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Research Article

Integrating Avian Diversity and Long-Term Population Trends Across Pakistan's Ramsar Wetland Network for Conservation

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Abstract | Pakistan's Ramsar wetlands are significant for both their own ecosystems and the Central Asian Flyway because they are vital hubs for bird migration. However, there are presently few long-term evaluations of the network as a whole concerning changes in bird populations. In order to examine spatiotemporal patterns and their conservation implications, the current study compiles bird abundance data from 19 Ramsar wetland sites in Pakistan that were gathered between 1990 and 2024. From 741,721 individuals in 1990 to less than 300,000 in the early 2000s, the annual total abundance of birds fell sharply. Thereafter, there was a period of erratic partial recovery, with 457,388 individuals by 2024. The significant contributions to the overall bird abundance came from the interior lakes and river barrages. In the peak years, Chashma Barrage alone contained around 250,000 birds; nevertheless, throughout time, it had a diminishing tendency with significant inter-annual variability. While coastal and delta wetlands, especially the Indus Delta and Miani Hor, experience population losses of more than 50% during the research period, inland lakes, such as Keenjhar and Haleji, maintained relatively constant population swings that frequently approached 100,000 individuals. Wetlands in moisture-deficient regions contained fewer birds overall, but they were seen to live longer. The study shows striking spatial variations and shifting non-linear temporal patterns, which were most likely brought about by changes in water flow, habitat degradation, and the impact of management approaches at specific locations. A solid baseline for adaptive management, the preservation of Ramsar ecological character, and flyway-scale conservation planning has been established because this is the first time that the change in bird population in the entire wetland network of Ramsar sites in Pakistan has been evaluated in an integrated long-term manner.

Novelty Statement | This study presents the first comprehensive, multi-decadal assessment of bird population data across Pakistan's entire Ramsar wetland network, connecting long-term patterns to wetland characteristics and the significance of conservation. The system uses a network-based framework which supports Ramsar treaty obligations and Central Asian Flyway conservation goals to create a national framework that manages wetlands through adaptive methods instead of studying individual locations or conducting research for limited time periods.

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Introduction

Worldwide as well as regional assessments show that the decline of waterbird populations is becoming a wider phenomenon, the case of long-distance migrants and habitat specialists is particularly pointed out (Wetlands International, 2021; BirdLife International, 2023). Wetlands reveal their status as the planet's most productive and biologically diverse habitats that offer a variety of ecosystem services, including water purification, flood regulation, carbon storage, and wildlife habitats (Mitsch and Gosselink, 2015). Despite their significant ecological and socio-economic functions, wetlands continue to be greatly affected by human activities and are thus among the globally most endangered ecosystems. It has been projected that more than a third of global wetlands (35%) have disappeared since 1970, mainly due to changes in land use, pollution, water abstraction, and climate-related alterations in the hydrology (Davidson, 2014). In this regard, birds most especially, waterbirds are considered the best indicators for assessing wetland health as their population size, distribution and diversity quickly reflect the changes in habitat quality and water supply (Green *et al*., 2017). One of the main characteristics of migratory waterbirds is a strong dependence on wetland networks rather than isolated individual habitats. During their yearly cycle, the birds use different wetlands for breeding, non-breeding, staging, and refueling, which often cross several countries and continents. Thus, the degradation or disappearance of essential wetlands can cause an entire migratory route to be affected (Haig *et al*., 1998; Runge *et al*., 2014). The paradigm shift in conservation has turned from protecting single sites to the more holistic approach of conserving connected wetlands throughout the functional landscape by maintaining and enhancing their connectivity, redundancy, and complementarity perspectives.

Ramsar Convention on Wetlands, signed in 1971, is the main global framework for wetland protection and their wise use. One of the most important aims of the Convention is the designation and effective management of Wetlands of International Importance (Ramsar sites), lots of which are recognized for their huge waterbird populations, among other ecological reasons (Ramsar Convention Secretariat, 2016). The monitoring of bird populations at Ramsar sites serves two essential purposes i.e. it enables scientists to study ecological patterns and processes while protecting the site's natural environment and verifying compliance with international conservation treaties. Pakistan has a very important role in the migration of birds from north to south and vice versa as it lies along the Central Asian Flyway, one of the major routes for birds and is linked with breeding in northern Eurasia and wintering in South Asia, the Middle East, and Africa (Kirby *et al*., 2008; BirdLife International, 2023). The extremely diverse wetlands of Pakistan are the reason for the millions of migratory birds using this flyway as their stopover and wintering area every year. The country boasts of a variety of wetland types like huge freshwater lakes, riverine barrages powering the Indus River system, coastal lagoons, deltaic and saline wetlands, as well as freshwater wetlands in dry and semi-dry lands. More than 20 Ramsar sites have been designated by Pakistan which are home to the country's most vital wetland ecosystems.

Pakistan's wetlands are under the increasing pressure of human activities despite their global importance. The rapid growth of the human population together with increases in agricultural production has caused the Indus Basin to suffer extensively from water pollution and drought (Gleick, 2003). Besides climate change is one of the factors that make the situation worse by changing the amount and distribution of rainfall, making extreme hydrological events more common, melting glaciers more rapidly, and causing the rise of the sea level in coastal areas (IPCC, 2021). All these factors threaten the existence of wetlands and at the same time their connectivity through which migratory birds might get access to the entire country's wetlands which might be disastrous for them.In South Asia, various studies have reported the decline of waterbirds in relation to certain wetlands which were often due to habitat degradation and changes in water regimes. In Pakistan, on the one hand, site-level surveys and government censuses have produced data that are significant; on the other hand, comprehensive analyses that cover the entire Ramsar network so as to integrate the long-term avian population trends have yet to be completed. Such integration is vital in order to know whether the observed changes are the result of localized disturbances, wider regional pressures, or processes across the flyways. The long-term ecological datasets are very useful in answering these questions since they show both the gradual directional trends and the occasional fluctuations caused by the changing climate or management interventions (Magurran *et al*., 2010). Studies conducted over a short period of time might give an inaccurate picture of the state of the population because they might occur at the same time or overlap with very good or very bad conditions, whereas multi-decadal datasets can give an indication of the ecosystem developments that are more reliable. Furthermore, the long-term data support the comparison of different types of wetlands and thereby the discovery of their different environmental change sensitivities and resilience levels.

Wetland conservation is another critical aspect that deals with different types of wetlands having different reactions to human and climate pressures. Typically, large freshwater lakes and reservoirs are the habitats with the highest number of waterbirds, but their presence is greatly influenced by water management decisions. Coastal and deltaic wetlands are undergoing a series of negative changes due to fewer freshwater inflows, cutting down of mangroves, and rising sea levels (Davidson, 2014). On the other hand, arid and semi-arid wetlands, though frequently little in size and less noticeable, might serve as vital refugia for specialized bird species under the conditions of increasingly extreme climates (Finlayson *et al*., 2018). To come up with proper adaptive and specific conservation strategies, it is necessary to have a thorough understanding of the different dynamics. In this context, combining avian diversity and long-term population trends across the Ramsar wetland network in Pakistan is a very effective tool for evaluating the health and effectiveness of conservation measures. This study, by looking at the variations over time across the different inland freshwater, riverine, coastal, and arid-zone wetlands over a period of more than three decades, aims to: (i) evaluate the long-term trends in avian population across the Ramsar network in Pakistan; (ii) point out the wetlands that are strongholds of bird populations or present relative resilience in the face of environmental change; and (iii) indicate the role of the trends observed in the network-based wetlands conservation and flyway-scale management.

Materials and Methods

Study area

There are 19 Ramsar sites in Pakistan (Figure 1), totaling 1,343,807 hectares (Ramsar, 2021). For this study, all 19 Ramsar sites in the current study area were selected. The research was carried out in 19 Ramsar Wetlands of Pakistan that were designated as International Importance and are shown in the map (Figure 1). Their ecological settings are quite varied as they include inland freshwater lakes and reservoirs (like Keenjhar Lake, Haleji Lake), river wetlands and those associated with barrages along the Indus River System (such as Chashma Barrage, Taunsa Barrage, Indus Dolphin Reserve), coastal and marine wetlands (like Indus Delta, Miani Hor, Astola Island), and arid to semi-arid wetlands (like Uchhali Complex, Deh Akro-II Desert Wetland Complex). All these wetlands in total depict the different major habitat types through which both migratory and resident waterbirds along the Central Asian Flyway move.

Wetland classification and analytical framework

As a part of the comparative analysis, the wetlands were classified into four main types: inland freshwater wetlands, riverine and barrage wetlands, coastal and marine wetlands, and arid to semi-arid wetlands. The analyses were mainly directed towards the descriptive assessment of the long-term trends, interannual variability, and the relative contributions of individual sites and wetland types to the

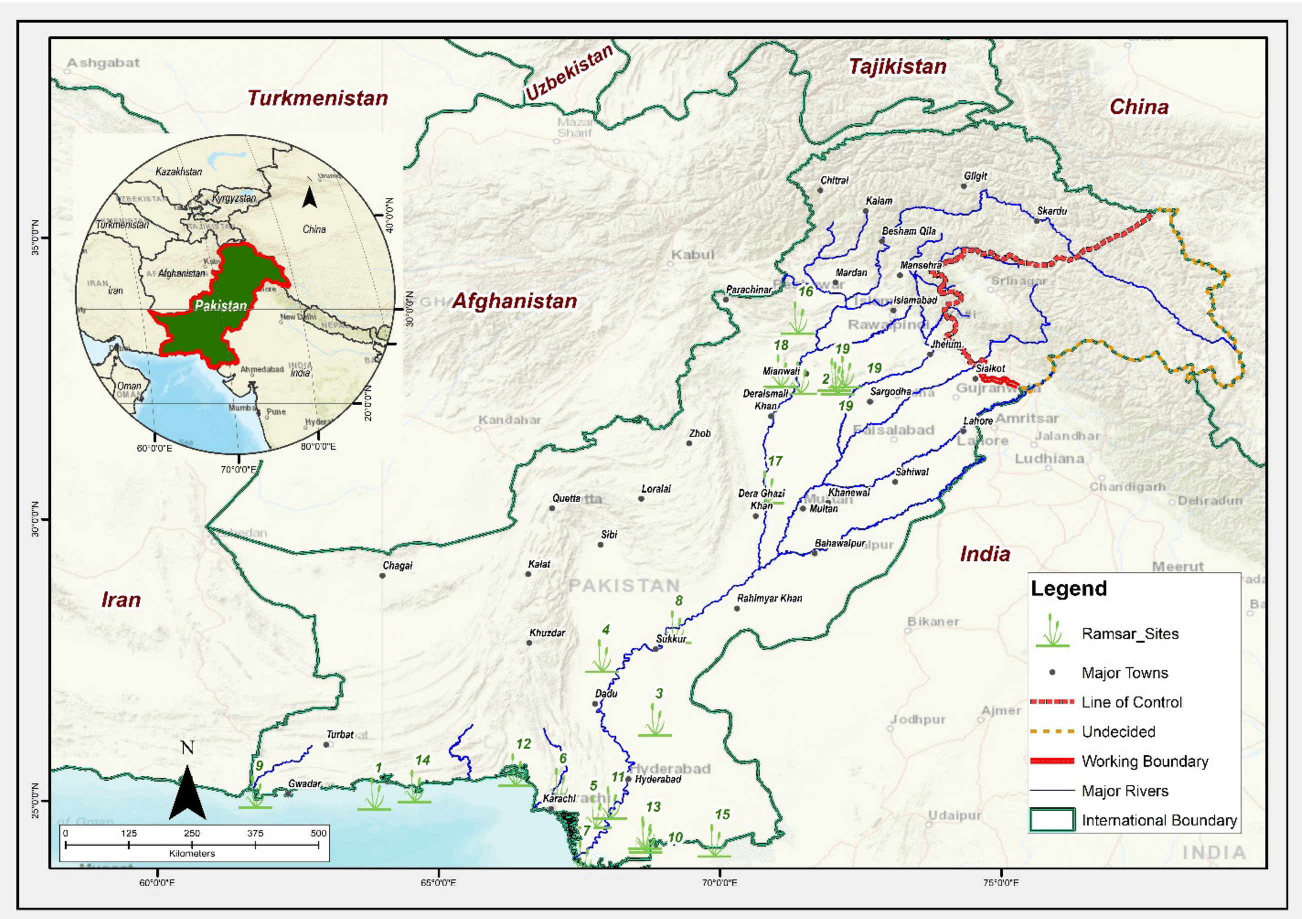

Figure 1: Ramsar Sites in Pakistan.

1, Astola Island; 2, Chashma Barrage; 3, Deh Akro-II Desert Wetland Complex; 4, Drigh Lake; 5, Haleji Lake; 6, Hub Dam; 7, Indus Delta; 8, Indus Dolphin Reserve; 9, Jiwani Coastal Wetland; 10, Jubho Lagoon; 11, Keenjhar Lake; 12, Miani Hor; 13, Nurri Lagoon; 14, Ormara Turtle Beaches; 15, Runn of Kutch; 16, Tanda Dam; 17, Taunsa Barrage; 18, Thanedar Wala Game Reserve; 19, Uchhali Complex-Uchhali Lake-Khabbaki Lake-Jahlar Lake.

national bird population. Due to the irregular temporal coverage and gaps in the data, the formal time-series modelling was not applied; instead, the study relied on the powerful interpretation of long-term directional patterns (Magurran *et al*., 2010). Wetlands function as natural water barriers, nurseries for fish, and breeding grounds for a wide range of animals, some of which are even listed as endangered. The Ramsar Convention Secretariat (2016) defines marine wetlands as coastal wetlands that consist of intertidal areas which include seagrass beds, coral reefs, and the tidal flats that are being covered and uncovered by the oceanic tides, plus the permanent shallow marine waterways such as sea bays and straits. The list of wetlands can be found in Supplementary Table S1.

Data sources and temporal coverage

Avian population data from 1990 to 2024 were collected from various sources including national mid-winter waterbird censuses, provincial wildlife department surveys, Ramsar site monitoring reports, and institutional datasets. Surveys were usually conducted in the winter season (December–February),which is the time of maximum migratory waterbird abundance in Pakistan. For each location and year, total bird abundance (all species combined) was obtained to enable consistent comparison across sites and decades. The years for which there was no reliable or verifiable data were considered as missing values and were not included in the analysis.

Field methodologies for bird population assessment

The total number of birds were observed through methods as per international bird monitoring guidelines, such as the standardized systems for the collection of standardized data (e.g. Bibby *et al*., 2000; Ramsar Convention Secretariat, 2016) This data was gathered throughout the wetland area of interest to ensure adequate and accurate sample sizes for each specific species. Especially for big and open wetlands like barrages and huge lakes, total counts were employed. The observers thoroughly scanned the whole wetland area from the shoreline using binoculars and spotting scopes, and the method of total counting is mainly through birds congregating and estimation due to high detection probability. Point counts were used in the marshes and lagoons that have an uneven vegetation structure, including swamps. The point counts with the fixed-radius were done for standardized time intervals, with all birds seen or heard recorded. To capture spatial variation in avian abundance, the study area included multiple points distributed across representative habitat types.

The line transect surveys were applied to wetland margins, banks, and riverine corridors. The observers documented birds that were along the predetermined routes, whether on foot, in a vehicle, or by boat, depending on the conditions of the site. The method of line transect is very effective in the sense of being able to determine the relative abundance and distribution of birds across large or elongated wetland areas (Buckland *et al*., 2001). Occasionally, at some of the big or hard-to-reach sites, aerial counts or reconnaissance counts were done on an opportunistic and supplementary basis to increase coverage, especially for large flocks in remote locations.

Survey timing and observer considerations

Surveys were carried out by trained wildlife staff and ornithologists who were proficient in waterbird identification and census methods. Counting was usually done in the early morning or late afternoon during good weather conditions to facilitate the detection of birds. Counting methods were coordinated to prevent double counting, and the movement of flying flocks within the survey area was recorded only when it was clear (Bibby *et al*., 2000).

Data standardization and quality control

Total avian abundance per site per year was created by aggregating species-level observations. The counts were expressed as the absolute number of individuals, which corresponded to Ramsar and flyway-scale monitoring goals that focus on population thresholds and congregation sizes (Wetlands International, 2021). Records were compared for consistency, and unusual values were checked against original sources whenever possible.

Data standardization and survey effort

To ensure comparability of avian data across sites and time periods, a standardized approach to effort correction and data harmonization was adopted. To account for minor variations in sampling duration or spatial coverage, raw abundance data were converted into a census index (birds per hectare) by dividing the total individuals observed by area of the Ramsar site in hectare (Bibby *et al*., 2000). This standardization allows for meaningful comparisons of population density across sites and time.

While effort-adjusted indices were used for most density comparisons, raw total abundance was retained for species richness estimation and presence-absence analyses. Raw totals are appropriate for these metrics as species richness is less sensitive to moderate effort variation once detection probability is saturated (Gotelli and Colwell, 2001). This dual approach aligns with standard ecological survey practices (Bibby *et al*., 2000).

Ethical considerations and limitations

The entire survey process was non-invasive and in accordance with the laws regarding wildlife in the respective countries. The researchers were able to use only secondary data from existing monitoring programs, and birds were not handled or disturbed at any point. The limitations of the study included the different survey efforts and observers' experience across the decades; however, the application of the standardized census methods and the attention to large, visible waterbird populations have made the broad-scale trend inference robust.

Results

Temporal patterns in avian abundance across ramsar wetlands

The analysis of the assembled dataset (Table 1; 1990–2024) shows a considerable change in the total number of birds in Pakistan's Ramsar wetland network over time, thus indicating not only the environmental changes' impact but also the site-specific ecological dynamics operating within a wider regional context. The total annual number of birds reached a high point of more than 740,000 individuals in 1990; however, a drastic and gradual reduction followed during the late 1990s and early 2000s, which may be attributed to the combined impacts of hydrological changes, habitat loss, and mounting human activities in several wetlands. Selected years, notably 2010 and 2024, recorded the recording of subsequent partial recoveries; however, these rebounds were not uniform across sites and did not possess long-term stability, thus revealing the limited resilience of the system. The resulting non-linear population trajectories correspond with the trends observed for South Asian wetlands, where the interactions among climate variability, altered flow regimes, and human disturbance have given rise to complex and temporally heterogeneous avian responses (Amano et al., 2018; Wetlands International, 2023).

Temporal analysis

With the databases established in the initial years, altogether over an all-inclusive wetland and riverine barrage lists most significant sites with excessively high counts including Chashma Barrage, Haleji Lake, Keenjhar Lake, along with Jubho Lagoon. Such locations would harp on bygone days when one could feel oneself belonging to a congregation of birds gathered at these sites before taking their flight for wintering grounds on the Central Asian Flyway; large aggregations were quite common at these scenic sights, where Anatidae gathered in the hundreds of thousands at times, while sizeable congregations of shorebirds, a range of winged species, depended on water of this nature for drinking, along with various water-dependent taxa.

Only in the subsequent period during the 2000-2005 period was similar avian abundance even displayed. First, the total number of birds in 1990 hit around 742,000 and then started to decline in the late 1990s all the way through the early 2000s-present, pointing out system-wide chronic stress. The trend in bird numbers within the Ramsar wetlands of the country has not been the type that would have moved in a smoothly linear manner but has instead presented nuanced inter-annual fluctuations thereof in the intensive wetland use by birds; a large embodiment of it has also been evident during especially the changing hydrological conditions, altering episodic management used at sites, and climatic variability across the countries.

A partial recovery pulse appears around 2010 and again around 2024, but both of these sharp increases are ephemeral, so it does not reach to levels from the early 1990s, thus showing much limited long-term resilience from a network view. Bottom point on the time series, by 2016, declines to an abundance level close to 139,000 individuals, and will represent probably the exclusive denuded state of the Ramsar network during the study period. Perhaps it reflects several immense high throughputs wetlands' cumulative impacts. The meek upturn in the Figure 2 is shown after 2020, which implies signs of the initial stage of recovery. Nevertheless, this trend is uneven among some of the years and sites, and further demonstrates the existing vulnerability and uncertainty of a continuous rebuilding of these populations.

From the data visualization, the trend of declining abundance can thus be represented in the graph as a line with its declining intercept with maximum slope greater than 1.00. In other words, its maximum slope should be greater than 100,000 after canonical transformation of both the abscissa and ordinate.

The slope in Figure 2 looks flat because the regression estimates from the chosen metric all reliable data (r) which model residuals and predictor significance and the total model output-to-observed data relation. The slope stays the same even though these factors affect it. Moreover, the coefficient of determination for the above linear regression model shows 34.14% significance in the decreased abundance of avian population data in the period under consideration, which the following equation shows.

$$y= -8409.9x + 2\times10^{7}$$
$$R^{2}= 0.3414$$

The linear equation $y= -8409.9x + 2\times10^{7}$ establishes the negative trend on a monthly basis of the response variable (avian abundance). The interpretation of its slope, however, is that the mean change of bird abundance would be about -8409:9 persons per year.

Here, the coefficient of determination, $R^2 = 0.3414$, gives the percentage of variance in avian abundance over time that can be explained by the linear model, which amounts to about 34%. A model with this low-to-moderate explanatory power has a wide range of variation in which it is incorporated. It is only clear that there is declining trend still noticed with many of the variability, appearing to result from such non-linear dynamics as inter-annual hydrological intra-annual variability, episodic

Table 1: Temporal counts in Avian Abundance Across Ramsar Wetlands.

	1990	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2008	2010	2011	2012	2013	2015	2016	2017	2019	2020	2021	2022	2024
Astola Island					102							114							195	293			241	213
Ormara Turtle Beaches	527	113			97				4489							3331					2310			2411
Miani Hor	20393	14000	19000		20000	17000	12485						10393										13201	12781
Jubho Lagoon	69074	60000	67000		31000							44000					37000				31900		19000	44621
Nurri Lagoon	20500	21449		15000				19500						19074						12700			11250	12531
Indus Delta	17000	20415		22453	15000	15000		17600	19412		10,000			17000				4280				7223		6712
Runn of Kutch	12451	11240	17301			16520				7820				547				6700			3100		3200	4312
Jiwani Coastal Wetland	3100	4174	7000	5896		7785	960	1534	2150	4611	6418	6374				5600			4300			1450		6721
Chashma Barrage	257,377	67021	87000	95000	156000	180000	110000	97000	113600	121543	92300	127300	152134	46700	77340	25681	43100	45200	43000	16371	56000	29400	30,360	79681
Deh Akro-II Desert Wetland Complex	24618	17021				17000			12000		20,000					9870						6440	5215	17622
Drigh Lake	8000		4029	11423	12618	6387	10842	8485		600			23391						9320				6700	12712
Haleji Lake	100000	79144	150500			9300				76000			87100		93212	76439	100000		74298			91000	114000	96321
Hub Dam	64252		45000		13,128	14431	8374	2476	2638		19200		3447	280	1404		12931			43000			19200	34221
Indus Dolphin Reserve	24424	18250		5000				1956	4202			17200					12220				8320			12371
Keenjhar Lake	49612	45700		95000	110000	83000	67000	176000	84000	90000	197000	93000	215668	176500	119000	74000	36932	47000	46000	72800	45900	72100	56000	69321
Tanda Dam	6383		3100				414			3710				2297		5260		5410				2900		3451
Taunsa Barrage	34000	31250	27000	32000	32000	27000	3100	25000	26000	29000	11000	7930	35174	31000	55000	13690	12700	17000	14560	12700	10845	11320	6,283	17616
Thanedar Wala Game Reserve	9400	3300				4500	18881				9500		3200				6100							12860
Uchhali Complex	20610	19000	17000	14200	17000	16600	17000	19560	11900	12890	17900	15500	14,000	16,200	13210	15,361	15428	13342	19732	11000	16700	17,450	13,536	10910
Total	741721	412077	443930	295972	406945	414523	249056	369111	280391	346174	383318	311418	544507	309598	359166	229232	276411	138932	211405	168864	175075	239283	298186	457388

Links Researchers

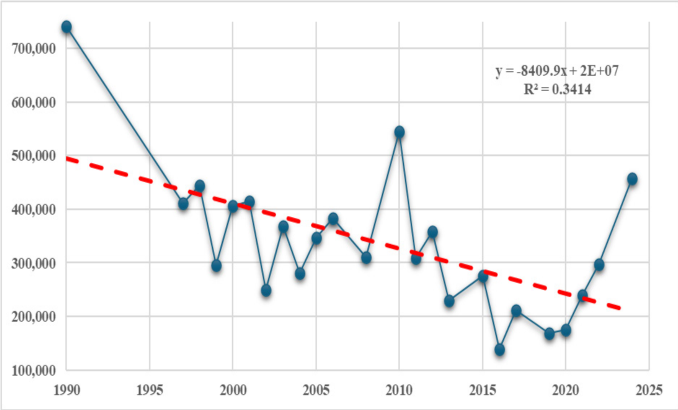

Figure 2: Temporal Patterns in Avian Abundance Across Ramsar Wetlands.

management actions, and site-specific ecological responses. As such, it seems that the broad outline of overall tendencies thus promoted by the regression model has been recorded over the past years, although this of course is not the only type of trend that can be said to be lasting in this region.

Site-level variability and wetland typology

Much variation was evident between types of wetlands. Riverine barrages, especially Chashma and Taunsa, exhibited a large and very definite extremely long duration and the highest counts. Singular Chashma Barrage bore the most substantial share in the national tallies for most years, the counts peaking at more than 250,000 individuals in the early 1990s. Nevertheless, an overall decline is punctuated with episodic recoveries that reveal variability. These are nicely demonstrated from one year to the next, amply indicative of the strong dependency of the barrage wetlands on the flow regime, time and volume of reservoir operations, and seasonal drawdown patterns as determined by the immediate implications for waterbirds habitat available; see Baalousha *et al.* (2019).

On the other hand, the lake reservoirs like Keenjhar and Haleji were found to be more stable in terms of time trends with greater fluctuations. In fact, Keenjhar Lake has been stocking up with an average ranging between 20,000-25,000 birds for over a decade, the peak having exceeded 200 000 birds through various years. The probably reason behind maintain its consistent large numbers of birds is because of its vast expanse, its stable hydrology comparatively and due to continued management attention because of its importance for water supply. The Haleji Lake is very much similar. Nevertheless, there had been periods of dwindling bird populations, leading to concerns of sensitivity exhibited to deteriorating water quality and eutrophication which were reported for most peri-urban wetlands (Mitsch and Gosselink, 2015).

Wetlands of arid and desert zones exhibited relatively smaller population sizes and included the examples of the Uchhali Complex and Deh Akro-II Desert Wetland Complex, which were impressive in terms of persistence over time. The Uchhali Complex displayed somewhat substantial inter-period variability but observed a consistent presence of birds in multiple decades. This stability indicates that saline and semi-arid wetlands are to be considered as refugia during drought years in the midst of dry environmental conditions (Sutherland *et al.*, 2004).

Coastal and deltaic wetlands

These coastal wetlands have extremely sporadic patterns like Indus Delta, Miani Hor, Jubho Lagoon, Astola Island and the Jiwani Coastal Wetland. Jubho Lagoon produced very high counts as compared to other coastal sites, especially in the early 1990's a general decline was observed and partial recovery over later years. Miani Hor also supported dense populations; however, the trend was downward in the long term. The decline occurs because people removed mangroves and stopped freshwater flow and coastal areas suffered from pollution according to IUCN Pakistan (2020). The Indus Delta experienced relative degradation throughout the study period which researchers demonstrated through a major decrease in bird populations that dropped from more than 20000 birds during the early 1990s to under 10000 birds in later years. The environmental degradation, delta system pollution made the area more saline and destroyed its intertidal zones result in decline of species. The total species count has decreased across all areas yet one island shows either stable or increasing species numbers during the past few years. The protected area designation caused nesting behaviors to change which led to different levels of human disturbance according to the research study.

Avian population trend analysis

Following graph (Figure 3) illustrates the overall bird population trend across Ramsar sites in Pakistan from the 1900s to the 2020s. The total bird population showed a significant decline over the decades, with the steepest drop occurring between the 2010s and 2020s. Phase/ decade wise description with respect to already classified wetlands as Arid to semi-arid wetlands, Coastal and marine wetlands, Inland freshwater wetlands, and Riverine and barrage wetlands are provided in detail in the following table (Table 2).

Species richness and census index

The research examined bird species diversity and population density throughout Pakistan's 19 Ramsar wetland sites by calculating species richness and bird census index. The study counted 1,025,657 individual birds which resulted in a total of 5,110 species found at all research locations. The study found wetlands to have substantial differences as certain locations maintained high species diversity but other sites showed remarkable bird populations despite their limited size. Table 3 presents site-wise data on species richness, total abundance, area, and calculated census index for each Ramsar site.

The study of bird populations in 19 Ramsar sites across Pakistan shows that different locations have distinct levels of species diversity and bird population density. The total number of species across all locations reached 5,110 species, with Indus Delta showing the most species at 342, followed by Keenjhar Lake with 325 species and Chashma Barrage which had 323 species. The coastal areas which included Astola Island and Jiwani Coastal Wetland and Ormara Turtle Beaches showed the least amount of species diversity. The Chashma Barrage site had the most birds with 257,800 individual birds, while Keenjhar Lake had 216333 birds and Haleji Lake had 150942 birds. The Astola Island site recorded its lowest bird population with 2024 individual birds. The census index (birds per hectare) provides critical insight into actual bird density, revealing that smaller wetlands often function as critical congregation hotspots. The Drigh Lake site, although it is the smallest area, shows a bird density which exceeds all other sites by large amounts at 150.58 birds per hectare. The highest bird densities at Drigh Lake reached 150.58 birds per hectare,

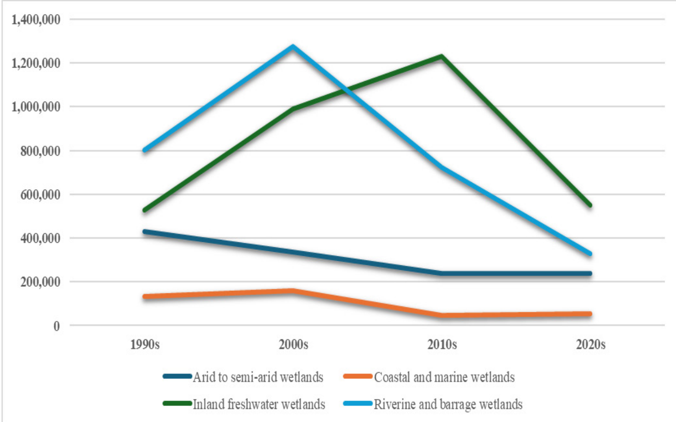

Figure 3: Trends in bird populations across different types of Ramsar sites in Pakistan.

Table 2: Decade wise temporal trend analysis of avian population across Pakistan's 19 Ramsar sites.

Wetland type	1990s → 2000s	2000s → 2010s	2010s → 2020s	Overall Trend (1990s→2020s)
Arid to semi-arid wetlands	-22.10%	-29.30%	0.10%	-44.8% (Steep Decline)
Coastal and marine wetlands	20.20%	-71.80%	17.30%	-60.3% (Collapse and Partial Recovery)
Inland freshwater wetlands	86.90%	24.50%	-55.30%	+4.1% (Peak and Crash)
Riverine and barrage wetlands	59.40%	-43.20%	-54.60%	-58.9% (Severe Decline)

Table 3: Biodiversity metrics across Ramsar sites in Pakistan.

S. No.	Ramsar site	No. of species (Species Richness)	No. of individuals (Count)	Area (hectares)	Census index (Count / Area)
1	Astola Island	67	2,024	5,000	0.4048
2	Chashma Barrage	323	257,800	34,099	7.5603
3	Deh Akro-II Desert Wetland Complex	238	26,106	20,500	1.2735
4	Drigh Lake	290	24,695	164	150.5793
5	Haleji Lake	320	150,942	1,704	88.5810
6	Hub Dam	313	65,761	27,000	2.4356
7	Indus Delta	342	22,518	472,800	0.0476
8	Indus Dolphin Reserve	298	24,813	125,000	0.1985
9	Jiwani Coastal Wetland	145	8,536	4,600	1.8557
10	Jubho Lagoon	288	70,110	706	99.3059
11	Keenjhar Lake	325	216,333	13,468	16.0627
12	Miani Hor	236	20,895	55,000	0.3799
13	Nurri Lagoon	291	22,479	2,540	8.8500
14	Ormara Turtle Beaches	170	7,109	2,400	2.9621
15	Runn of Kutch	288	18,226	566,375	0.0322
16	Tanda Dam	260	10,324	405	25.4914
17	Taunsa Barrage	293	35,498	6,756	5.2543
18	Thanedar Wala Game Reserve	306	19,889	4,047	4.9145
19	Uchhali Complex	317	21,599	1,243	17.3765
	Total	5,110	1,025,657	1,343,807	

while Jubho Lagoon showed 99.31 birds per hectare and Haleji Lake reached 88.58 birds per hectare. The Runn of Kutch site and Indus Delta site which have the largest areas recorded their lowest bird densities at 0.03 and 0.05 birds per hectare, respectively, which shows that these large wetlands support many species but their bird populations spread out through their entire territory. The research shows that both extensive biodiversity-rich wetlands and compact areas with dense bird populations play essential roles in protecting birds throughout Pakistan.

Methodological considerations and data limitations

The long-term trends cannot be interpreted without taking into account the variations in survey effort, timing, and methodology. The years with no data are nothing more than a signal of the lack of surveys, not the lack of birds. Nevertheless, the application of uniform census methods and continuous observation at crucial places allows a wide recognition of patterns. In the same manner, these difficulties are acknowledged by the waterbirds monitoring programs that are in place in numerous areas of the world for the long term (Gregory *et al*., 2004; Wetlands International, 2023).

Future deployment of new technologies such as drones and remote sensing will be of great help by providing consistency and extensive coverage. The Proof-of-Concept approach will be able to combine such methods with the traditional field counts and citizen science projects, thus not only increasing the quality of the national waterbird datasets but also facilitating the carrying out of more rigorous trend analyses (Hodgson *et al*., 2018).

Discussion

This research marks the first comprehensive, multi-decadal compilation of bird numbers in Pakistan's Ramsar wetland network, demonstrating a high degree of spatial diversity, temporal variations that are not very continuous, and different site responses to environmental and management factors. The analysis suggests that the wetlands of Pakistan still host numbers of waterbirds that are significant at the international level, but many sites show instability or decline in the long run which brings up the issue of conservation at the wetland scale and the affected flyway being one's ecological character.

Spatiotemporal variability in avian populations

The large temporal variations seen in the dataset are a sure sign of the dynamism of wetland ecosystems, which over the years have been affected by human activities and changes in climate. The national aggregate numbers of birds dropped sharply from the early 1990s to the early 2000s, followed by partial and sporadic recovery. Similar non-linear trends have been noted in the case of Southwest and Central Asia, where waterbird populations are quick to respond to changes in hydrology, habitat availability, and disturbance (Amano *et al*., 2018; Wetlands International, 2023). The lack of a general declining trajectory points to the fact that local factors and site-specific management play a decisive role in influencing population results.

On the east side of the country, only a few wetlands made a relatively big contribution to the overall national bird population. The river barrages and large inland lakes always had the highest populations, thus confirming their significance as wintering and staging sites for birds migrating along the Central Asian Flyway (Kirby *et al*., 2008). However, this concentration of birds comes with increased vulnerability as the degradation of a few key sites could have major repercussions for both national and flyway-level populations.

Riverine barrages: High productivity, high vulnerability

The riverine wetlands especially the Chashma and Taunsa Barrages boasting the top bird counts also had the most inter-annual variability. Such systems heavily rely on factors like flow regulation, reservoir drawdown, and sediment dynamics which in turn more directly affect the shallow foraging habitats used by waterbirds (Baalousha *et al*., 2019). It could well be that the areas of high abundance are the ones where the water levels are favourable and the prey is abundant while the sharp drops are coinciding with altered release schedules, excessive drawdown, or disturbance during the critical wintering times. The long-term downward trend at these barrages is a cause for concern as they have historically been important. Similar declines in controlled river systems have been reported from other parts of Asia, where disruption of hydrological cycle leads to decline in wetland productivity and alteration of food-web structure (Amano *et al*., 2018). Such results bring forth the very fact that barrage operation and water allocation planning need to consider ecological needs.

Inland lakes: Relative stability and management influence

Not very far from riverine wetlands, the Keenjhar and Haleji lakes, the important inland ones, exhibited a relatively greater long-term stability but the drops in the bird population were still seen from time to time. The continued presence of waterbirds at these lakes can be seen as a combined effect of physical size, huge lakeshore buffer area, and stable management due to their economic socially important gathering places importance. But, the drop in population from time to time indicates the lakes are possibly losing their appeal due to increased water quality degradation, eutrophication, and detrimental land-use changes in the watershed which are the most common threats to lake ecosystems globally (Mitsch and Gosselink, 2015).

These lakes have not only been the beneficiaries of active protection and monitoring but have also been the ones benefiting from it. Their continued significance underscores the need for long-term protection and monitoring. However, reliance on a few large wetlands may decrease the overall resilience of the whole system especially under the future climate and water-demand scenarios.

Arid-zone wetlands as refugia

Arid and semi-arid wetlands, comprising the Uchhali Complex and Deh Akro-II Desert Wetland Complex, had fewer birds but showed an impressive endurance across decades. Such wetlands are often the last refuge for species in the surrounding inhospitable landscapes, supplying essential resources during drought years or when conditions become unliveable elsewhere (Sutherland *et al*., 2004). Their relative stability underlines the value of conserving smaller and less noticeable wetlands as part of a larger network strategy.

Overall combined decline interpretation

The four-decade forward-and-backward path shows a cascade failure in the wetland ecosystems of Pakistan, where what seemed to be early victories covered up the main weak points of the system. The summary data gives a gloomy scenario of serial habitat deterioration: Waterbirds used to relocate to other wetland sources as one dry up and subsequently those remnants succumbed to the pressure of increased use together with the already existing environmental stress.

The pattern that makes the strongest point is seen by comparing the peak and the current states. Riverine and barrage systems dropped 59% from their peak, inland freshwater systems diminished 55% from their maximum, and coastal habitats are still 60% short of their 1990s levels. This is not just about population changes, but rather about all major wetland types having undergone fundamental reductions in habitat carrying capacity.

It can be argued that the simultaneous decline of the 2020s is a clear indication that regional environmental pressures, probably comprising climate change impacts, water scarcity, pollution build-up, and habitat fragmentation have become so strong that even the most resilient managed systems can no longer filter them. The information shows that the wetlands of Pakistan are now facing stress factors that are compounded and spread out through individual habitat management.

Implications for migratory waterbirds

Trends that were noted have considerable significance for the conservation of migratory waterbirds along the Central Asian Flyway. Decreasing numbers at major stopover and wintering sites might have an effect on the populations that reach all the way across the countries involved, due to the fact that migratory species have flyway-scale connectivity (Kirby *et al*., 2008). The fact that a very high percentage of the bird population in Pakistan is concentrated at just a few sites, for example, Chashma Barrage and Keenjhar Lake, demonstrates even more how susceptible the waterbird populations of Pakistan are to habitat degradation that is localized.

The long-term variable counts of waterbirds have also pointed to the necessity of a network of wetland areas that are diverse in function being maintained. The wetlands in the desert and coastal areas, which are not very large or significant, may still be able to serve as very important alternative habitats during years of bad conditions at the major inland wetlands. This view of the network of wetlands is in agreement with Ramsar principles that stress the total ecological value of wetland systems rather than that of isolated sites (Ramsar Convention Secretariat, 2016).

Although fewer birds are present in arid-zone wetlands, the combined effect of these wetlands in maintaining regional connectivity and providing population fluctuation buffer is probably considerable. Thus, the findings are in agreement with the Ramsar principles emphasizing the collective value of the ecological functions of wetland networks rather than the isolation of individual sites (Ramsar Convention Secretariat, 2016).

Conclusion

The integration of multi-decadal avian abundance data through all the Ramsar sites of Pakistan has disclosed strong population trajectories influenced by hydrological regulation, habitat condition and human activities. Some wetlands have shown long-term resilience and still support large bird populations, but many others have plunged and need immediate conservation action. The noted trends portray a diversity of stability, oscillation and decline in the national wetland network. This research, which through the implementation of long-term monitoring within a network-based framework, not only enhances understanding of wetland-dependent avifauna but also points at the necessity for adaptive, threshold-informed management to protect the Ramsar wetlands of Pakistan and the migratory bird populations at both the national and flyway scales. To protect both the ecological integrity of the delta and its birds from human impacts, this study identifies a need for a multi-faceted conservation approach that assesses upstream hydrological changes, limits human-induced pollution, and facilitates local community involvement to promote sustainable use over the long term.

Declarations

Funding

The study received no external funding.

IRB approval

The advanced Studies and Research Board of Lahore College for Women University approved the study (No. Reg/LCWY/69, Dated: 25/01/2023)

Ethical considerations

All surveys for birds were non-intrusive and done according to the national wildlife regulations and the best international practices for waterbird monitoring. Data collection was mainly through secondary analysis of existing records, and the study did not involve any handling or disturbance of birds in any way.

Generative AI and AI assisted technology statement

The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Statement of conflict of interest

The authors have declared no conflict of interest.

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Supplementary Material

Supplementary Table S1: Categorization of Ramsar Sites in Pakistan.

S. No.	Ramsar code	Ramsar site	Habitat classification	Longitude	Latitude
1	2PK009	Astola Island	Coastal and marine wetlands	69.19087	28.08714
2	2PK002	Chashma Barrage	Coastal and marine wetlands	71.41701	32.50486
3	2PK017	Deh Akro-II Desert Wetland Complex	Coastal and marine wetlands	67.89512	27.57177
4	2PK007	Drigh Lake	Arid to semi-arid wetlands	67.13269	25.28905
5	2PK008	Haleji Lake	Arid to semi-arid wetlands	68.04819	24.95983
6	2PK010	Hub Dam	Coastal and marine wetlands	64.56428	25.25823
7	2PK018	Indus Delta	Arid to semi-arid wetlands	72.03123	32.55930
8	2PK011	Indus Dolphin Reserve	Coastal and marine wetlands	71.07019	32.62408
9	2PK012	Jiwani Coastal Wetland	Riverine and barrage wetlands	70.83355	30.56968
10	2PK013	Jubho Lagoon	Arid to semi-arid wetlands	71.37551	33.57416
11	2PK006	Keenjhar Lake	Arid to semi-arid wetlands	69.89110	24.29016
12	2PK014	Miani Hor	Inland freshwater wetlands	68.66622	24.42870
13	2PK015	Nurri Lagoon	Riverine and barrage wetlands	66.35794	25.54719
14	2PK016	Ormara Turtle Beaches	Riverine and barrage wetlands	61.73715	25.15552
15	2PK019	Runn of Kutch	Inland freshwater wetlands	67.77639	24.80432
16	2PK004	Tanda Dam	Inland freshwater wetlands	63.85460	25.12398
17	2PK003	Taunsa Barrage	Riverine and barrage wetlands	68.67216	24.36144
18	2PK001	Thanedar Wala Game Reserve	Riverine and barrage wetlands	67.55273	24.00348
19	2PK005	Uchhali Wetland Complex (Uchali, Khabeki and Jhaler Lakes)	Arid to semi-arid wetlands	72.21448	32.62180
				72.08739	32.49823
				68.84118	26.44070