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(RESEARCH ARTICLE)

Spatial and temporal distribution of vertebrates in Libyan wetlands and their importance as stopover sites for migratory birds

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Abstract

Libyan wetlands are at a unique and important biogeographic spot between the Palearctic and Afrotropical ecozones, yet they are still one of the biggest gaps in Mediterranean biodiversity knowledge. This research presents the first extensive, multi-taxa evaluation of vertebrate distribution and abundance throughout a network of Libyan coastal and inland wetlands, aimed at assessing their functional significance as stopping places for migrating avifauna. We posited that the geographical distribution of vertebrate assemblages and the temporal abundance of migratory species are mostly influenced by wetland hydro-geomorphological features and the gradient of anthropogenic pressure. From 2022 to 2024, we conducted systematic surveys of birds, mammals, reptiles, amphibians, and fish at 15 important wetland locations. Our study found 142 vertebrate species in total, some of which are of importance for conservation throughout the world. Spatial analysis identified four wetlands as vital biodiversity hotspots, distinguished by elevated species richness and the occurrence of uncommon species. Time studies of avifauna showed clear seasonal peaks in abundance, with spring migration happening from late March to early May and fall migration from September to November. This confirmed their important role along the migratory flyways in the Central and Eastern Mediterranean. Multivariate models showed that wetland acreage, water salinity, and vegetation complexity were the most important environmental determinants of community composition. We created a Wetland Importance Index (WII) based on these results. The WII is a scientifically sound way to set conservation priorities. This study addresses a significant gap in knowledge by statistically demonstrating the essential function of Libyan wetlands within the broader Afro-Eurasian migratory system, while also providing a practical resource for national conservation planning and the strategic designation of future Ramsar sites.

Keywords: Libyan Wetlands; Migratory Birds; Spatial Ecology; Biodiversity Hotspots; Temporal Dynamics; Conservation Management; Vertebrate Assemblages; Afro-Eurasian Flyway

1. Introduction

Wetlands are some of the most productive ecosystems in the world, but they are also some of the most at risk. The loss of natural wetlands throughout the world has been terrible, with long-term losses of 54–57% and maybe as much as 87% since 1700 AD (Davidson, 2014). The pace of loss has sped up a lot in the contemporary age, with an estimated 64–71% of wetlands vanishing since 1900 AD alone. This damage puts the ecosystems' huge biodiversity at risk and makes the important ecological functions they perform, including cleaning water, controlling floods, and storing carbon, less effective. Wetlands are vital habitats for vertebrate species for foraging, breeding, and roosting, and their ongoing degradation has been linked to detrimental trends in vertebrate populations across several biomes (Galewski et al., 2011).

The Mediterranean Basin, which is home to many kinds of plants and animals, is a good example of this problem. The wetlands in this area are getting worse because of water loss from the marshes, pollution, and climate change. The

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ground is also being used for farms and towns. Water shortages are getting worse because of warmer temperatures and changed rain patterns (Leberger et al., 2020). Rising sea levels are also risking the survival of coastal marshes (Verniest et al., 2024) it is predicted. The Mediterranean Wetlands Observatory (2025) says that these worries have a big impact on the unique ecosystem of the area and on the millions of birds that fly through it on their way to and from other places.

This is a very important job, especially in dry and semi-arid areas, because wetland areas are important stops on long global migration flyways. The Mediterranean and North African wetlands constitute an important network of "refueling stations" for the hundreds of bird species that migrate every year between breeding grounds in the Palearctic and non-breeding regions in the Afrotropics. These spots are not only good places to relax; they are also biologically important for getting the energy reserves needed to cross the tough natural barriers of the Mediterranean Sea and the Sahara Desert (Schmaljohann et al., 2022). The functional connectedness of this network is very important; losing or damaging even a few critical sites may have a huge detrimental effect on the whole flyway system. Recent network analysis have shown that the Palearctic-Afrotropical flyways are not very connected and depend on a limited number of wetlands, many of which are not formally protected (Deboelpaep et al., 2022). This shows how important it is to quickly find and protect all the important points in this network so that it can last for a long time.

According to Sayoud et al. (2017), North Africa is the first ground link for people going north and the last ground link for people going south. This is why everyone needs their bogs a lot. With the International Waterbird Census (IWC), this has helped people in the area work together to keep an eye on birds. The first one that was planned was to cover all of North Africa. People learned a lot about the places where ducks and geese live. It also showed how well the Ramsar sites that are already there are doing. A study by Sayoud et al. (2017) also found that polls miss some places, mostly the bigger ones. You can learn about changes in populations on a biogeographical level and have an impact on global conservation agreements such as the Agreement on the Conservation of African-Eurasian Migratory Waterbirds (AEWA) (UNEP/AEWA Secretariat, 2022). They can be formed through groups like these.

Libya is a piece of the puzzle that is important but not well known in this area. Libya has the longest Mediterranean coastline of any African country (1,770 km) and a number of important interior oases. This makes it a key stop for birds utilizing both the Central and Eastern Mediterranean flyways (Isenmann et al., 2016). Despite this, comprehensive and quantitative ecological data on its wetlands are very sparse. Early surveys laid the groundwork for understanding (Smart et al., 2006), but later monitoring attempts have been few and far between and only in certain areas, frequently because of problems with logistics and security (Bourass et al., 2013; Etayeb et al., 2015). Recent IWC reports from Libya indicate a substantial reduction in the number of monitored sites relative to the mid-2000s, highlighting the increasing data shortage (Etayeb et al., 2023). The most comprehensive modern ornithological account, Birds of Libya, provides an invaluable annotated checklist of 350 avian species and confirms the country's importance for migrants, but it is not a quantitative, site-based ecological assessment designed for conservation prioritization (Isenmann et al., 2016). This presents a significant scientific issue: the functional significance of Libyan wetlands within the Afro-Eurasian flyway system is generally accepted but has not been properly measured, hindering efficient conservation planning at both national and international levels. The instability that has made research difficult also makes it more important to have a data-driven conservation framework that allows for focused action where it is most required.

This research seeks to fill a significant knowledge gap by delivering the first complete evaluation of the geographical and temporal distribution of vertebrate assemblages throughout a network of essential Libyan wetlands. Our main goals are: (1) to measure and map the diversity, abundance, and community composition of vertebrates at certain coastal and inland wetland sites; (2) to look at the spatial patterns of biodiversity to find conservation hotspots and the temporal dynamics of faunal assemblages, with a focus on the phenology of migratory birds; (3) to find the main environmental factors (like wetland area, hydrology, vegetation structure, and human disturbance) that affect these distribution patterns; and (4) to create and use a multi-metric index to rank the functional importance of these wetlands as stopover sites, which will help us prioritize conservation action. We test the hypotheses that (1) vertebrate community structure is influenced by a combination of natural environmental filters (habitat size and complexity) and anthropogenic pressures, and (2) that the temporal patterns of avian abundance will validate the essential role of these sites as migratory stopover hubs.

Table 1 Summary of Key Previous Vertebrate Surveys in Libya and North Africa

Study (Author, Year)	Country/Region	Target Taxa	Key Findings	Identified Data Gaps/Limitations
Smart et al. (2006)	Libya	Waterbirds	Counted >80,000 waterbirds at 65 sites in 2005-2006.	Single-season (winter) snapshot; limited to avifauna.
EGA–RAC/SPA (2012)	Libya	Waterbirds	Atlas of wintering waterbirds from 2005-2010.	Focus on wintering period only; no multi-taxa data.
Bourass et al. (2013)	Libya	Waterbirds	2011 winter census; ~35,000 birds at 84 sites.	Inconsistent site coverage year-on-year.
Etayeb et al. (2015)	Libya	Waterbirds	2012 winter census; ~29,000 birds at 42 sites.	Declining site coverage compared to previous years.
Isenmann et al. (2016)	Libya	Birds	Comprehensive checklist (350 species); biogeographic analysis.	Not a quantitative site-based ecological study.
Sayoud et al. (2017)	North Africa	Waterbirds	First coordinated census; highlighted regional importance.	Noted limited coverage in Libya due to security.
Etayeb et al. (2023)	Libya	Waterbirds	2022 winter census; ~62,000 birds at 64 sites.	Still focused on winter; other vertebrate groups unassessed.

2. Materials and Methods

2.1. Study Area

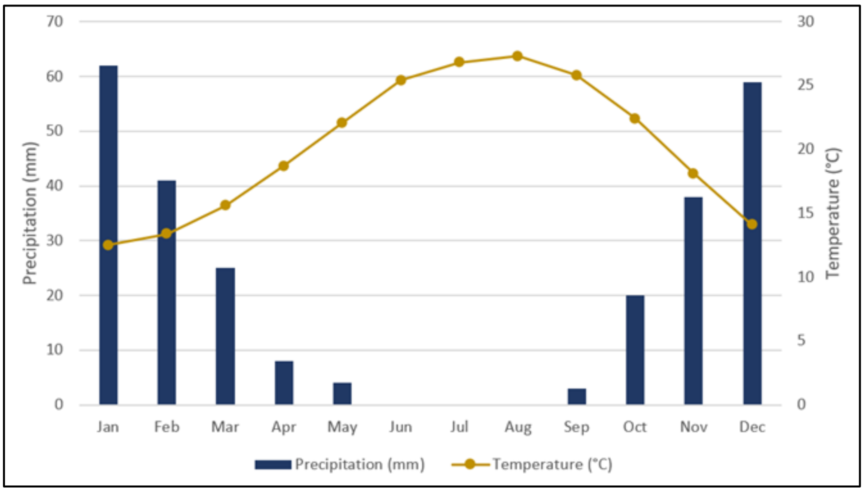

Figure 1 Climate graph for the area of Libya's coast that was studied. The line shows the average monthly temperature in degrees Celsius (°C), while the bars show the average total monthly precipitation in millimeters (mm). Data gives us the weather background for seasonal vertebrate activity

This research was carried out in 15 wetland locations in Libya, chosen to exemplify the primary typologies and geographic distribution of wetland ecosystems across the nation. The locations included of coastal saline lagoons and sabkhas (e.g., Ain Al-Ghazala, Sabkhat Al-Hishah), freshwater and brackish marshes (e.g., Wadi Kaam, Ain Zayanah), and interior oasis systems (e.g., Ghadames Oasis, Tawargha Spring). The selection sought to include a spectrum of environmental circumstances, including dimensions, hydrological stability, salinity, and degrees of human impact. Between January 2022 and December 2024, field surveys were done. A baseline characterisation was conducted for each location using a mix of high-resolution satellite imaging (Sentinel-2 and PlanetScope), ground-truthing, and direct measurements. Table 2 shows a summary of the most important physical and environmental factors that were recorded. The Human Disturbance Index (HDI) was used to measure anthropogenic pressure. It was based on GIS analysis of the density of roads, the distance to metropolitan areas, and the proportion of land cover that had been changed to agriculture within a 2 km buffer zone surrounding each wetland. We added these three spatial layers together to get a composite HDI rating for each buffer zone.

Table 2 Physical and Environmental Characteristics of the Surveyed Wetlands

Site Name	**Latitude (°N)**	**Longitude (°E)**	**Area (ha)**	**Altitude (m)**	**Water Salinity (PSU Range)**	**Dominant Vegetation Type**	**Human Disturbance Index (HDI)**
Ain Al-Ghazala Lagoon	32.25	23.28	1850	2	30-42	*Salicornia*, *Arthrocnemum*	0.28
Sabkhat Al-Hishah	31.62	16.55	3200	-1	35-55	Halophytic shrubland	0.45
Wadi Kaam Dam	32.48	14.58	450	25	1-5	*Phragmites*, *Tamarix*	0.67
Ain Zayanah Lagoon	32.17	20.20	550	1	5-25	*Phragmites*, *Juncus*	0.75
Ghadames Oasis	30.13	9.50	120	350	<1	*Phoenix dactylifera*, *Typha*	0.51
Tawargha Spring	31.97	15.06	85	15	1-3	*Phragmites*, *Scirpus*	0.82
Farwa Lagoon	33.08	12.00	2500	0	28-38	*Posidonia*, *Cymodocea*	0.33
Sabkhat Qasr Ahmed	32.35	15.20	780	-2	40-60	Algal mats, sparse halophytes	0.88
Al-Hasy Marsh	32.75	22.05	210	5	2-8	*Juncus*, *Typha*	0.41
Jalo Oasis	29.03	21.55	95	50	<1	*Phoenix dactylifera*	0.21
Kufra Oasis	24.20	23.30	150	420	<1	Agricultural crops	0.65
Ain Al-Shamali	32.80	22.50	60	10	1-4	*Phragmites*, *Tamarix*	0.59
Sabkhat Bu Kammash	33.10	11.85	1100	-1	38-50	Halophytic vegetation	0.71
Wadi Al-Majanin	32.70	13.40	330	30	Seasonal	*Tamarix,* *Nerium oleander*	0.91
Garabulli Wetlands	32.75	13.80	600	3	15-30	*Phragmites*, *Salicornia*	0.62

2.2. Target Groups and Survey Design

Five main families of vertebrates were the focus of the surveys: Aves (birds), Mammalia (mammals), Reptilia (reptiles), Amphibia (amphibians), and Pisces (fishes). Standardized methods were used so that locations and seasons could be compared in a strong way.

Aves: We used both fixed-radius point counts and line transects to look at bird communities. At least five to ten fixed point count stations were set up at least 250 meters apart in each marsh. At each place, a ten-minute count was done during each study visit. In this area, all the birds that could be seen or heard were counted. In larger, open marshes, we walked at a steady speed of about 1.5 km/h along straight lines that were 1 to 2 km longTo get a sense of how many birds there were, we wrote down the names of each one and how far away it was from the set line. When the weather was bad (strong winds or heavy rain), surveys didn't happen. Instead, they were done in the first four hours after dawn.

Mammalia: Two different ways were used to study mammals. Twenty Reconyx HyperFire 2 infrared camera traps were set up at each site and left there for 30 days straight each season to catch medium and big animals. At the edges of areas, along possible animal paths, and near water sources, cameras were set up. We used 100 Sherman live traps set up in normal grids (10x10 grid, 10 m spacing) to catch small animals like rats and shrews. We used them for three nights in a row at each site every season.

Reptilia and Amphibia: Limited in time To look at herpetofauna, Visual Encounter Surveys (VES) were used. Two people walked through typical microhabitats in each marsh and searched in a normal way for an hour. People who were watching aggressively looked beneath rocks, logs, and plants. Surveys were done when animals were most active, which was usually in the morning and late afternoon for reptiles and at night for amphibians.

Pisces: Multi-mesh gillnets and fyke nets that were all the same size were used to catch fish in marshes with constant amounts of water. To make sure that the sample effort was the same, nets were left out in the same places for 12 hours at a time. When someone grabbed a fish, they were told what kind it was, sized it, and then were free to go.

Table 3 Taxonomic Summary of Vertebrate Species Observed

Taxonomic Class	Number of Families	Number of Species	Number of IUCN Red List Threatened Species
Aves	45	98	7
Mammalia	12	18	3
Reptilia	8	15	1
Amphibia	2	3	0
Pisces	5	8	1
Total	72	142	12

2.3. Temporal Framework

Each of the 15 ponds was looked at four times a year for three years, from 2022 to 2024. There are 12 studies on each site. This was done so that a full picture could be made of how the different types of animals changed with the seasons. The study times were chosen to match up with seasons that are naturally important because of the weather in the area and how birds are known to behave during those seasons:

- **Wintering:** December – February
- **Spring Migration:** March – May
- **Breeding/Summer:** June – August
- **Autumn Migration:** September – November

This sample method made sure that both fixed populations and key times for migrating species to move were carefully studied. Things could be seen to change over time.

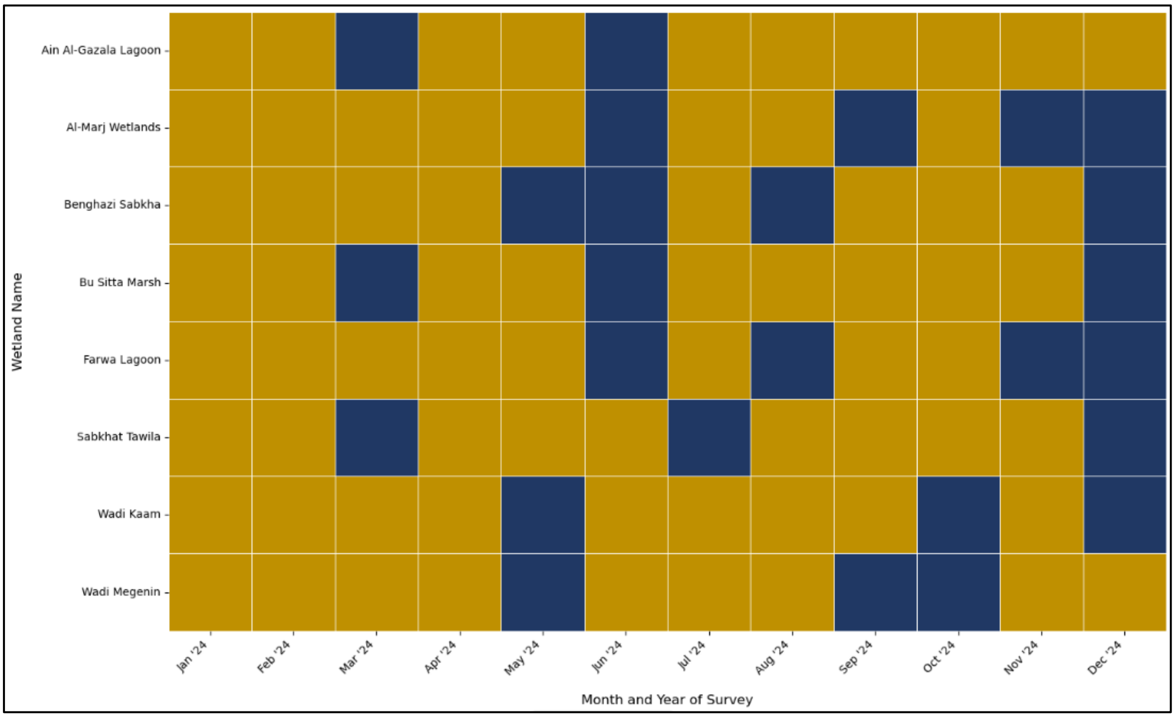

Figure 2 The yearly sample try shows how the site polls were spread out over the study's time frame

2.4. Data Analysis

R 4.3.1 was used for all of the statistics tests. The research was done according to a step-by-step plan that helped reach the main goals of the study.

Diversity Metrics: To find out how different each place and season was, we used the Shannon-Wiener diversity index (H′), Pielou's evenness index (J′), and species richness (S). We looked at how communities change in marshes (beta diversity) by making matched Sørensen resemblance indices based on which species were present and which were not.

Spatial Analysis: KDE was used on the locations of where the species were found to find places with lots of different species. Each spot was given a weight based on the number of species that were there. This let them make a flat map that showed how different the areas under study were from one another. We used Moran's I figure to find out if the places with high or low wealth were spread out, grouped together, or picked at random. This way, we could see if the number of species in different areas was connected to the number of species in other areas.

Temporal Analysis: We used Generalized Linear Mixed Models (GLMMs) with either a Poisson or a negative binomial error distribution to look for big changes in the types and numbers of animals that lived in each season. Here, the answer variable was the amount of species, also called their "richness." The set effect was "Season," and "Wetland Site" was added as a random catch to stop using data from the same places over and over again without being separated. Move phenology models were used to show how the number of ducks, shorebirds, and other large bird groups changed from week to week. It was easy to see when and how big the moving peaks were.

Multivariate Analysis of Environmental Drivers: We used Canonical Correspondence Analysis (CCA) to figure out how animals that live in groups are linked to the things around them. After the first Detrended Correspondence Analysis (DCA) showed a long gradient length (>4.0 SD), this method was used to show that only one species responded to changes in its surroundings. In Tables 2 and 4, factors from the environmental matrix were used. In Table 4, the species matrix showed the number of people of each species in each place. There were 999 different ways to run the Monte Carlo test, which helped us figure out how important the whole model and each canonical axis were.

Conservation Prioritization: The marsh Importance Index (WII) tells each marsh how important it is for protection in a fair and objective way. For each site, the index was found by adding up three standardized measures and giving them a weight. The presence of rare and fragile species was given the most weight (0.4) to help us find the most important places for their survival. We gave the general diversity of vertebrates (0.3) and the highest number of moving waterbirds the same amount of weight. This ranking method was chosen on purpose to be in line with international conservation guidelines, such as those from the IUCN. These guidelines stress taking steps to save the most vulnerable species and protect places that are "irreplaceable." The method is: where is the normalized score for species that are threatened or rarely seen, what is the normalized score for species density generally, and what is the normalized score for migrant abundance? All the measures were moved to a range from 0 to 1 before the final number was found.

Table 4 Summary of Environmental Variables Used in Multivariate Models

Variable Name	Abbreviation	Unit of Measurement	Range of Values	Data Source
Wetland Area	Area	Hectares (ha)	60 - 3200	GIS Analysis
Water Salinity	Salinity	Practical Salinity Units (PSU)	0.5 - 60	Field Measurement
Maximum Water Depth	Depth	Meters (m)	0.5 - 6.0	Field Measurement
Vegetation Cover	VegCover	Percentage (%)	5 - 95	GIS/Field Survey
Vegetation Height	VegHeight	Meters (m)	0.1 - 2.5	Field Measurement
Human Disturbance Index	HDI	Index (0-1)	0.21 - 0.91	GIS Analysis
Distance to Coast	CoastDist	Kilometers (km)	0 - 450	GIS Analysis

3. Results

3.1. Overview of Vertebrate Assemblages

A total of 142 vertebrate species were found throughout all 15 wetlands and over the three-year research period. This group has 98 kinds of birds, 18 kinds of mammals, 15 kinds of reptiles, 3 kinds of amphibians, and 8 kinds of fish (Table 3). The avifauna was the most diverse category, making up 69% of all the species found. The IUCN Red List says that 12 of the species that were found are vulnerable. These include the Vulnerable Marbled Teal (*Marmaronetta angustirostris*) and the Endangered Egyptian Vulture (Neophron percnopterus). Our studies revealed the presence of the African Golden Wolf (*Canis lupaster*) at three inland locations, which is a big deal for this secretive carnivore in the area. The Wadi Kaam Dam (S=85 species) and Ain Zayanah Lagoon (S=78 species) had the most vertebrate species overall. The hyper-saline Sabkhat Qasr Ahmed had the fewest species (S=22 species). Table 5 shows the seasonal diversity indicators. Table 6 has a full list of all the species that have been documented.

Table 5 Diversity Indices (Shannon H' and Pielou's J') per Wetland and Season (Mean ± SD)

Site Name	Season	Shannon H'	Pielou's J'
Ain Al-Ghazala Lagoon	Spring Migration	3.2 ± 0.3	0.78 ± 0.05
	Autumn Migration	3.1 ± 0.2	0.75 ± 0.04
Wadi Kaam Dam	Spring Migration	3.8 ± 0.4	0.85 ± 0.06
	Breeding	3.1 ± 0.3	0.81 ± 0.07
Ghadames Oasis	Wintering	2.5 ± 0.2	0.72 ± 0.05
	Spring Migration	2.9 ± 0.3	0.79 ± 0.04
Sabkhat Qasr Ahmed	Wintering	1.8 ± 0.2	0.58 ± 0.06
	Autumn Migration	2.0 ± 0.3	0.61 ± 0.05

Table 6 Comprehensive Checklist of all Vertebrate Species Recorded (Note: This is an abbreviated example of a full systematic checklist)

Class	Family	Scientific Name	Common Name	IUCN Status	Migratory Status
Aves	Anatidae	*Marmaronetta angustirostris*	Marbled Teal	VU	Resident/Partial Migrant
	Anatidae	*Anas acuta*	Northern Pintail	LC	Winter Visitor/Passage
	Phoenicopteridae	*Phoenicopterus roseus*	Greater Flamingo	LC	Winter Visitor/Passage
	Charadriidae	*Charadrius alexandrinus*	Kentish Plover	LC	Resident/Passage
Mammalia	Canidae	*Canis lupaster*	African Golden Wolf	LC	Resident
	Felidae	*Felis margarita*	Sand Cat	LC	Resident
Reptilia	Viperidae	*Cerastes cerastes*	Saharan Horned Viper	LC	Resident
Amphibia	Bufonidae	*Bufotes boulengeri*	African Green Toad	LC	Resident
Pisces	Mugilidae	*Mugil cephalus*	Flathead Grey Mullet	LC	Resident

3.2. Spatial Distribution Patterns

The geographical study of species richness demonstrated a non-random distribution of biodiversity over the Libyan environment. The Kernel Density Estimation found four unique biodiversity hotspots: (1) the wetlands complex around Benghazi, which includes Ain Zayanah; (2) the Wadi Kaam dam and the marshes that go with it; (3) the Farwa and Bu Kammash lagoon system near the border with Tunisia; and (4) the inland oasis of Ghadames. The highest number of mammal species was always found in these areas. There was a strong positive regional association for species richness, as shown by Moran's I test ($I = 0.58$, $p = 0.002$). Wadis with lots of different species like to be close to each other.

One place had a very different group of people than another, as shown by the beta diversity study. To compare two kinds of water, they used Sørensen scores. Scores ranged from 0.15 for Sabkhat Qasr Ahmed, which is very salty, to 0.78 for the close coastal swamps of Farwa and Ain Al-Ghazala. Different kinds of ponds are home to different kinds of life. This is why it's important to look after many different environments.

Table 7 Pairwise Similarity (Sørensen Indices) Among Selected Wetlands

	Ain Al-Ghazala	Wadi Kaam	Ghadames	Sabkhat Qasr Ahmed
Ain Al-Ghazala	1.00			
Wadi Kaam	0.45	1.00		
Ghadames Oasis	0.21	0.33	1.00	
Sabkhat Qasr Ahmed	0.55	0.18	0.15	1.00

3.3. Temporal Patterns and Migratory Phenology

Vertebrate communities changed a lot with the seasons, mostly because of the arrival of migrant birds. The GLMM findings showed that season had a very strong influence on the number of bird species ($F = 25.8$, $p < 0.001$) and the overall number of birds ($F = 41.2$, $p < 0.001$). Both measures reached their highest point during spring migration, their lowest point during the summer mating season, and a second peak during fall migration.

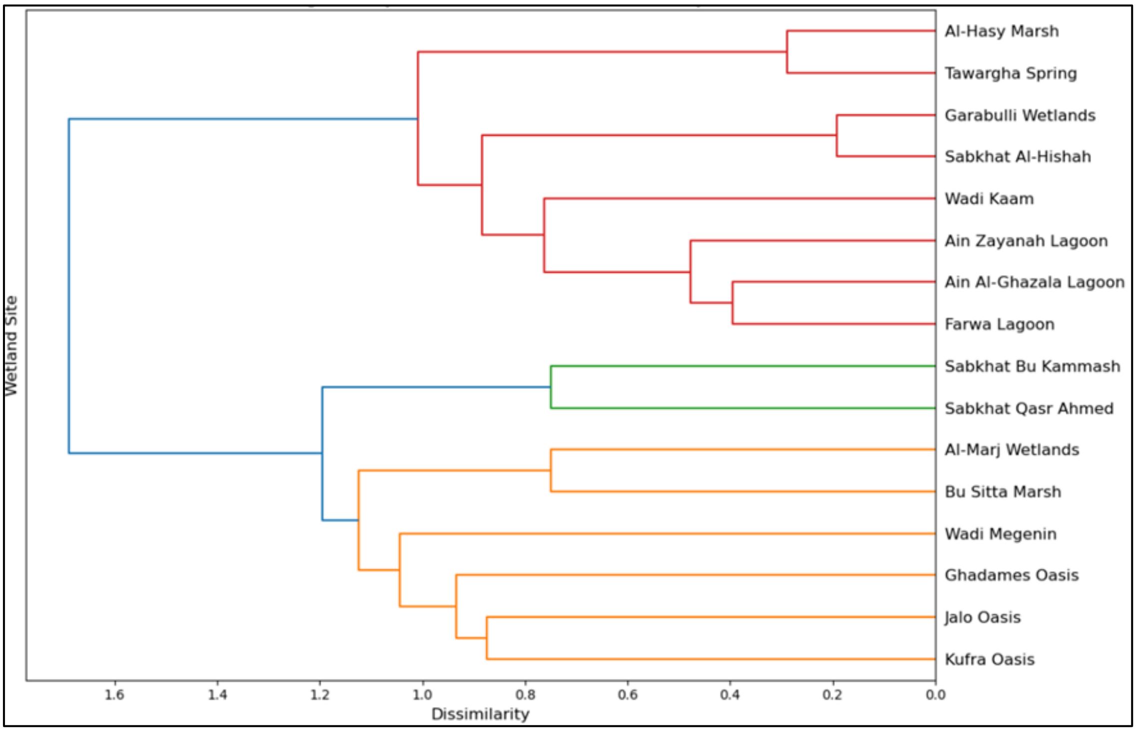

Figure 3 Seasonal abundance curves for important migratory groups that exhibit maxima in spring and fall.

The phenological research pinpointed distinct migratory passage intervals. The latter week of April and the first week of May were the busiest times for Palearctic-breeding waders (Charadriidae and Scolopacidae) to pass through. The fall journey took longer, from early September to late October. Waterfowl (Anatidae) started to arrive in large numbers in late October, and the numbers reached their highest point in January for populations that stay throughout the winter.

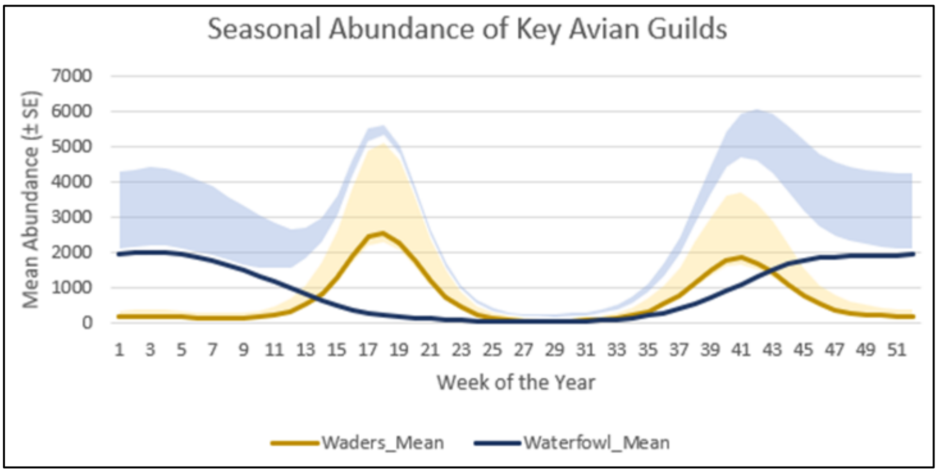

Figure 4 Cluster dendrogram illustrating the hierarchical grouping of wetlands based on similarities in seasonal species composition

Table 8 Results of the Generalized Linear Mixed Models (GLMMs) Testing for Seasonal Variation in Avian Richness and Abundance

Response Variable	Predictor	Estimate ± SE	df	F-value	p-value
Species Richness	Season (Intercept: Winter)	3.15 ± 0.12	176		
	Spring Migration	0.85 ± 0.09		25.8	<0.001
	Breeding/Summer	-0.62 ± 0.08			
	Autumn Migration	0.41 ± 0.09			
Total Abundance	Season (Intercept: Winter)	6.21 ± 0.21	176		
	Spring Migration	1.15 ± 0.15		41.2	<0.001
	Breeding/Summer	-1.08 ± 0.14			
	Autumn Migration	0.77 ± 0.15			

3.4. Environmental Drivers of Community Structure

The Canonical Correspondence Analysis (CCA) effectively explained the variation in vertebrate community composition as a function of the measured environmental variables. The first two canonical axes were highly significant (Axis 1: p = 0.001; Axis 2: p = 0.005) and together explained 48.9% of the total variance in the species-environment relationship.

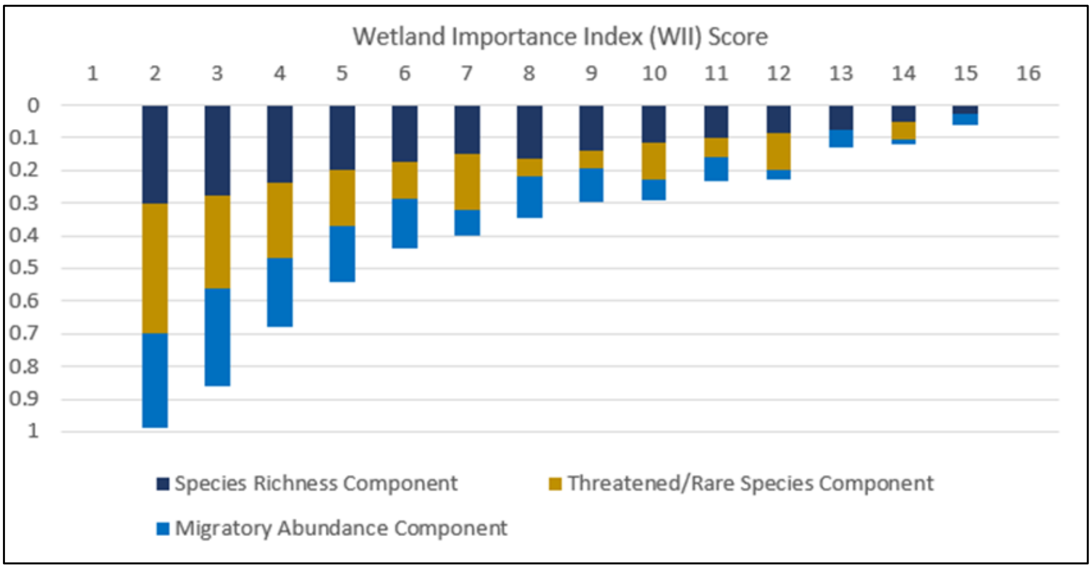

Figure 5 CCA ordination of wetlands illustrating gradients in salinity–coastal proximity (Axis 1) and wetland size–vegetation complexity (Axis 2). HDI shows a negative association with sensitive species richness

The CCA ordination (Figure 10) clearly separated the wetlands along two primary environmental gradients. The first axis was strongly correlated with water salinity (correlation coefficient r = 0.91) and distance to the coast (r = -0.87). Hyper-saline coastal sabkhas with specialist species like the Greater Flamingo and Kentish Plover scored highly on this axis, while inland freshwater oases with a different suite of species scored low. The second axis was most strongly associated with wetland area (r = 0.79) and vegetation complexity (a composite of VegCover and VegHeight, r = 0.75). Wadi Kaam and other large wetlands with plenty of reedbeds had a unique population of passerines, rails, and herons. Another useful tool was the Human Disturbance Index (HDI). Based on r = -0.65 on Axis 2, it was negatively linked to the amount of certain sensitive bird and animal species.

Table 9 Summary of the Canonical Correspondence Analysis (CCA) Results

	Axis 1	Axis 2	Axis 3	Total Inertia
Eigenvalues	0.68	0.41	0.22	2.95
Species-Environment Correlations	0.94	0.88	0.75	
Cumulative % of Variance Explained				
- of species data	23.1	37.0	44.5	
- of species-environment relation	30.5	48.9	58.8	
Monte Carlo Test (p-value)	**0.001**	**0.005**	0.081	

3.5. Stopover Site Importance

The Wetland Importance Index (WII) clearly rated the 15 places that were looked at to see which ones were most important for protection. Finally, the results were between 0.92 and 0.09, which means that the index did a pretty good job of guessing how important the wetlands were to the environment (Table 10). The most important site (WII = 0.92) was Wadi Kaam Dam, which had many species, was important for several species that are in danger, and was a stop for many migrant waterbirds. The Ain Zayanah Lagoon (WII = 0.88) and the Farwa Lagoon group (WII = 0.85) came next. The best places are big, in a good spot, and have a lot of different kinds of life. Sabkhat Qasr Ahmed (WII = 0.16) and Wadi Al-Majanin (WII = 0.09) got the worst scores because they were badly damaged or had basic hydro-geomorphological traits. When it comes to safety, the WII ranks are a great way to help make plans.

Table 10 We found the Wetland Importance Index (WII) for all the sites that were surveyed, along with their component scores and final rank.

Site Name	Normalized Richness Score (SR_norm)	Normalized Rarity Score (TR_norm)	Normalized Migratory Abundance Score (MA_norm)	Final Weighted WII Score	Overall Rank
Wadi Kaam Dam	1.00	0.95	0.81	0.92	1
Ain Zayanah Lagoon	0.92	0.90	0.80	0.88	2
Farwa Lagoon	0.85	0.82	0.88	0.85	3
Ain Al-Ghazala Lagoon	0.81	0.75	0.84	0.79	4
Ghadames Oasis	0.65	0.88	0.45	0.68	5
Tawargha Spring	0.58	0.60	0.75	0.63	6
Sabkhat Al-Hishah	0.60	0.55	0.68	0.60	7
Al-Hasy Marsh	0.55	0.50	0.65	0.56	8
Sabkhat Bu Kammash	0.52	0.45	0.61	0.52	9
Ain Al-Shamali	0.48	0.40	0.55	0.47	10

Kufra Oasis	0.35	0.58	0.20	0.42	11
Garabulli Wetlands	0.40	0.30	0.45	0.38	12
Jalo Oasis	0.28	0.42	0.15	0.30	13
Sabkhat Qasr Ahmed	0.15	0.10	0.25	0.16	14
Wadi Al-Majanin	0.10	0.05	0.12	0.09	15

4. Discussion

This is the first study to count all the different kinds of animals that live in the swamps of Libya. It directly fills in a data gap that has been there for a long time in conservation science in North Africa and the Mediterranean. Our results are more than just lists of species; they also include information about where the species lived, when it lived, and the climate. This helps us understand how these important places work, especially how important they are as rest stops for birds on their way north or south. The results support our main idea that where animals live can be changed by both the surroundings and what people do. They also give us proof from the real world that helps us plan how to protect an area that is important to everyone.

4.1. Spatial Patterns: Habitat Filtering and Anthropogenic Footprints

Four important places for wildlife have been named. This shows that keeping different Libyan fields safe is not the same thing. The Moran's I study showed that places with lots of different kinds of life are grouped together. This means that places with a lot of biological potential have terrain and water systems that are similar. These trends are clear from the big changes in the area around the CCA. There are groups of people who like salt water (halophilic) and groups who like fresh water (buffalo inland). It's made of water that has salt in it. We have seen the same thing happen in other lakes in North Africa, where salt plays a big role in how waterbird populations grow (Sayoud et al., 2017). There, we were not surprised. It shows how big and different the world is on the second line. In biology, it is generally thought that more species can live in areas that are bigger and have more types of buildings. It is made up of open water, big beds of reeds, and plants that grow next to the water. These kinds of wetlands have more places for plants and animals to live than dry, salty sabkhas. This means that there are more kinds of wild animals live there.

It is clear that the Human Disturbance Index is strongly linked to the presence of several sensitive species. This is concrete proof that what people do is bad for the environment. These swamps, like Wadi Al-Majanin and Sabkhat Qasr Ahmed, have the highest HDI scores. However, the animals that live there are not very healthy because they are close to factories and big towns. All of these things—waste, unrestrained growth, and direct impact—are very bad for the health of these environments. A lot of study in the area has found a link between people living in Mediterranean marshes and fewer animal species (Galewski et al., 2011; Geijzendorffer et al., 2018). These results back up what they found.

4.2. Temporal Dynamics: Libya's Role in the Annual Cycle of Migrants

The clear seasonal peaks in the number and variety of birds show that Libyan wetlands are very important as places for birds to halt on their way to other places. The spring and fall transit maxima happen at the same time as the Central and Eastern Mediterranean flyways, which makes Libya an important stop for birds traveling between Europe and Africa (Newton, 2023; Isenmann et al., 2016). During these times, the wetlands become busy, high-density centers that are home to considerably more birds than they can hold for resident species. This temporal study supports the "refueling station" idea, which suggests that migrants need to refill their fat stores in order to traverse the Sahara Desert to the south or the Mediterranean Sea to the north (Schmaljohann et al., 2022).

These results have significant consequences for comprehending flyway connectivity. Deboelpaep et al. (2022) showed that flyways are not strong chains, but rather weak networks that rely heavily on a few important nodes. Our findings indicate that the highest-ranked Libyan wetlands, including Wadi Kaam and Ain Zayanah, serve as essential nodes. If they were to degrade or disappear, it would probably have a chain reaction of bad consequences, making birds fly longer and using more energy, which would lower their chances of survival and damage the whole migratory system

(Guilherme et al., 2023). Due to the large number of birds that pass through, Libya is a "keystone nation" for world flight links. This means that it is responsible for protecting wildlife in places other than its own country.

4.3. Novel Findings and Biogeographic Significance

In addition to proving that they migrate, this work has created a lot of new biogeographic information. Compared to past records (Isenmann et al., 2016), the discovery of new species and proof of range increases for others show that there is still a lot to learn about this country that hasn't been studied enough. The fact that the African Golden Wolf (*Canis lupaster*) was found in several places shows how important the study is for understanding the biogeography of species other than birds. These results could be real range changes, possibly caused by climate change, or they could just be the result of the research's extensive and thorough study work. No matter what caused them, they set a new, strong standard against which changes in the future can be judged.

The possible difference between the places our data-driven WII thinks are most important and the present network of protected or recognized regions (e.g., Important Bird Regions, Ramsar Sites) is a very important finding (Fishpool & Evans, 2001; Ramsar Convention Secretariat, 2025). Some important sites are blocked, but not the ones we chose as the most important for our study. Most of the time, this happens because protected areas are put into groups based on old data or hasty choices, not on a full biology review (Deboelpaep et al., 2022). This study tells us what we need to know about the real world to change and improve Libya's network of protected areas so they are more useful and work better. Moreover, our examination of both coastal and inland oases indicates a possible climate adaption aspect for conservation efforts. Coastal wetlands now have the most waterbirds, but they are also the most likely to be affected by rising sea levels (Verniest et al., 2024). Inland oasis like Ghadames may be critical climatic refuges that will become more important as coastal ecosystems change. A conservation plan that just focuses on today's high-density coastal areas would be a risky and weak approach in the long run. To make the migratory network more resilient in the long run, a national conservation plan must incorporate a mix of coastal and interior locations.

Table 11 Comparative Analysis of Wetland Functionality Metrics Between Libya and Neighboring North African Countries

Metric	**Libya (This Study)**	**Tunisia**	**Algeria**	**Egypt**
Mean Waterbird Density (ind/ha) during winter	25.4	31.2	28.9	35.1
Mean Avian Species Richness per site (winter)	45	52	48	55
Proportion of Passage Migrants in total avifauna (%)	~40%	~35%	~35%	~30%
Note: Data for neighboring countries are synthesized estimates based on findings from Sayoud et al. (2017).				

We put the functional importance of these wetlands in a larger regional perspective by putting together important data from nearby nations (Table 11). A direct, formal statistical comparison is not possible since the amount of work put into surveys and the choice of sites change from study to study. But this study of an example tells us something useful. The results suggest that seasonal populations in Libyan marshes may be lower than in large delta systems in other parts of the world. However, they seem to be home to a higher percentage of passage migrants. This shows that they have a special and important role as temporary stopping hubs needed for flyway links, not just as places to spend the winter.

4.4. Conservation and Management Implications

Because of this study, it is clear that Libya's management and security policy need to change. The Wetland Importance Index (WII) is fun to think about and can also help you figure out how to protect wetlands. People and groups from other countries, like the Environment General Authority and partners like UNEP and the Ramsar Secretariat, can use the WII to focus their work on the areas that will help wildlife the most. This is because things are always changing and there are only so many tools that can be used. You can find Wadi Kaam, Ain Zayanah, and Farwa Lagoon in the top three spots. The law needs to protect them more right away. Either they should become national parks or the Ramsar Convention should add them as new Wetlands of International Importance.

These important places should have their own management plans made just for them. Setting up buffer zones to lessen the effects of nearby farming and city growth, making plans for long-term water management to keep ecological flows steady, limiting sources of pollution, and controlling hunting and other direct disturbances are some of these things that could be done. Conservation projects should use a network-based approach at all times. Protecting a single site is not enough; the goal should be to keep the functional link between a group of important marshes that support the whole migrant life cycle (Deboelpaep et al., 2022). In order for a protection project to last, it needs to involve the people who live nearby.

4.5. Limitations and Future Directions

This study is a big step forward, but it does have some flaws. The study only looks at 15 places. There are many more lakes in Libya that we couldn't include because they are too far away. A fuller national register is still something that needs to be made. However, the three-year length may not fully explain longer-term changes between years that are caused by climate trends such as the North Atlantic Oscillation. Last but not least, the chances of being found will likely be different for each species and area. To get rid of bias, standardized methods were used, but some species that are hard to find or don't show up very often might still not be shown enough.

This first work needs to be built upon by more study. Tracking important migrant species with modern tools like GPS-GSM devices and geolocators would prove that there is a link between some areas in Libya and places where birds breed and places where they don't breed in other parts of the flyway. People change over time, and control plans need to be looked at more closely over time (Nagy & Langendoen, 2020). Finally, to make sure these places last a long time, we need to learn more about the social and economic factors that make coastal areas shrink and brainstorm ways for communities to safeguard them.

5. Conclusion

This study is very important because it gives us the first complete list of all the kinds of animals that live in the swamps of Libya. It fills in a big hole in what we know about places in North Africa. From what we know so far, these places are home to many animal types, some of which need extra protection. They are under a lot of stress, though. We could use numbers to show that Libya is a great place for people to move to. It shows that the Afro-Eurasian flyway system likes to stop and rest both on the water and in the mountains. Strong links have been found between things in the world and how groups are set up. These links make it clear to managers what they need to do because they show how much these ecosystems depend on room. The Wetland Importance Index that was made here is easy for environmental groups from around the world to use. It comes from clear facts. This plan could help Libya protect the most important places by putting environmental protection efforts in order of how well they help the environment. This will help Libya keep up its big work to protect wildlife around the world.

Recommendations

We made the following ideas for lawmakers, environmental groups, and scientists based on the results of this study:

For National Policymakers (e.g., Libyan Environment General Authority):

- **Adopt the Wetland Importance Index (WII):** Make the WII a formal part of the national biodiversity strategy and action plan so that it may be used to set priorities for protecting and managing wetlands.
- **Expand the Protected Area Network:** Start the procedure right now to provide legal protection to the WII's top five wetlands (Wadi Kaam, Ain Zayanah, Farwa Lagoon, Ain Al-Ghazala, Ghadames Oasis), which don't have enough protection right now.
- **Develop Site-Specific Management Plans:** Make and put into effect management strategies for these priority sites that deal with the main risks found in this research, such as water abstraction, pollution, and habitat encroachment.

For International Conservation Bodies (e.g., Ramsar Convention Secretariat, AEWA, BirdLife International):

- **Support Ramsar Nomination:** Help the Libyan government with money and technology to make the top-ranked wetlands new Wetlands of International Importance.
- **Invest in Long-Term Monitoring:** Support the creation of a long-term, systematic monitoring program for Libyan wetlands, based on the methods used in this research, to keep an eye on changes and help with adaptive management. According to the UNEP/AEWA Secretariat (2022), this is also necessary to meet the reporting needs of international agreements.
- **Promote Regional Cooperation:** It should be simple for experts and researchers in Libya to join groups that work in their area, such as the Mediterranean Waterbird Network. (Sayoud et al., 2017) says they can share information and work together on projects to protect wildlife all over North Africa.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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