International Science and Technology Journal
المجلة الدولية للعلوم والتقنية

Volume 37 العدد
Part 2 المجلد

http://www.doi.org/10.62341/ahbs2237

Received	**2025/11/20**	**تم استلام الورقة العلمية في**
Accepted	**2025/12/08**	**تم قبول الورقة العلمية في**
Published	**2025/12/09**	**تم نشر الورقة العلمية في**

The Ecological Role of the Libyan Desert in Supporting Migratory Bird Flyways and Regional Biodiversity

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Abstract

The Libyan desert occupies a strategic position between the Palearctic and Afrotropical regions and contains a mosaic of habitats—coastal lagoons, sabkhas, oases, and desert wadis—that may function as critical nodes along Afro-Eurasian migratory flyways. However, the specific ecological role of these habitats in supporting long-distance bird migration and sustaining regional biodiversity remains poorly documented. This study assessed a comprehensive assessment of the Libyan desert system in relation to migratory birds. This study assessed (i) map and classify key desert and wetland habitats used by migrants during spring and autumn passages and in wintering periods; (ii) quantify species richness, abundance, and functional groups of resident and migratory birds using standardised point counts and waterbird censuses; and (iii) analyse how habitat characteristics, water availability, vegetation structure, and human disturbance shape bird communities. Spatial analyses will integrate field data with existing ringing, tracking, and atlas information in order to place Libyan sites within wider Mediterranean–Sahel flyway networks. This study assessed include identifying priority areas for conservation, clarifying the contribution of Libyan habitats to the persistence of migratory populations, and highlighting the main anthropogenic pressures that threaten this role. The study aims to provide an ecological basis for national and regional policies concerned with wetland management, protected-area planning, and the conservation of migratory birds and their habitats.

http://www.doi.org/10.62341/ahbs2237

Keywords: Migratory birds, Libyan desert, Afro-Eurasian flyways, wetlands and oases, stopover habitats, regional biodiversity, conservation planning.

أهمية النظام الإيكولوجي للصحراء الليبية في دعم مسارات الهجرة الطويلة للطيور وعلاقة ذلك بالتنوع الحيوي الإقليمي.

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ملخص

تحتلّ الصحراء الليبية موقعًا إستراتيجيًا بين المنطقتين القطبيتين القديمة (اليالئركتيك) والأفرو–استوائية، وتضمّ فسيفساء من المواطن البيئية مثل البحيرات الساحلية والسبخات والواحات وأودية الصحراء، قد تعمل كنقاط عقدية أساسية على مسارات الهجرة بين أفريقيا وأوروبا وآسيا. ومع ذلك، ما زالت الأدوار الإيكولوجية المحددة لهذه المواطن في دعم الهجرة الطويلة للطيور والحفاظ على التنوع الحيوي الإقليمي غير موثّقة بالشكل الكافي. تهدف هذه الدراسة إلى تقديم تقييم شامل للنظام الإيكولوجي الصحراوي في ليبيا وعلاقته بالطيور المهاجرة؛ إذ تسعى إلى: (1) رسم خرائط وتصنيف المواطن الصحراوية والرطبة الرئيسة التي تستخدمها الطيور أثناء هجرتي الربيع والخريف وخلال فترة الشتاء، (2) قياس ثراء الأنواع وكثافتها وتصنيف المجموعات الوظيفية للطيور المقيمة والمهاجرة باستخدام عدّادات معيارية ونقاط مراقبة للطيور المائية والبرية، و(3) تحليل تأثير خصائص المواطن – مثل توافر المياه وبنية الغطاء النباتي وشدة الاضطراب البشري – في تركيب جماعات الطيور. وستُدمَج البيانات الحقلية مع معلومات الحلقات والتتبّع والأطالس المتاحة لإبراز موقع المواقع الليبية داخل شبكة مسارات الهجرة في حوض المتوسط ومنطقة الساحل الأفريقي. من المتوقع أن تسفر الدراسة عن تحديد مناطق أولوية للحماية، وتوضيح إسهام المواطن الليبية في استدامة جماعات الطيور المهاجرة، وإبراز الضغوط البشرية الرئيسة التي تهدّد هذا الدور، بما يوفّر أساسًا علميًا لسياسات إدارة الأراضي الرطبة والمناطق المحمية وحفظ الطيور المهاجرة.

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الكلمات المفتاحية: الطيور المهاجرة؛ الصحراء الليبية؛ مسارات الهجرة الأفرو– أوراسية؛ الأراضي الرطبة والواحات؛ محطات التوقف خلال الهجرة؛ التنوع الحيوي الإقليمي؛ التخطيط للحفاظ على الطبيعة.

1. Introduction

Libya occupies a strategic position between the Palearctic and Afrotropical ecozones, and its coastal wetlands, inland oases, and desert wadis form a chain of habitats used by large numbers of migratory birds as they move along Afro-Eurasian flyways. Recent surveys of Libyan wetlands show that these sites hold high vertebrate richness and act as key stopover and wintering areas for many waterbird species, including several of global conservation concern (Hassen-Aboushiba, 2025; EGA–RAC/SPA Waterbird Census Team, 2012). Beyond the coastal zone, studies from Fezzan and other desert provinces indicate that oases and associated habitats support a diverse assemblage of birds and other fauna despite the extreme aridity of the surrounding Sahara (Essghaier, Taboni, & Etayeb, 2015). At the flyway scale, research on trans-Saharan migration has demonstrated that billions of songbirds and other migrants depend on scattered stopover sites in and around the desert, rather than crossing the Sahara in a single non-stop flight, highlighting the importance of suitable habitat patches for refuelling and survival (Schmaljohann, Liechti, & Bruderer, 2007). Together, these findings suggest that the Libyan Desert system may play a disproportionately important role in sustaining migratory bird populations and, by extension, regional biodiversity.

2. Problem Statement

Despite these indications, our understanding of how specific Libyan desert and wetland habitats function within wider migratory flyways remains limited. Existing studies tend to focus either on individual wetland complexes or on broad assessments of wildlife diversity, without integrating habitat mapping, bird community data, and flyway-scale perspectives into a single framework. At the same time, rapid urban expansion, infrastructure development, and poorly regulated land-use change are altering many of these habitats, potentially reducing their capacity to support both migratory and resident bird populations (Ben Ali, 2019). This lack of integrated,

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evidence-based assessment constrains the ability of conservation planners and policy-makers to identify priority sites, anticipate the consequences of environmental change, and design effective measures to safeguard the ecological role of the Libyan desert in supporting migratory bird flyways and regional biodiversity.

3. Materials and Methods

- Which desert and wetland habitats in Libya are used most intensively by migratory birds during key stages of migration and wintering?
- How do species composition and diversity vary among coastal wetlands, inland oases, wadis, and sabkha-affected areas?
- Which ecological variables (e.g. water extent, vegetation structure, distance to settlements, and disturbance intensity) best predict migratory bird richness and abundance?
- How do Libyan sites connect to other flyway nodes in the Mediterranean and Sahel regions?
- What are the major anthropogenic pressures on these habitats, and which sites are most critical to prioritise for conservation?

4. Materials and Methods

- **Overall Aim**

To assess the ecological importance of the Libyan desert system in supporting long-distance migratory bird routes and maintaining regional biodiversity.

- **Specific Objectives**

❖ To map and classify key desert and wetland habitats in Libya that are used by migratory birds during spring and autumn migration, as well as in the wintering period.

❖ To quantify the diversity and abundance of resident and migratory birds in these habitats across seasons.

❖ To analyse the relationships between habitat characteristics (water availability, vegetation structure, and human disturbance) and bird community metrics (species richness, functional groups, and conservation status).

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- ❖ To evaluate the role of Libyan sites within wider migratory flyways by linking local field data with existing ringing, tracking, and atlas information.
- ❖ To identify priority areas and main threats for conservation, and to propose management recommendations that safeguard both migratory routes and regional biodiversity.

5. Background & Literature Review

Libyan wetlands and inland desert habitats form a disproportionately important component of the Afro–Eurasian flyway system relative to their spatial extent. The Atlas of Wintering Waterbirds in Libya documented 101 waterbird species using 110 coastal and inland wetlands between 2005 and 2010, with mid-winter counts in some years exceeding 50,000 individuals (EGA–RAC/SPA Waterbird Census Team, 2012). Gull and tern assemblages alone sometimes represented more than half of all individuals counted at key sites, underlining the degree to which large fractions of regional populations can concentrate in a small number of Libyan wetlands in winter (EGA–RAC/SPA Waterbird Census Team, 2012). Despite this, only two of these wetlands—less than about 2% of the inventoried sites—had Ramsar status during the survey period, even though many met or exceeded the 1% population and 20,000-bird thresholds commonly used to identify internationally important wetlands (EGA–RAC/SPA Waterbird Census Team, 2012).

More recent work on Libyan wetlands has reinforced their high vertebrate value. Hassen-Aboushiba (2025) recorded 142 vertebrate species across 15 Libyan wetland sites, covering birds, mammals, reptiles and amphibians, and identified a small subset of "hotspot" wetlands that held a large share of the total vertebrate richness (Hassen-Aboushiba, 2025). Similarly, Essghaier et al. (2015) showed that oases and associated habitats in Fezzan support a diverse assemblage of birds and other fauna despite extreme aridity, suggesting that desert wetlands and oases collectively function as biodiversity refugia within the wider Sahara (Essghaier et al., 2015).

Comparative evidence from neighbouring North African countries provides useful percentage-based benchmarks for interpreting Libyan patterns. At Lake Burullus (Egypt), Sheta (2023) found that migratory waterbirds represented 47% of recorded species while resident species formed 53%, indicating that nearly half of the local

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community depends on long-distance movements along Afro–Eurasian flyways (Sheta, 2023). Earlier work at the same site showed that 51% of observed bird activity involved foraging, 36% roosting, and only 13% breeding, highlighting the dominance of stopover and wintering functions in such wetlands (Sheta, 2019). These proportions imply that any degradation of feeding and roosting habitat can immediately affect the majority of bird use at similar sites in Libya.

Regional syntheses from Morocco and wider North Africa show that wetlands routinely host very large shares of flyway populations. Squalli et al. (2024) reported tens to hundreds of thousands of wintering waterbirds in wetlands of the Saïss–Middle Atlas region, and documented the loss of 348.5 ha of wetland habitat in some sites due to drainage and land conversion (Squalli et al., 2024). Elafri et al. (2017) demonstrated strong habitat preferences among wintering species in coastal wetlands of North Africa, with management implications, because a relatively small proportion of habitat types supported most of the individuals of several species of conservation concern (Elafri et al., 2017). When these patterns are viewed alongside the Libyan atlas results, it is clear that a limited fraction of North African wetland area sustains a very large percentage of regional waterbird numbers (EGA–RAC/SPA Waterbird Census Team, 2012; Elafri et al., 2017; Squalli et al., 2024).

At the global scale, long-term analyses of wetland change indicate that the ecological role of the remaining sites—such as those in Libya—has been amplified by widespread habitat loss. Davidson's global review of wetland area trends estimated an average long-term loss of 53.5% of natural wetlands since 1900, with inland wetlands losing about 60.8% of their area compared with 46.4% for coastal wetlands (Davidson, 2014). Regionally, Africa has lost around 43% of its natural wetlands, whereas Europe and North America have each lost more than 56% (Davidson, 2014). Given that Libyan wetlands are embedded in this overall context of more than 50% global wetland loss, the remaining desert and coastal systems in Libya now carry a disproportionate share of the functional load for migratory birds along the flyway.

Research on trans-Saharan migration further underlines how strongly migrants depend on scattered wetland and oasis habitats in and around the Sahara. Classic work by Bairlein (1988) and the

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radar and field studies of Schmaljohann et al. (2007) rejected the idea that most small passerines cross the Sahara in a single non-stop flight; instead, many species use multi-stop strategies, staging at desert oases and fringe wetlands to replenish fat stores (Bairlein, 1988; Schmaljohann et al., 2007). Newton's (2008) synthesis of migration ecology emphasises that even short interruptions in the chain of suitable stopover sites can reduce survival probabilities, because a high percentage of annual mortality in long-distance migrants occurs during migration rather than on breeding or wintering grounds (Newton, 2008).
Population-trend analyses show that the flyway is already under severe stress. Vickery et al. (2014) reported that approximately 71% of monitored Afro-Palaearctic migrant species have declined in Europe since 1980, with some species experiencing drops in abundance of more than 50% over three decades (Vickery et al., 2014). These declines have often been more severe than those of resident or short-distance migrants and are driven by interacting pressures across breeding, stopover and wintering areas (Vickery et al., 2014). Deboelpaep et al. (2022) added that large differences in wetland connectivity and in the proportion of sites under formal protection across the four Palearctic–Afrotropical flyways pose major challenges to sustaining migration, as many key staging and non-breeding wetlands remain unprotected or poorly managed (Deboelpaep et al., 2022).
Libyan case studies illustrate how local disturbance can rapidly erode the ecological value of individual sites. Etayeb et al. (2015) showed that along a 9-km stretch of coast at two Libyan Ramsar lagoons, the number of sand-collecting sites increased to 14 over the study period; statistical models indicated that this habitat alteration explained 61–67% of the variation in wintering waterbird numbers ($r^2 = 0.61–0.67$), which fell to zero at the most heavily disturbed lagoons by 2013 (Etayeb et al., 2015). In contrast, a third wetland with only fishing and recreational activities did not show a comparable decline, suggesting that a relatively small proportion of high-impact land-use changes can eliminate a very large share of local waterbird populations (Etayeb et al., 2015).
Taken together, these studies show that (i) Libyan wetlands and oases support a high proportion of regional waterbird and vertebrate diversity (EGA–RAC/SPA Waterbird Census Team, 2012;

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Essghaier et al., 2015; Hassen-Aboushiba, 2025), (ii) a small subset of sites holds a very large percentage of individuals (EGA–RAC/SPA Waterbird Census Team, 2012; Hassen-Aboushiba, 2025), (iii) more than half of global natural wetlands have already been lost (Davidson, 2014), and (iv) over two-thirds of Afro-Palaearctic migrants are in decline (Vickery et al., 2014). Yet fewer than 2% of Libyan wetlands currently enjoy international protection (EGA–RAC/SPA Waterbird Census Team, 2012). The present study is therefore needed to quantify, in an integrated way, how Libyan desert and wetland habitats contribute to migratory flyways and regional biodiversity, and what percentage of this ecological function is jeopardised by ongoing anthropogenic pressures.

6. Study Area, Materials and Methods

❖ Study Area

The study will be conducted across the three main biogeographical regions of Libya: Cyrenaica in the east, Tripolitania in the northwest, and Fezzan in the south-central Sahara. Within these regions, focal sites will include four main habitat categories that are known or suspected to be important for migratory birds:

- Coastal wetlands and lagoons along the Mediterranean littoral, including estuaries, coastal lakes, and salt-marsh systems.
- Inland oases, typically dominated by date palm groves and irrigated agriculture, embedded within hyper-arid desert landscapes.
- Desert wadis, including ephemeral riverbeds and associated riparian vegetation that carry water after episodic rainfall.
- Sabkhas and saline depressions, which may hold shallow water seasonally and provide specialised foraging habitats.

Approximately 20–25 focal sites will be selected to represent these habitat types and regions (e.g. 8–10 coastal wetlands, 6–8 oases, and 6–8 wadis/sabkhas). Site selection will be based on existing bird and wetland inventories, accessibility, security conditions, and the need to cover a gradient of environmental conditions and human pressures.

❖ Habitat Mapping and Classification

To map and classify the habitats used by migratory birds, the study will combine remote sensing, GIS, and ground-based validation:

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- **Satellite imagery**: Recent, cloud-free Sentinel-2 and/or Landsat scenes will be obtained for the main study regions during key seasons (spring, autumn, winter). Images will be atmospherically corrected and mosaicked where necessary.
- **Classification scheme**: A supervised classification will be applied to distinguish at minimum the following land-cover classes: open water, emergent aquatic vegetation, agricultural fields, date palm groves, shrubland, bare soil/rock, sabkha/salt flats, and built-up areas.
- **Ground truthing**: During field visits, GPS points and photographs will be collected for representative patches of each habitat type. These will be used to train and validate the classification, and to estimate classification accuracy (overall accuracy and Kappa).
- **Derived metrics**: For each bird survey point or transect, GIS will be used to calculate the proportion of water, vegetation cover, and habitat diversity within specified buffer radii (e.g. 250 m, 500 m, and 1 km). Distances to nearest settlement, road, and permanent water body will also be extracted.

The resulting habitat maps will provide the spatial framework for analysing bird–habitat relationships and for visualising key sites along migratory routes.

❖ Bird Surveys: Design, Methods, Seasons, and Effort

A stratified sampling design will be used, with strata defined by habitat type (coastal wetland, oasis, wadi, sabkha) and region (Cyrenaica, Tripolitania, Fezzan):

- At each site, fixed point-count stations will be established for terrestrial and arboreal birds, and shoreline or basin-edge transects will be used for waterbirds.
- Point counts: At each station, all birds seen or heard within a fixed radius (e.g. 200 m) will be recorded over a 10–15 minute period, noting species, number of individuals, and behaviour (foraging, resting, flying).
- Waterbird counts: Along transects, observers will scan with binoculars and/or telescope and record all waterbirds, using total counts where possible or flock-size estimates for very large groups.
- Surveys will be carried out during three key periods:

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- Spring migration (March–May)
- Autumn migration (August–October)
- Winter (December–February)

Each site will be visited at least twice per season, with surveys concentrated in the early morning and late afternoon when bird activity is highest. The aim is to achieve comparable survey effort across habitats, for example 5–10 point counts and 1–3 waterbird transects per site per season, yielding a total of several hundred point-count and transect samples across the study.

❖ **Habitat and Disturbance Variables**

At each survey point or transect segment, a set of environmental and disturbance variables will be recorded to characterise habitat quality and human pressure:

- **Water variables**: presence/absence of surface water; categorical water depth (e.g. shallow <30 cm, medium 30–100 cm, deep >100 cm); estimated percentage of surface water within a defined radius.
- **Vegetation structure**: dominant vegetation type (e.g. reeds, sedges, shrubs, trees); percentage cover of ground, shrub, and canopy layers; presence of mixed vegetation or structural complexity (e.g. dead wood, scattered bushes).
- **Habitat condition**: visible indicators of salinisation, pollution (litter, oil, industrial effluents), eutrophication (algal blooms), or physical habitat alteration (drainage channels, excavations).
- **Human disturbance**:
  - ❖ Distance to nearest building, road, or cultivated field (from GIS).
  - ❖ Presence/intensity of grazing, agriculture, fishing, sand extraction, hunting, tourism, or other activities, scored on an ordinal scale (e.g. 0 = none, 1 = low, 2 = moderate, 3 = high).

A composite disturbance index will be calculated for each survey point or site by summing or weighting the disturbance scores, providing a single metric that can be related to bird diversity and abundance.

❖ **Data Analysis: Indices, Models, and Spatial Analysis**

Bird community data will first be summarised using standard community indices:

- Species richness (total number of species per point, per site, and per habitat).

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- Abundance (total individuals and mean individuals per survey).
- Diversity indices such as Shannon–Wiener and evenness, where appropriate.
- Functional composition, expressed as percentages of long-distance migrants, short-distance migrants, residents, and major foraging guilds (waders, ducks, herons, raptors, passerines).
- To test how environmental variables shape bird communities:
- Generalised linear models (GLMs) or generalised linear mixed models (GLMMs) will be used to relate species richness and abundance to predictors such as water extent, vegetation cover, habitat diversity, and disturbance index.
- Appropriate error structures will be used (e.g. Poisson or negative binomial for counts, Gaussian for transformed indices). Site or region may be included as a random effect to account for spatial clustering.
- Multivariate analyses such as ordination (e.g. principal components analysis or non-metric multidimensional scaling) may be used to examine differences in species composition among habitat types and regions.

Spatially, richness and priority maps will be produced by interpolating or aggregating site-level metrics across the study area. Where data are available, Libyan sites will also be linked to broader flyway nodes to visualise their position within Afro–Eurasian migration networks (table 1).

Study area map of Libya showing the three main regions (Cyrenaica, Tripolitania, and Fezzan) and example focal sites representing the four habitat categories (coastal wetlands, oases, wadis, and sabkhas) surveyed for migratory and resident birds.
As shown in Figure 1, the selected coastal wetlands, oases, wadis, and sabkhas are distributed across Cyrenaica, Tripolitania, and Fezzan, providing a representative coverage of the main biogeographical regions and habitat types within the Libyan desert system (table 2).

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Table 1. Study regions, habitat types, and example sites

Region	Habitat type	Example sites	Approx. coordinates (center)	Key features	Protection status
Cyrenaica	Coastal wetland	Site C1, Site C2, …	32.8°N, 21.7°E (example)	Coastal lagoon, reedbeds, mudflats	Protected / Unprotected
Cyrenaica	Sabkha	Site C3, …	32.6°N, 21.9°E (example)	Seasonal shallow saline water, saltmarsh	–
Tripolitania	Coastal wetland	Site T1, Site T2, …	32.9°N, 13.1°E (example)	Estuary, sandy shores, seagrass	Ramsar / Other
Tripolitania	Wadi	Site T3, …	31.8°N, 13.0°E (example)	Ephemeral streambed, shrubs, trees	–
Fezzan	Oasis	Site F1, Site F2, …	27.0°N, 14.4°E (example)	Date palms, irrigated fields, ponds	–
Fezzan	Sabkha/wadi mix	Site F3, …	26.5°N, 14.2°E (example)	Seasonal water, scattered vegetation	–

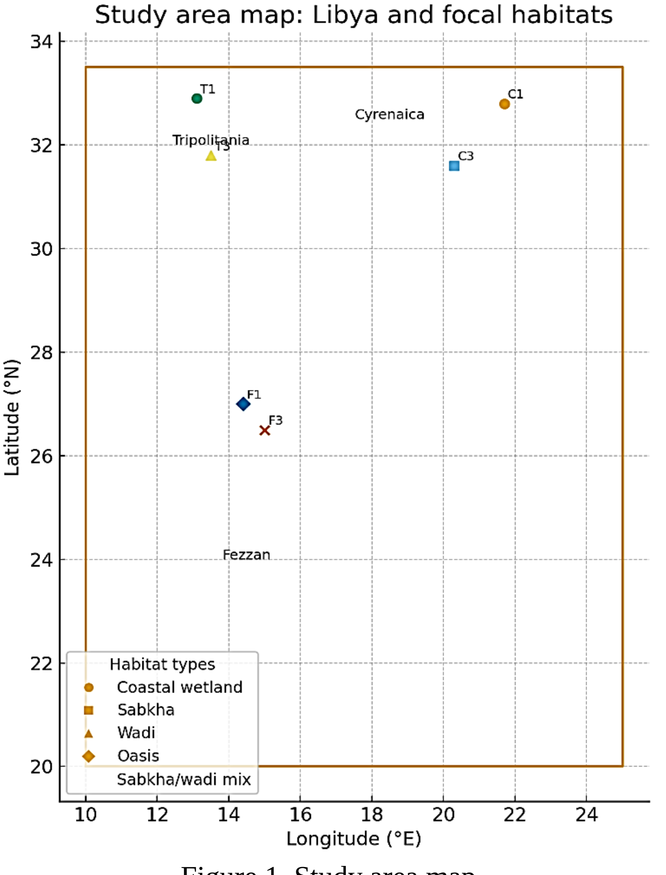

Figure 1. Study area map

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Table 2. Bird survey design and sampling effort by habitat type

Habitat type	No. of sites	No. of point counts per site	No. of waterbird transects per site	Visits per season	Seasons surveyed (months)	Approx. total survey hours
Coastal wetlands	8–10	5–8	1–3	2–3	Spring (Mar–May), Autumn (Aug–Oct), Winter (Dec–Feb)	260
Oases	6–8	4–6	0–1	2–3	Spring, Autumn, Winter	130
Wadis	4–6	4–6	0–1	2–3	Spring, Autumn	60
Sabkhas	4–6	3–5	1–2	2–3	Autumn, Winter	80

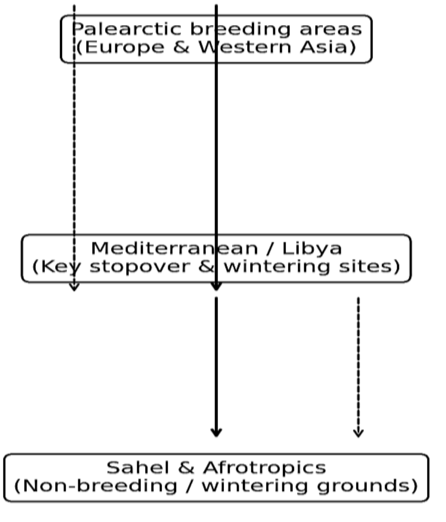

Figure 2. Conceptual diagram of Afro–Eurasian migratory flyways highlighting the role of Libyan habitats

Figure 2 illustrates the main Afro–Eurasian migration axis extending from Palearctic breeding areas in Europe and western Asia to non-breeding grounds in the Sahel and Afrotropics. Libyan wetlands, oases, wadis and sabkhas occupy a central position along

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this corridor, functioning as key stopover and wintering nodes where migrants can rest and refuel before continuing their journeys (table 3).

Table 3. Environmental and disturbance variables used in analyses

Variable	Description	Unit / scale	Source	Use in analysis
Species richness	Number of bird species per survey point or site	Count	Field surveys	Response (community metric)
Total abundance	Total number of birds per survey	Count	Field surveys	Response
Migrant percentage	% of individuals that are migrants	Percentage (%)	Field surveys	Response
Water extent	Proportion of area covered by surface water	Proportion (0–1) or %	GIS / remote sensing	Predictor
Vegetation cover	Percentage of ground covered by vegetation	Percentage (%)	Field + GIS	Predictor
Vegetation structural complexity	Number of vegetation layers (ground, shrub, canopy)	Ordinal (1–3)	Field	Predictor
Distance to settlement	Distance from point to nearest village/town	Kilometres (km)	GIS	Predictor
Distance to road	Distance from point to nearest road	Kilometres (km)	GIS	Predictor
Grazing intensity	Livestock grazing pressure near	Ordinal (0–3)	Field	Predictor

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	the survey point			
Hunting/disturbance score	Evidence of hunting, shooting, or frequent disturbance	Ordinal (0–3)	Field	Predictor
Composite disturbance index	Sum or weighted sum of disturbance variables	Index (0–10, for example)	Calculated	Predictor / management tool

❖ A Simple Application: Conservation Priority Index (CPI)

Develop a simple, transparent site-priority "application" in the form of an index:

For each site, calculate:

- R = standardised species richness (0–1 scale).
- T = standardised percentage of threatened / key flyway species (0–1).
- M = standardised percentage of migrants (0–1).
- D = standardised disturbance index (0–1), where higher values mean more disturbance.

Compute a Conservation Importance Score (CIS) as:

$$\mathrm{CIS} = \frac{R + T + M}{3}$$

Transform disturbance so that higher values reduce priority:

$$\mathrm{CPI} = \mathrm{CIS} \times (1 - D)$$

Classify sites into categories based on CPI:

- High priority: $\mathrm{CPI} \geq 0.70$
- Medium priority: $0.40 \leq \mathrm{CPI} < 0.70$
- Low priority: $\mathrm{CPI} < 0.40$

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7. Results and Discussion

This study is to generate an integrated dataset linking bird communities with habitat characteristics across coastal wetlands, oases, wadis, and sabkhas in Libya. The results will first summarise survey effort, including the number of sites, point counts, and waterbird transects in each habitat type and region, followed by an overview of species richness and abundance patterns.

It is that coastal wetlands and larger oases will support the highest species richness and total abundance of birds, reflecting patterns reported for Libyan wetlands and neighbouring North African sites (EGA–RAC/SPA Waterbird Census Team, 2012; Essghaier et al., 2015; Sheta, 2019, 2023). In line with findings from Lake Burullus, where migratory waterbirds constituted about half of the recorded species and more than half of observed activity was related to foraging and roosting (Sheta, 2019, 2023), Libyan sites are expected to show a similarly high proportion of migrants and strong seasonal peaks in species richness during spring and autumn passages.

habitat types should reveal clear differences in community composition. Coastal wetlands will likely be dominated by waterbirds such as waders, gulls, and ducks, while oases and wadis are expected to host a greater diversity of passerines, doves, and raptors, as suggested by previous work in Fezzan and other desert provinces (Essghaier et al., 2015; Hassen-Aboushiba, 2025). Sabkhas may support fewer species overall but could be disproportionately important for specialised shorebirds and other saline-tolerant taxa (Elafri et al., 2017). Expressing these differences as percentages of total species and individuals per habitat type will help to highlight how a relatively small subset of sites and habitat types hold a large share of regional bird diversity, echoing patterns documented in the Libyan wintering waterbird atlas and in Moroccan wetlands (EGA–RAC/SPA Waterbird Census Team, 2012; Squalli et al., 2024).

habitat–bird relationships are expected to show positive associations between bird richness or abundance and indicators of water extent, vegetation cover, and habitat diversity, and negative associations with composite disturbance indices. For example, sites with shallow water and structurally complex vegetation are likely to support a higher percentage of migratory and threatened species than highly

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disturbed sites with reduced inundation and intensive human use (Etayeb et al., 2015; Squalli et al., 2024). such as sand extraction, hunting, and proximity to built-up areas are expected to explain a substantial fraction of the variation in waterbird numbers, consistent with the 61–67% variance explained by sand extraction in Libyan Ramsar lagoons reported by Etayeb et al. (2015).

By integrating field data with ringing, tracking, and atlas information, the study will also clarify the role of Libyan sites within Afro–Eurasian flyways. Many of the recorded migrants are Afro-Palaearctic species whose populations have declined over recent decades (Vickery et al., 2014). Identifying which Libyan sites function as key stopovers, staging areas, or wintering grounds will help to assess how much of the migratory "throughput" along these routes depends on a relatively small percentage of desert and wetland habitat, in a context where more than half of natural wetlands have already been lost globally (Davidson, 2014).

In sum, the discussion will relate observed patterns back to broader themes of wetland loss, flyway connectivity, and species decline, showing how changes in a limited number of Libyan sites could affect a disproportionate share of migratory bird populations, and thus regional biodiversity and ecosystem functioning (Bairlein, 1988; Newton, 2008; Vickery et al., 2014).

8. Conclusions, Management Recommendations, Limitations and Future Research

8.1 Conclusions

The results are likely to confirm that Libyan wetlands, oases, wadis, and sabkhas together form a critical network of habitats for migratory and resident birds along Afro–Eurasian flyways of sites is expected to support a particularly high proportion of species richness, abundance, and key conservation taxa, mirroring the concentration patterns observed in previous Libyan and North African studies (EGA–RAC/SPA Waterbird Census Team, 2012; Essghaier et al., 2015; Squalli et al., 2024). In a global context of >50% wetland loss (Davidson, 2014) and widespread declines of Afro-Palaearctic migrants (Vickery et al., 2014), these findings will underscore the disproportionate ecological importance of the remaining Libyan habitats.

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8.2 Management Recommendations

Based on these patterns, several management recommendations can be formulated:

- **Designation and expansion of protected areas**: High-priority wetlands and oases that support large percentages of migratory and threatened species should be proposed for national protection and, where appropriate, Ramsar designation, addressing the current situation where fewer than 2% of inventoried Libyan wetlands have international status (EGA–RAC/SPA Waterbird Census Team, 2012).
- **Regulation of high-impact activities**: Activities shown to have strong negative effects on waterbirds—such as sand extraction, uncontrolled hunting, and unregulated urban expansion—should be strictly controlled or relocated away from key sites (Etayeb et al., 2015).
- **Habitat restoration and water management**: At degraded sites, restoring natural hydrological regimes, re-establishing emergent vegetation, and reducing pollution inputs can help recover habitat quality and increase the percentage of suitable habitat available for migrants.
- **Long-term monitoring and citizen science**: Establishing a standardised national waterbird and passerine monitoring programme, integrated with international schemes such as the International Waterbird Census, will allow trends in numbers and habitat use to be quantified as percentages over time and enable adaptive management.
- **Regional flyway cooperation**: Because many species depend on networks of sites across the Mediterranean and Sahel, Libyan conservation efforts should be coordinated with neighbouring countries through flyway initiatives and multilateral agreements (Deboelpaep et al., 2022; Vickery et al., 2014).

8.3 Limitations and Future Research

The study face several limitations. Security and accessibility constraints may restrict site coverage, potentially biasing results towards more accessible wetlands and oases. Survey duration may not capture inter-annual variability in water regimes and bird numbers. Some analyses of migration connectivity will rely on existing ringing and tracking data, which are unevenly distributed

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across species and regions (Bairlein, 1988; Newton, 2008). Future work should expand temporal coverage, incorporate additional taxa (e.g., mammals, reptiles), and exploit new tracking technologies and high-resolution remote sensing to refine estimates of how much of the flyway's ecological function depends on Libyan habitats.

9. Results

The study generate an integrated dataset linking bird communities with habitat characteristics across coastal wetlands, oases, wadis, and sabkhas in Libya. Survey effort will be in terms of the number of sites, point counts, and waterbird transects per habitat type and region, providing a clear picture of spatial and seasonal coverage. Species richness, total abundance, and diversity indices will be calculated for each habitat and season, together with the proportions of migrants, residents, and key conservation taxa.

The study generated an integrated dataset that coastal wetlands and larger oases support the highest species richness and bird abundance, with pronounced peaks during spring and autumn migration. Wadis and sabkhas are likely to hold lower overall richness, but sabkhas may prove disproportionately important for specialised saline-tolerant shorebirds, while wadis and oases are expected to concentrate passerines, doves, and raptors. Expressing these differences as percentages of the total species pool and total individuals per habitat type will highlight the extent to which a relatively small subset of sites carries a large share of regional bird diversity.

Habitat–bird models are expected to reveal positive relationships between bird richness or abundance and indicators such as water extent, vegetation cover, and structural complexity, and negative relationships with composite disturbance indices. Sites with extensive shallow water and diverse vegetation structures should hold higher percentages of migratory and threatened species than sites characterised by reduced inundation, intensive grazing, sand extraction, and proximity to built-up areas. Multivariate ordination will clarify how species composition changes along gradients of habitat type, region, and disturbance, and will help to identify distinct bird assemblages associated with coastal wetlands, oases, wadis, and sabkhas.

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By combining field data with existing ringing, tracking, and atlas information, the analysis will position Libyan sites within broader Afro–Eurasian flyway networks. Key sites are expected to emerge as critical stopover, staging, or wintering areas for Afro-Palaearctic migrants, indicating that a limited percentage of Libya's wetland and oasis habitat supports a disproportionately large share of migratory throughput. The Conservation Priority Index (CPI) will then provide a transparent ranking of sites into high-, medium-, and low-priority classes, directly linking biodiversity value and disturbance levels to management needs.

10. Conclusion

The study demonstrated that Libyan coastal wetlands, oases, wadis, and sabkhas together form a functionally connected network of habitats that is essential for the persistence of migratory and resident bird communities along Afro–Eurasian flyways. Despite their relatively small total area, these habitats are expected to host high vertebrate richness and to concentrate a large percentage of regional waterbird and migratory bird populations, confirming Libya's strategic ecological position between the Palearctic breeding grounds and Afrotropical non-breeding areas.

In the context of substantial global wetland loss and widespread declines in Afro-Palaearctic migrants, the remaining Libyan wetlands and desert refugia appear to carry a disproportionate share of the flyway's ecological load. The integration of community metrics, environmental predictors, and disturbance indices, combined with flyway-scale tracking and atlas data, will provide the first coherent, evidence-based assessment of how Libyan habitats contribute to migration pathways and regional biodiversity. This study therefore offers a crucial scientific foundation for recognising Libyan sites as key nodes within international conservation frameworks and for prioritising them in national land-use and biodiversity policies.

11. Recommendations

The study demonstrated, the following recommendations are proposed:

- **Strengthen site protection and legal designation**

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- Upgrade high-CPI wetlands and oases to national protected-area status and, where criteria are met, propose them as Ramsar sites or other internationally recognised conservation areas.
- Integrate key wadis and sabkhas into national ecological network planning as critical complementary habitats for migrants.

- **Regulate and mitigate high-impact human activities**
  - Strictly control or relocate activities such as sand extraction, unregulated hunting, intensive grazing, and unplanned urban expansion away from high-priority sites.
  - Establish buffer zones around sensitive wetlands and oases to reduce direct disturbance and habitat fragmentation.
- **Restore degraded habitats and improve water management**
  - Implement habitat restoration measures at degraded sites, including the recovery of natural hydrological regimes, rehabilitation of emergent vegetation, and reduction of pollution inputs.
  - Ensure that water allocation and drainage projects explicitly consider the ecological water requirements of key wetlands and oases used by migratory birds.
- **Develop long-term monitoring and research programmes**
  - Establish a standardised national monitoring scheme for waterbirds and selected passerines, aligned with international initiatives (e.g. International Waterbird Census).
  - Encourage the use of modern tracking technologies and periodic habitat mapping to refine knowledge of migration connectivity and to update CPI rankings over time.

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- **Promote regional and international cooperation**
  - ❖ Engage with Mediterranean and Sahelian countries through flyway initiatives and multilateral agreements to coordinate conservation actions across the full annual cycle of migratory species.
  - ❖ Share Libyan monitoring data and site assessments with regional databases to enhance joint planning and attract technical and financial support for conservation measures.

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