A black and white kingfisher with a small crest. A black band extends over the eyes; supercilium white.

***Halcyon gularis* (Kuhl, 1820)**
White-throated Kingfisher
Figure 6E

Observations. INDIA – Uttar Pradesh • Bijnor; Site 2; 29.3097°N, 078.0996°E; 200 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Hapur; Site 3; 28.8758°N, 078.1182°E; 180 m a.s.l.; 11.II.2021, A.A. Usmani obs. • Fatehpur; Site 12; 26.0813°N, 080.7241°E; 90 m a.s.l.; 28.II.2021, A.A. Usmani obs. • Prayagraj; Site 15; 25.5075°N, 081.7219°E; 70 m a.s.l.; 13.I.2021, A.A. Usmani obs.

Identification. A large kingfisher with a long, thick, red bill. Head and underparts chocolate-brown. Breast and throat white.

Family Falconidae

***Falco peregrinus* (Tunstall, 1771)**
Peregrine Falcon
Figure 6F

Observations. INDIA – Uttar Pradesh • Bulandshahr; Site 4; 28.4834°N, 078.2501°E; 170 m a.s.l.; 3.II.2020, A.A. Usmani obs. • Hardoi; Site 9; 27.2181°N, 079.7369°E; 110 m a.s.l.; 26.II.2021, A.A. Usmani obs. • Kaushambi; Site 15; 25.5206°N, 081.6753°E; 70 m a.s.l.; 13.I.2021, A.A. Usmani obs. • Prayagraj; Site 15; 25.4979°N, 081.7971°E; 70 m a.s.l.; 13.I.2021, A.A. Usmani obs.

Identification. Head prominently slaty-black, and upperparts grey, with narrow blackish barring. Chin and throat white.

Family Hirundinidae

***Hirundo smithii* (Leach, 1818)**
Wire-tailed Swallow
Figure 6G

Observations. INDIA – Uttar Pradesh • Bijnor; Site 2; 29.3701°N, 078.0385°E; 210 m a.s.l.; 4.XII.2019, A.A. Usmani obs.

Identification. Body glossy, steel-blue above; cap chestnut-brown. Easily recognised by the white underparts and two long tail wires.

DISCUSSION

Our study covers areas of the Ganga River that were not fully explored in earlier avifaunal studies. We observed 107 species, which is near the estimated species richness (Chao-1), indicating that the survey captured >98% of the species present. In the 80 km stretch within the State Wildlife Barasingha Sanctuary, Khan et al. (2013) reported 53 species of waterbirds, while we recorded 87 species. Joshi et al. (2021) and Arya et al. (2020) documented 66 and 92 aquatics species, respectively, from the Haiderpur Wetland, a backwater area of the Middle Ganga Barrage on the Ganga River. Rahmani (1981) reported 30 important waterbirds from a small stretch of the river near Narora Barrage, and Bashir et al. (2012) recorded 50 waterbirds from the same area. Rao (2001) documented 48 species from the stretch between Rishikesh and Kanpur. In comparison, we recorded 62 waterbirds from this stretch. While most previous studies focused on specific areas of the middle stretch, we covered the entire 750 km stretch from Balawali in District Bijnor to Sangam in District Prayagraj, Uttar Pradesh. That resulted in 102 aquatic species from the non-protected stretch.

Our study documented 33.5% of all waterbird species and 8% of the total avifauna reported from India (Kumar et al. 2005; BirdLife International 2024). The presence of eight globally threatened species (IUCN 2024), 15 species listed under schedule I of the *Indian Wild Life Protection Act*, and a significant proportion (30%) of migratory species indicate the rich avifaunal diversity of this stretch of the Ganga River. Our data highlight the importance of this riverine ecosystem as waterbird habitat, and this good avifaunal diversity, in addition to the presence of other remarkable fauna, underscores the ecological health and integrity of the riverine habitat. A part of middle stretch of the river is protected within the large terrestrial protected area encompassed by the State Wildlife Barasingha Sanctuary. However, anthropogenic activities such as habitat degradation, flow alteration of the river caused by dams and barrages, and overexploitation of resources are destroying riverine ecosystems and biodiversity (Dudgeon 2000; Collen et al. 2010). Therefore, it is imperative to prioritize conservation efforts to protect and manage these riverine habitats.

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ADDITIONAL INFORMATION

Conflict of interest

The authors declare that no competing interests exist.

Ethical statement

No ethical statement is reported.

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Author contributions

Conceptualization: SAH, RB. Data curation: AAU, PG. Formal analysis: AAU. Funding acquisition: RB, SAH. Investigation: RB, SAH. Methodology: AAU, SAH. Supervision: RB, SAH, VBM. Project administration: RB, SAH. Validation: AAU, PG, SAH. Visualization: AAU. Writing – original draft: AAU. Writing – review and editing: AAU, PG, VBM, SAH.

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Data availability

All data that support the findings of this study are available in the main text.

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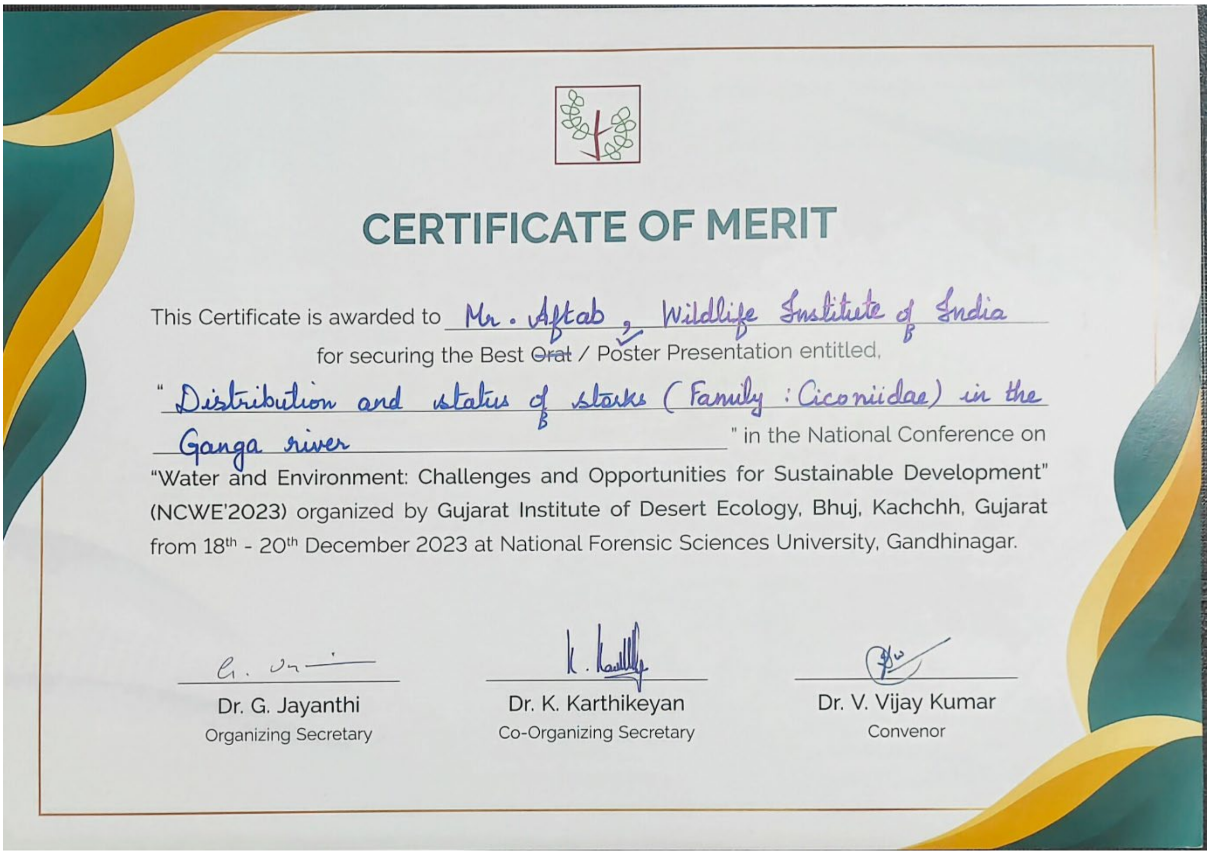

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