Trends in waterbird abundance and diversity at the Mandrozo Ramsar site, western Madagascar, 2009–2023

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Abstract

Long-term trends in waterbird populations at the Mandrozo Ramsar site, in western Madagascar, were analysed for the years 2009–2023. The study aimed to document species composition, diversity and abundance, assess population trends, and evaluate the site's conservation value for waterbirds. The total of 47 waterbird species recorded during the biannual surveys conducted each year (in January and July), included eight endemic and seven globally threatened species. The waterbird community, grouped into four foraging guilds, was composed mainly of wading birds (61.7%) and dabblers (21.3%), with diving birds accounting for 14.9% and raptors 2.1%. An average of 4,478 ± 1,693.6 individuals were counted annually over the 15-year period. Four families – Anatidae, Ardeidae, Threskiornithidae and Rallidae – accounted for 92% of all waterbirds counted. Overall, there was a significant annual increase of 6.4% in the number of waterbirds recorded, with 72.5% of species exhibiting positive trends. This long-term increase likely reflects improvements in habitat quality over the study period. Reduced anthropogenic pressure, improved wetland management, and the establishment and enforcement of conservation measures (protection status, community-based management and regulation of resource use) may have enhanced breeding success, survival rates and site fidelity of waterbird populations. Significant increases were observed for several endemic and threatened species, including the Malagasy Pond Heron *Ardeola idae*, Malagasy Sacred Ibis *Threskiornis bernieri* and Madagascar Grebe *Tachybaptus pelzenii*. Group-level trends revealed strong increases across all foraging guilds, particularly among the dabbling, wading and diving birds. The Mandrozo Ramsar site regularly supports > 1% of the global populations of six species (Humblot's Heron *Ardea humbloti*, Madagascar Fish Eagle *Ichtyophaga vociferoides*, Madagascar Jacana *Actophilornis albunica*, Malagasy Pond

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Heron, Malagasy Sacred Ibis and Sakalava Rail *Zapornia olivieri*), underscoring its international importance for waterbird conservation. These results highlight the effectiveness of conservation efforts at the Mandrozo wetland and reinforce the need for continued monitoring and adaptive management to maintain its ecological value.

Key words: conservation value, long-term trends, Mandrozo wetland, waterbird community.

Wetlands are biodiverse and productive but highly fragile ecosystems (Green *et al.* 2002). Regular and structured monitoring programmes of wetlands are essential to detect changes in their ecological character and identify necessary protection or restoration actions, and to implement appropriate management (Ramsar Convention Secretariat 2010). Since it is impractical to monitor all biological and physical components of wetland ecosystems, waterbirds are widely used as key biological indicators for assessing the quality and importance of wetlands in wider conditions (Everard 2008; Kushlan 1993; Amat & Green 2010; Green & Elmberg 2014). The capacity of waterbirds to function as effective indicators of wetland health derives from their wide distribution, charisma, mobility, rapid response to environmental change, varied habitat requirements, sensitivity to habitat quality and ease of observation (Everard 2008; Owino *et al.* 2001).

Long-term datasets on waterbird populations are increasingly used for answering important ecological and management questions that are useful for conservation management (Magurran *et al.* 2010; Hansen *et al.* 2021). While such approaches have been widely applied in many regions, their application remains limited in Madagascar. Yet, Malagasy wetlands are of critical importance for supporting biodiversity, including resident and migratory waterbird species, and for providing a wide range of ecosystem services. Given the importance of Madagascan wetlands, this study attempts to use long-term datasets to explore waterbird population trends for the ecological assessment and conservation management of Mandrozo Lake (Zone Humide de Mandrozo) Ramsar site in western Madagascar, which supports significant numbers of waterbirds.

In 2008, The Peregrine Fund established a system for the conservation and rational management of the biodiversity and natural resources of the Mandrozo Ramsar site. A biannual waterbird monitoring programme was initiated in 2009, which has now run for 15 years. Here, we use these annual count data to assess whether and how waterbird populations have changed at Mandrozo Lake, especially since they were last described in 2015 (Razafimanjato *et al.* 2015).

In this paper we aim to: (1) document the species composition, diversity and abundance of waterbirds at Mandrozo Lake, (2) assess trends in numbers for the entire species assemblage, as well as for a series of species of particular conservation interest, (3) assess the site's importance for waterbirds at

both the species and community levels, and (4) consider the conservation implications of our findings and propose directions for future research and conservation measures.

Methods

Study site

Mandrozo Lake (17°32.67'S, 44°05.75'E), the fifth largest natural lake in Madagascar, is located within the Mandrozo Protected Area in Maintirano District, Melaky Region, western Madagascar (Fig. 1). The 1,800 ha lake is surrounded by a mosaic of dry deciduous forest and wetland habitats extending over 15,145 ha. Due to its ecological importance, the site was designated a Ramsar Wetland of International Importance in 2012 (Ramsar Convention Secretariat 2012). It is part of the broader Tambohorano Wetland complex, recognised as an Important Bird Area (IBA), based on its support of significant numbers of waterbirds, including many threatened species (BirdLife International 2026).

Mandrozo is a permanent, shallow freshwater lake with an average depth of 2–3 m, which may reach up to 5 m during the rainy season. The lake is characterised by extensive stands of Common Reed *Phragmites communis* and marginal aquatic vegetation, including emergent species such as Spikerush *Eleocharis plantaginea*, Lesser Bulrush *Typha angustifolia*, Epiphytic Flatsedge *Cyperus latifolius* and Jointed Flatsedge *Cyperus articulatus*, as well as floating waterlilies *Nymphaea* sp. (Pruvot 2016; Pruvot *et al.* 2018). These aquatic plant communities play a key ecological role by maintaining the physico-chemical properties of the lake, stabilising sediments, and providing essential foraging, roosting, and nesting habitats for waterbirds. Seasonal flooding creates additional peripheral marshes around lake margins, used as feeding areas by many species. One large central reed-covered islet is an important breeding site for colonial waterbirds, particularly herons, egrets and ibis.

Mandrozo Lake supports diverse fauna, including the Critically Endangered Madagascan Big-headed Turtle *Erymnochelys madagascariensis*. The lake constitutes a major fish spawning ground and a crucial source of food and income for surrounding human communities. The site also holds strong cultural significance, as local communities maintain traditional fishing and agricultural practices that contribute to the sustainable use of natural resources (Ramsar Convention Secretariat 2019; The Peregrine Fund 2022).

Historically, Mandrozo Lake lacked any formal management or conservation framework prior to 2008, when structured governance was initiated by The Peregrine Fund through community-based conservation actions and ecological monitoring (The Peregrine Fund 2022). The site obtained temporary protected area status in 2010 under Madagascar Government regulation and was subsequently granted permanent protection status in 2015 as Protected Harmonious Landscape (IUCN Category V) (Madagascar Protected Areas 2026; UNEP-WCMC 2026). This legal recognition significantly strengthened the legitimacy and effectiveness of conservation measures implemented at the site.

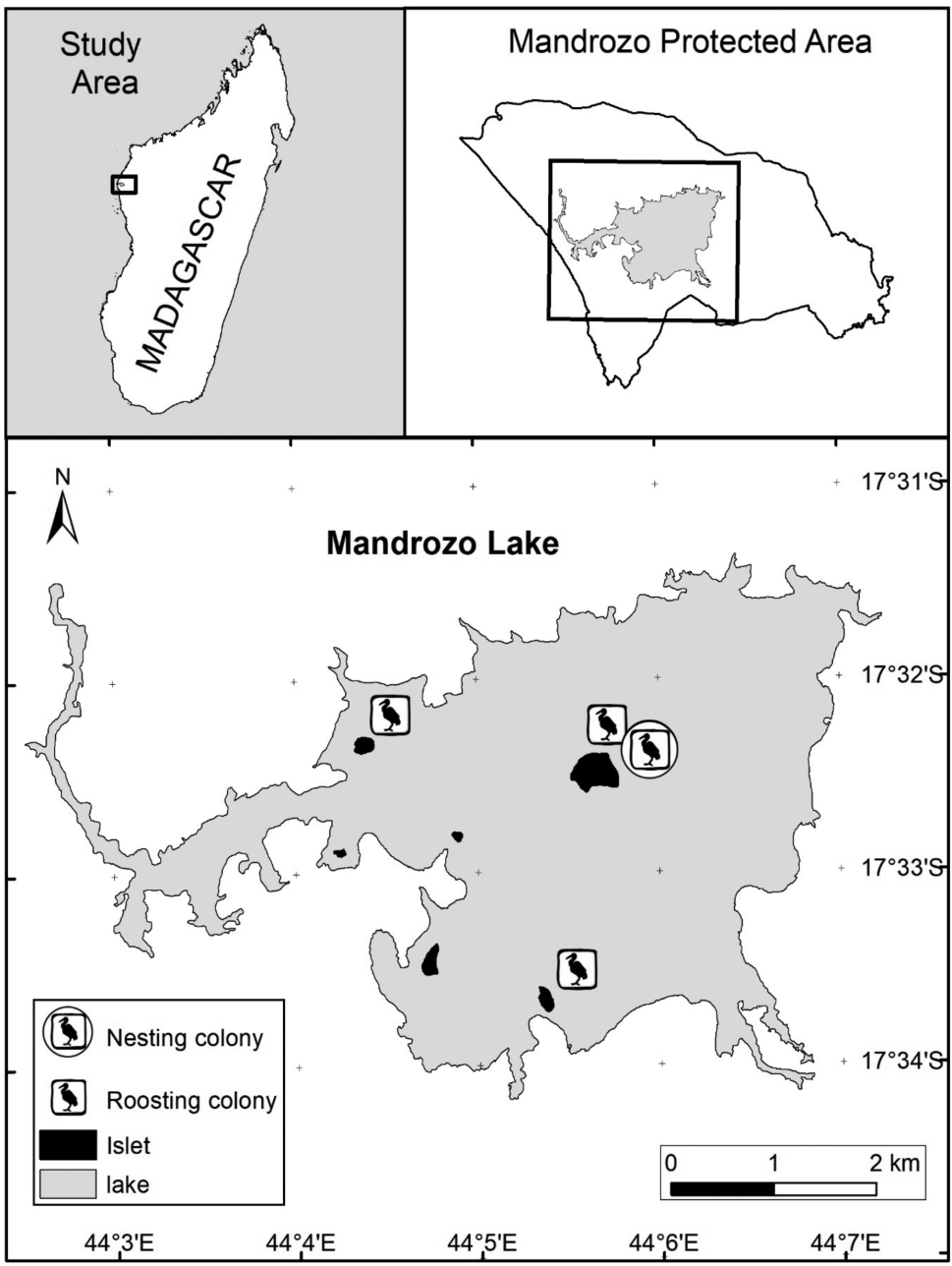


Figure 1. Map of Mandrozo Lake, western Madagascar.

Since 2010, the management of the Mandrozo Protected Area has been based on community co-management through the Transfer of Natural Resource Management (TGRN) framework, involving three local community-based associations (VOIs). Key actions include regular community patrols, forest and aquatic vegetation protection, fire prevention, and regulation of the use of natural resources under locally-defined management plans (The Peregrine Fund 2022). Fishing activities at Mandrozo Lake are strictly regulated, with a seasonal closure (December–April) and controlled access with maximum of 200 fishermen permitted, allocated across the three community-based organisations. These measures help limit disturbance to waterbirds while sustaining local livelihoods. Complementary conservation efforts include environmental awareness, education, and capacity-building programmes targeting local communities. These initiatives have strengthened local knowledge, improved compliance with management rules and enhanced the effectiveness of conservation actions (The Peregrine Fund 2022).

Overall, the integration of regulatory measures, community governance, traditional practices and outreach activities constitutes a comprehensive conservation strategy that has likely reduced anthropogenic pressures and thus supports habitat quality and waterbird populations at the site.

Data collection

Waterbird counts at the Mandrozo Lake and adjacent marshes were conducted biannually in January (wet season) and July (dry season) from 2009 to 2023, following the protocol of the annual African Waterbird Census (Perennou 1991).

Two teams of three people conducted surveys using binoculars (10 × 50), spotting scopes (20–6×), field guides and data sheets. Both teams began counting birds from the same starting point, and each team walked or paddled in fiberglass canoes along the lakeshore in opposite directions to the other team. The monitoring session ended when the two teams met. To avoid double counting, the observers did not record birds flying from behind them. Surveys started at 05:30 h and ended at *c.* 10:00 h in the morning. Communication (using long-range (10 km), hand-held, 2-way radios) and coordination between teams minimised the risk of double counting, particularly for more mobile species. Birds encountered were identified, counted, and recorded following Girard (2003). Small groups (< 100 birds) were counted individually; larger groups were estimated by counting in blocks. Homogenous multi-species groups were counted in the same way as for larger single species groups. Heterogeneous multi-species groups were counted in their entirety, then the abundance of each species was counted/estimated separately. Rarer species were counted precisely; abundant species were estimated using the techniques described above. For roosting and colonial-nesting species (*e.g.* herons and egrets *Ardeidae* sp. and ibis *Threskiornis* sp.), bird counts were also conducted at each localised roosting and nesting site from 17:00 h until shortly after sunset (*c.* 18:30 h), with observations made from two or three vantage points which provided an overall view of the birds' arrival routes, again using

binoculars and spotting scope. Bird species were identified through direct visual observations and acoustic methods. Playback of pre-recorded species-specific calls was used during morning and evening surveys to improve the detection of secretive species. In addition, vocalisations heard during surveys were recorded and later checked to confirm the identification of species that were not visually observed.

Bird count techniques were standardised during all survey sessions. At the end of each session, the population size of each recorded species was determined by summing the numbers of individuals counted by both survey teams. Each survey session spanned two days and, for each species, the highest count recorded during this period was retained. The monitoring teams were composed of expert ornithologists, field technicians and members of local communities. All participants were trained in waterbird identification and counting methods to ensure the reliability and consistency of the data collected. Species classification and naming systems used in this study follow the Global Avian Check List (AviList Core Team 2025).

Data analysis

Data were analysed using descriptive statistics, by parametric tests (with Shapiro-Wilk tests confirming that the data were normally distributed; following Dytham 2011) and the TRIM (Trends and Indices for Monitoring Data) method. Descriptive results were expressed as means and/or percentages. Mean values are given ± s.d. (standard deviation) and null hypotheses were rejected at $P \leq 0.05$. All statistical analyses were performed in R Studio version 4.3.2.

A *t*-test was applied to compare the mean abundance of all waterbirds recorded during the months of January and July in each year, to determine whether there was a significant difference between months in the number of waterbirds encountered.

The percent frequency of occurrence (FO) for each species was calculated using the formula: FO = (number of years in which the species occurs/total number of years of observations) × 100. Species encountered in 100% of the 15-year survey period were classified as omnipresent; those recorded in 80–99% of the years were classed as constant, in 50–79% as regular, in 21–49% as irregular, and if encountered in ≤ 20 % of the period as occasional.

Pearson's correlations were used to test the strength and direction of a linear relationship between year and annual species richness, calculated as the total number of distinct waterbird species recorded across the two biannual surveys conducted each year. This approach was adopted to capture seasonal variation in species presence, by including both resident and migratory species.

Long-term trends in the count data were assessed for: (i) the entire waterbird assemblage, (ii) the assemblage of threatened species, (iii) the assemblage of endemic species, (iv) each functional guild (dabbling, diving and wading birds), and (v) each of the 40 species which occurred consistently at Mandrozo Lake during annual surveys. We retained, for each species and each year, the maximum count recorded during either the January or July survey. These annual maxima

values were then used as the input for the trend analyses. Trend analyses were performed using the "rtrim" package in R (Bogaart *et al.* 2024), implementing Model 3 of the TRIM program, which is specifically designed to analyse time-series data from systematically repeated biological surveys (Pannekoek & van Strien 2005). The "rtrim" process estimates a multiplicative trend value for each species, so that, for instance, a value of 1.00 indicates a stable population, 1.10 represents a 10% average annual increase and 0.95 indicates a 5% average annual decline. Each trend is then classified based on its multiplicative value and the 95% confidence interval (CI), using the following categories: (1) strong increase (a significant increase of > 5% per year, with the lower CI at > 1.05); (2) moderate increase (a significant increase of ≤ 5% per year; lower CI between 1.00 and 1.05); (3) stable (no significant change; CI includes 1.00, with its lower bound > 0.95 and upper bound < 1.05); (4) uncertain (no certainty about the trend; CI includes 1.00, with lower bound < 0.95 or upper bound > 1.05); (5) moderate decline (a significant decrease of less than 5% per year; upper CI between 0.95 and 1.00); and (6) strong decline (a significant decrease of more than 5% per year, with the upper CI < 0.95, corresponding to a halving of the numbers within 15 years).

In addition, the "rtrim" package reports the statistical significance of deviations from a linear trend based on the Wald test. It provides an annual abundance index for each species, set to 1 in the baseline year (2009). Each subsequent year's index reflects abundance relative to this reference.

Results

Species richness and community structure

From 2009 to 2023, a total of 47 waterbird species belonging to 17 families were recorded at the Mandrozo wetland. Among these, eight species (17%) are endemic to Madagascar, 14 (29.8%) strict residents, 27 (57.4%) resident migrants, six (12.8%) strict migrants, and one species is considered as vagrant (Table 1). The family Ardeidae was the most species-rich, comprising 12 species, followed by Anatidae and Rallidae, each represented by seven species. The other families were represented by one to three species. Seven threatened species were recorded, including six endemic species – the Madagascar Fish Eagle *Icthyophaga vociferoides* (CR), Madagascar Jacana *Actophilornis albunica* (EN), Humblot's Heron *Ardea humbloti* (EN), Madagascar Grebe *Tachybaptus pelzelnii* (EN), Malagasy Sacred Ibis *Threskiornis bernieri* (EN) and Sakalava Rail *Zapornia olivieri* (EN) – and also one migratory breeder, the Malagasy Pond Heron *Ardeola idae* (EN). The waterbird community of Mandrozo was distributed between four feeding guilds, composed of 29 waders (61.7%), 10 dabblers (21.3%), seven divers (14.9%) and one raptor (2.1%). Based on percent frequency of occurrence, 25 species (53.2%) were assessed as omnipresent, 10 species (21.3%) as constant, six (12.8%) as regular, three (6.3%) as irregular and three (6.3%) as occasional (Table 1). Species richness varied annually, ranging from a minimum of 31 species observed in 2010 to a maximum of 45 species in 2023. A statistically significant increasing trend in

Table 1. List of waterbird species recorded at Mandrozo wetland in the months of January and July from 2009 to 2023, their red list conservation status (CR = Critically Endangered, EN = Endangered, NT = Near Threatened, LC = Least Concern), residing status (E = Endemic, R = Resident, RM = Resident Migrant, Mi = Migratory, Va = Vagrant), foraging guild (Da = Dabbling, Di = Diving, Gle = Gleaning, Wa = Wading, Ra = Raptor, Pdi = Plung-Divers), mean ± s.d. annual counts of 2009–2023, percent frequency of occurrence (FO%) and occurrence status (OS): O = Omnipresent, C = Constant, Re = Regular, I = Irregular, Oc = Occasional.

Species name	Red list status	Residing* status	Foraging guild	Mean ± s.d.	FO (%)	OS
Accipitridae						
Madagascar Fish Eagle *Icthyophaga vociferoides*	CR	E, R	Rap	2.9 ± 1	100%	O
Acrocephalidae						
Madagascar Swamp Warbler *Acrocephalus newtoni*	LC	E, R	Gle	111.4 ± 110.6	100%	O
Alcedinidae						
Malagasy Kingfisher *Corythornis vintsioides*	LC	E, R	Pdi	42.3 ± 23.2	100%	O
Anatidae						
Red-billed Teal *Anas erythrorhyncha*	LC	RM	Da	26.1 ± 30.7	80.0%	C
Fulvous Whistling Duck *Dendrocygna bicolor*	LC	RM	Da	682.8 ± 403	100%	O
White-faced Whistling Duck *Dendrocygna viduata*	LC	RM	Da	957.2 ± 520.1	100%	O
African Pygmy Goose *Nettapus auritus*	LC	RM	Di	130.8 ± 87.2	100%	O
Knob-billed Duck *Sarkidiornis melanotos*	LC	RM	Da	333.5 ± 202.9	100%	O
Blue-billed Teal *Spatula hottentota*	LC	RM	Da	28.6 ± 27.4	93.3%	C
White-backed Duck *Thalassornis leuconotus*	LC	RM	Di	4.8 ± 7.9	33.3%	I
Anhingidae						
African Darter *Anhinga rufa*	LC	R	Di	6.9 ± 6.3	80.0%	C

Table 1 (*continued*).

Species name	Red list status	Residing* status	Foraging guild	Mean ± s.d.	FO (%)	OS
Ardeidae						
Great Egret *Ardea alba*	LC	RM	Wa	74.9 ± 41.6	100%	O
Grey Heron *Ardea cinerea*	LC	RM	Wa	39.2 ± 20.9	100%	O
Humblot's Heron *Ardea humbloti*	EN	E, R	Wa	34.4 ± 13.8	100%	O
Purple Heron *Ardea purpurea*	LC	RM	Wa	40.1 ± 12.9	100%	O
Malagasy Pond Heron *Ardeola idea*	EN	Mi	Wa	12 ± 10.6	100%	O
Squacco Heron *Ardeola ralloides*	LC	RM	Wa	205.3 ± 186.9	100%	O
Western Cattle Egret *Ardea ibis*	LC	RM	Wa	635.6 ± 259.9	100%	O
Little Heron *Butorides atricapilla*	LC	R	Wa	22.3 ± 15.9	100%	O
Black Heron *Egretta ardesiaca*	LC	RM	Wa	128.5 ± 69	100%	O
Western Reef Egret *Egretta garzetta dimorpha*	LC	RM	Wa	26 ± 20.9	86.7%	C
Little Bittern *Botaurus minutus*	LC	RM	Wa	7.3 ± 8.9	73.3%	Re
Black-crowned Night Heron *Nycticorax nycticorax*	LC	RM	Wa	65.3 ± 51.1	93.3%	C
Charadriidae						
Three-banded Plover *Thinornis tricollaris*	LC	RM	Wa	3.4 ± 4.4	46.7%	I
Ciconiidae						
African Openbill *Anastomus lamelligerus*	LC	RM	Wa	39.3 ±39.3	100%	O
African Woolly-necked Stork *Ciconia microsceles**	LC	Mi, Va	Wa	0.1 ± 0.3	6.7%	Oc
Yellow-billed Stork *Mycteria ibis*	LC	Mi	Wa	18.7 ± 14	100%	O

Table 1 (*continued*).

Species name	Red list status	Residing* status	Foraging guild	Mean ± s.d.	FO (%)	OS
Jacanidae						
Madagascar Jacana *Actophilornis albinucha*	EN	E, R	Wa	54.8 ± 11.3	100%	O
Phalacrocoracidae						
Reed Cormorant *Microcarbo africanus*	LC	R	Di	24.7 ± 26.2	100%	O
Phoenicopteridae						
Lesser Flamingo *Phoeniconaias minor*	NT	Mi	Wa	0.3 ± 0.7	20.0%	Oc
Greater Flamingo *Phoenicopterus roseus*	LC	Mi	Wa	0.7 ± 1.2	33.3%	I
Podicipedidae						
Madagascar Grebe *Tachybaptus pelzelnii*	EN	E, R	Di	4.4 ± 5.3	73.3%	Re
Little Grebe *Tachybaptus ruficollis*	LC	RM	Di	1.9 ± 2.5	53.3%	Re
Rallidae						
White-throated Rail *Dryolimnas cuvieri*	LC	R	Wa	13.9 ± 13.7	86.7%	C
Red-knobbed Coot *Fulica cristata*	LC	RM	Di	7.6 ± 7.8	66.7%	Re
Common Moorhen *Gallinula chloropus*	LC	RM	Da	164.5 ± 40.2	100%	O
Purple Swamphen *Porphyrio porphyrio madagascariensis*	LC	R	Wa	47.9 ± 26.4	100%	O
Allen's Gallinule *Porphyrio alleni*	LC	RM	Wa	42.3 ± 24.4	100%	O
Sakalava Rail *Zapornia Olivieri*	EN	E, R	Wa	11.3 ± 3.6	100%	O
Baillon's Crake *Zapornia pusilla*	LC	RM	Wa	9.6 ± 10	66.7%	Re
Recurvirostridae						
Black-winged Stilt *Himantopus Himantopus*	LC	RM	Wa	15.9 ± 15	86.7%	C

Table 1 (*continued*).

Species name	Red list status	Residing* status	Foraging guild	Mean ± s.d.	FO (%)	OS
Scopidae						
Hamerkop *Scopus umbrette*	LC	R	Wa	0.3 ± 0.8	13.3%	Oc
Sternidae						
Whiskered Tern *Chlidonias hybrida*	LC	RM	Pdi	11 ± 10.6	86.7%	C
White-winged Tern *Chlidonias leucopterus**	LC	RM	Pdi	12.8 ± 8.9	73.3%	Re
Threskiornithidae						
African Spoonbill *Platalea alba*	LC	Mi	Wa	27.3 ± 20.5	86.7%	C
Glossy Ibis *Plegadis falcinellus*	LC	RM	Wa	322.6 ± 168.1	100%	O
Malagasy Sacred Ibis *Threskiornis bernieri*	EN	E, R	Wa	24.6 ± 23.2	86.7%	C

*Note: In this article, Resident Migrant (RM) species are those considered migratory in the AEWA list, but which are observed in Madagascar (in the study site) throughout the year. We acknowledge that White-winged Tern is a rare vagrant. The records have been explicitly highlighted, and we note that identification was confirmed by experienced observers using diagnostic plumage characters. The African Woolly-necked Stork was observed at Mandrozo in 2023, with a single individual recorded. It was documented for the first time in Madagascar, and this observation was subsequently published as a short note in the *Bulletin of the African Bird Club* (see Razafimanjato *et al.* 2024, at https://www.africanbirdclub.org/bulletin/volume-31-1/).

the species richness was observed over the 15-year period (r_{13} = 0.76, P < 0.001).

An annual average of 4,478 ± 1,694 waterbirds (n = 15 years) was counted, with a maximum of 7,406 individuals recorded during the two surveys in 2021 and a minimum of 1,975 individuals in 2013. Families Anatidae (mainly dabbling birds), Ardeidae (wading birds), Threskiornithidae (wading birds) and Rallidae (wading and dabbling birds) were the most abundant, contributing to 92% of the total abundance. Of all species observed, Fulvous Whistling Duck *Dendrocygna bicolor*, White-faced Whistling Duck *Dendrocygna viduata*, Glossy Ibis *Plegadis falcinellus*, Western Cattle Egret *Ardeaibis* and Knob-billed Duck *Sarkidiornis melanotos* were the most abundant, contributing to 65.5% of the total counts (Table 1). Waterbird abundance differed significantly between dry (January) and wet (July) seasons over the 2009–2023 study period ($t_{26.9}$ = –2.71, P < 0.05; Supporting Materials Table S1). During the 15 years of surveys, there were always more waterbirds counted in the dry period than in the wet period, except for 2010.

Abundance trends

The mean total waterbird count for the last five years of the study (6,369 ± 722 individuals in 2019–2023) was 84.3% higher compared to the first five years (3,453 ± 1,516 individuals in 2009–2013) and 75.9% higher than in the second five years (3,617 ± 730 individuals in 2014–2018), indicating that the number of waterbirds using the area has increased over the 15-year period. Overall trends in abundance for all waterbirds showed a significant strong increase (Wald test: W_{13} = 4583.1, P < 0.001), rising by 6.4% per year from 2009 to 2023 inclusive (Fig. 2).

Trend estimates for all 40 analysed species are presented in Table 2. The analysis showed that most species, 29 (72.5%), exhibited a significant increase in abundance, four (10%) remained stable, and only two (5%) species showed a moderate declining trend (Whiskered Tern *Chlidonias hybrida* and Common Moorhen *Gallinula chloropus*). Population trends for five species were assessed as uncertain. Of the 29 species with increasing populations, 17 showed a strongly increasing trend (> 5% per year), while 12 species exhibited moderately increasing trends (< 5% per year).

Calculations of population alerts for the two declining species showed that the Whiskered Tern was declining by 6.5% and the Common Moorhen by 1.9% over the 15-year period.

Of the seven threatened species, three exhibited a strongly increasing trend (Malagasy Pond Heron, Madagascar Grebe and Malagasy Sacred Ibis), one showed a moderate increase (Humblot's Heron), and two remained stable (Madagascar Jacana and Sakalava Rail). The population trend of the Madagascar Fish Eagle was assessed as uncertain (Table 2, Fig. 3).

Group-level trend analyses over the 2009–2023 period revealed a strong significant increase in the abundance of diving birds (W_{13} = 437.2, P < 0.01) and wading birds (W_{13} = 1677.6, P < 0.01), while dabbling birds exhibited a moderate but significant increase (W_{13} = 4329, P < 0.05). There was an annual increase of 5.1% for dabbling, 7.8% for wading and 13% for diving birds

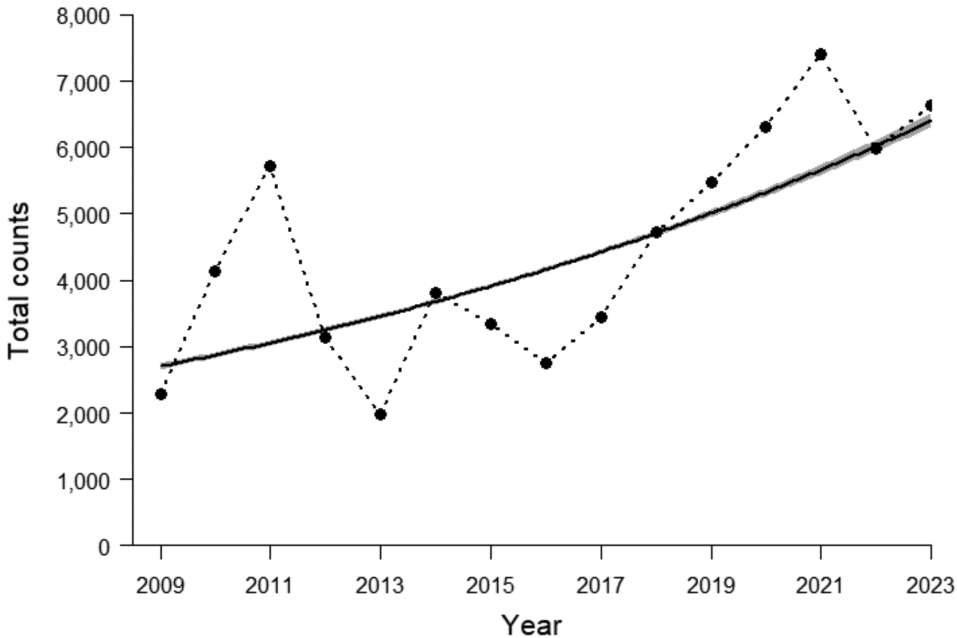


Figure 2. Overall trends in numbers of waterbirds counted at the Mandrozo wetland from 2009 to 2023 (*i.e.* the sum of birds recorded during biannual surveys, in January and July), implemented in rtrim (TRIM: Trends and Indices for Monitoring data). Black points = observed annual total counts; black dotted line = interannual variation in raw counts; black solid line = modelled population trend derived from log-linear Poisson regression accounting for missing data, overdispersion and serial correlation; grey shaded band = 95% confidence interval around the fitted trend. The overall slope reflects the long-term population trajectory over the study period.

(Fig. 4, Table 3). Among the dabbling birds, Red-billed Teal, Knob-billed Duck and Fulvous Whistling Duck exhibited strong increasing trends by more than 10% per year. The greatest increases among the wading birds included Western Reef Egret, Malagasy Pond Heron, Squacco Heron *Ardeola ralloides*, Little Bittern *Botaurus minutus* and Yellow-billed Stork *Mycteria ibis*. Only two species among the diving birds showed a strong increase trend: the African Pygmy Goose *Nettapus auritus* and Madagascar Grebe (Tables 1 & 2).

Site importance for waterbirds

Six waterbird species regularly observed at Mandrozo Lake met Criterion 6 for designating wetlands of international importance under the Ramsar Convention (*i.e.* a wetland supporting ≧ 1% of the individuals in a global population of one or more waterbird species or subspecies) and category A4i of the Important Bird Area (IBA) criteria, enabling the Mandrozo wetland to maintain its Ramsar site status and its consideration as an IBA. Indeed, the Mandrozo Lake supports 3.2% (n = 8) of

Table 2. Trends in numbers for 40 waterbird species occurring at the Mandrozo wetland from 2009 to 2023. Note: **add** = additive trend (the estimated average annual change in absolute terms); **se_add** = standard error (s.e.) of the additive trend; **mul** = multiplicative trend (the estimated trend expressed as a growth factor or index); **se_mul** = standard error (s.e.) of the multiplicative trend; ***P*** = probability value, indicating whether the trend is statistically significant. Trend classification: ↑↑ = strong increase; ↑ = moderate increase; ↔ = stable; ↓ = moderate decline; ?? = uncertain.

Species name	add	se_add	15-year slope (mul)	15-year slope s.e. (se_mul)	*P*	Trend classification
Knob-billed Duck	0.116	0.004	1.123	0.005	< 0.001	↑↑
African Darter	0.119	0.054	1.127	0.060	0.044	↑
African Openbill	0.169	0.013	1.184	0.015	< 0.001	↑↑
African Pygmy Goose	0.123	0.006	1.131	0.007	< 0.001	↑↑
African Spoonbill	0.157	0.084	1.170	0.098	0.084	??
Allen's Gallinule	0.094	0.010	1.099	0.011	< 0.001	↑↑
Baillon's Crake	0.031	0.016	1.031	0.017	0.083	??
Black Heron	0.084	0.007	1.088	0.008	< 0.001	↑↑
Black-crowned Night-heron	0.051	0.007	1.052	0.008	< 0.001	↑
Black-winged Stilt	0.161	0.069	1.175	0.081	0.036	↑
Blue-billed Teal	0.138	0.061	1.148	0.070	0.042	↑
Little Bittern	0.209	0.037	1.232	0.046	< 0.001	↑↑
Common Moorhen	–0.019	0.005	0.981	0.004	0.001	↓
Fulvous Whistling Duck	0.112	0.004	1.119	0.004	< 0.001	↑↑
Glossy Ibis	0.056	0.004	1.058	0.004	< 0.001	↑
Great White Egret	0.086	0.008	1.090	0.008	< 0.001	↑↑
Little Heron	0.158	0.023	1.171	0.027	< 0.001	↑↑
Grey Heron	0.034	0.009	1.034	0.009	0.003	↑
Reed Cormorant	0.136	0.117	1.145	0.134	0.269	??
Madagascar Fish Eagle	–0.060	0.038	0.942	0.036	0.141	??
Madagascar Grebe	0.207	0.038	1.230	0.046	< 0.001	↑↑
Humblot's Heron	0.049	0.010	1.050	0.011	< 0.001	↑
Madagascar Jacana	–0.011	0.008	0.989	0.008	0.182	↔

Table 2 (*continued*).

Species name	add	se_add	15-year slope (mul)	15-year slope s.e. (se_mul)	*P*	Trend classification
Malagasy Kingfisher	0.048	0.009	1.049	0.009	< 0.001	↑
Malagasy Pond Heron	0.224	0.035	1.251	0.044	< 0.001	↑↑
Malagasy Sacred Ibis	0.094	0.011	1.099	0.012	< 0.001	↑↑
Madagascar Swamp Warbler	0.176	0.007	1.192	0.009	< 0.001	↑↑
Purple Heron	0.039	0.010	1.040	0.010	0.002	↑
Purple Swamphen	0.107	0.010	1.113	0.012	< 0.001	↑
Red-billed Teal	0.355	0.039	1.426	0.055	< 0.001	↑↑
Red-knobbed Coot	–0.015	0.015	0.986	0.015	0.351	↔
Sakalava Rail	0.000	0.019	1.000	0.019	0.991	↔
Squacco Heron	0.209	0.007	1.232	0.008	< 0.001	↑↑
Western Cattle Egret	0.052	0.002	1.053	0.003	< 0.001	↑
Western Reef Egret	0.243	0.079	1.275	0.101	0.009	↑↑
Whiskered Tern	–0.065	0.020	0.937	0.019	0.006	↓
White-faced Whistling Duck	0.032	0.003	1.032	0.003	< 0.001	↑
White-throated Rail	0.002	0.013	1.002	0.013	0.891	↔
White-winged Tern	0.027	0.015	1.027	0.016	0.105	??
Yellow-billed Stork	0.204	0.030	1.227	0.037	< 0.001	↑↑

individuals in the global population of the Sakalava Rail, 2.81% (n = 58) of individuals in the global population of the Madagascar Jacana, 2.53% (n = 38) of individuals in the global population of Humblot's Heron, 1.75% (n = 57) of individuals in the global population of the Malagasy Sacred Ibis, 1.25% (n = 3) of individuals in the global population of the Madagascar Fish Eagle and 1.2% (n = 30) of individuals in the global population of the Malagasy Pond Heron.

Discussion

Waterbird diversity status, abundance and long-term trends

Over the 15 years described here, Mandrozo Lake supported 47 waterbird species, including eight endemics and seven globally threatened taxa. The dominance of Ardeidae, Anatidae and Rallidae reflects the habitat mosaic of shallow water, open water and dense emergent vegetation typical of tropical freshwater wetlands (Taylor &

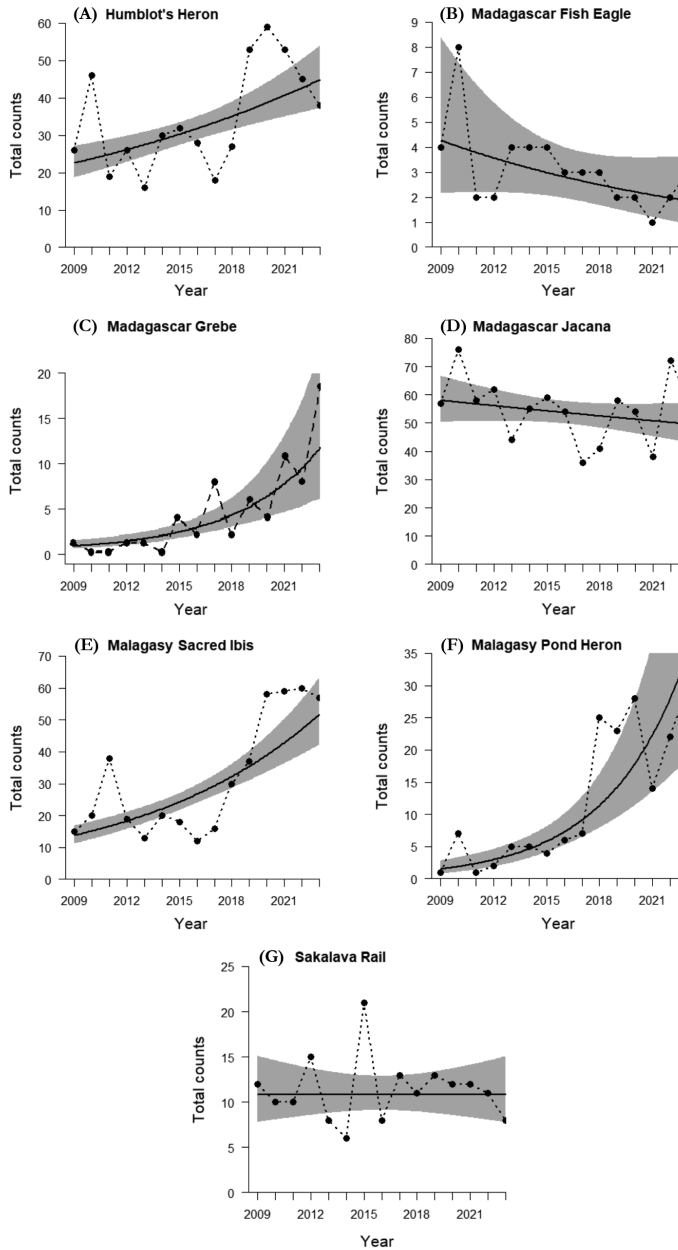


Figure 3. Trends in numbers (2009–2023) for seven endemic and globally threatened waterbird species recorded during biannual counts at the Mandrozo wetland, western Madagascar. Black points = numbers counted each year; continuous line = trend in numbers (from log-linear Poisson regression in TRIM); shaded area = 95% confidence interval, about the trend.

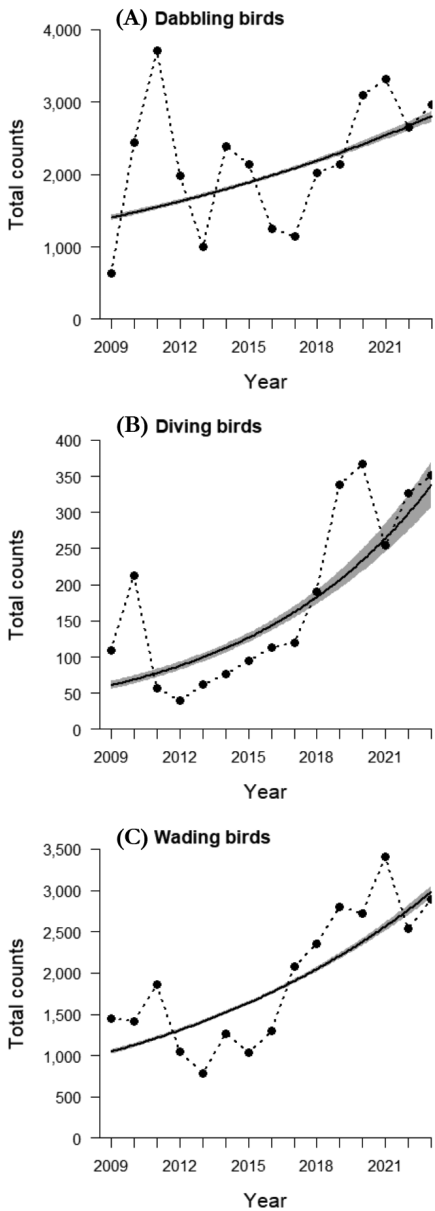


Figure 4. Group-level trends of mean estimated counts of species over the study period (2009–2023), using log-linear Poisson regression implemented in rtrim (TRIM). (A) = dabbling birds, (B) = diving birds and (C) = wading birds.

van Perlo 1998; Delany *et al.* 2006). High proportions of wading and dabbling birds (> 80% of the community) suggests that habitat heterogeneity and prey availability shape community composition, consistent with patterns in other Madagascar and Afrotropical wetlands (Dodman *et al.* 1999; Project ZICOMA 2001; Rabarisoa *et al.* 2020; Pruvot *et al.* 2022).

Species richness increased significantly over time, suggesting improving habitat quality and/or recovery from past disturbance. Although interannual variation in richness (31–45 species) reflects natural hydrological and climatic variability (Kingsford & Norman 2002), the persistence of a large core of omnipresent species (> 50%) shows that Mandrozo functions as a stable or semi-permanent year-round habitat for many waterbirds. Similar fidelity and seasonal aggregations have been reported at other Malagasy wetlands of international importance, such as the Manambolomaty (Razafimanjato *et al.* 2007).

Abundance trends and seasonal patterns

High mean annual abundance (> 4,400 individuals recorded during the biannual counts; range = 1,975–7,406 birds) and dry-season peaks reflect tropical wetland dynamics, where declining water levels concentrate aquatic prey and increase foraging efficiency (Zwarts *et al.* 2009). However, the seasonal pattern observed in 2010 differed from the general trend, with relatively higher wet-season abundance despite annual totals remaining within the normal range of interannual variation. Rather than indicating a major demographic

Table 3. Trends of group-species level of waterbirds at the Mandrozo Lake from 2009 to 2023. Note: **add** = additive trend (the estimated average annual change in absolute terms; **se_add** = standard error (s.e.) of the additive trend; **mul** = multiplicative trend (the estimated trend expressed as a growth factor or index); **se_mul** = standard error (s.e.) of the multiplicative trend; ***P*** = probability value, indicating whether the trend is statistically significant; ↑↑ = strong increase; ↑ = moderate increase; ↔ = stable; ↓ = moderate decline; ?? = uncertain.

Group level	add	se_add	15-year slope (mul)	15-year slope s.e. (se_mul)	*P*	Trend classification
Overall waterbirds (*n* = 47 species)	0.062	0.001	1.064	0.001	< 0.0001	↑↑
Overall dabbling (*n* = 6)	0.049	0.001	1.051	0.002	< 0.0001	↑
Overall diving (*n* = 7)	0.122	0.005	1.130	0.006	< 0.0001	↑↑
Overall wading (*n* = 29)	0.075	0.001	1.077	0.002	< 0.0001	↑↑
Overall endemic species (*n* = 8)	0.0861	0.0036	1.090	0.004	< 0.0001	↑↑
Overall threatened species (*n* = 7)	0.050	0.005	1.051	0.005	< 0.0001	↑

increase, this temporary inversion may reflect interannual variability in habitat use and regional movements of waterbirds, which are strongly influenced by fluctuations in resource availability and wetland accessibility across tropical wetland networks (Kingsford & Norman 2002; Davidson 2016). Additional hydrological and environmental data would be required to identify the precise drivers of this anomaly.

The significant long-term increase in total waterbird abundance (6.4% per year), contrasts with widespread declines at many African and Malagasy wetlands (Davidson 2014). Although regional wetland loss may cause waterbird redistribution, several lines of evidence suggest genuine improvements in the ecological status at Mandrozo. For instance, increases occurred across all foraging guilds (wading, dabbling and diving birds), persisted for more than a decade, and included disturbance-sensitive species. Such patterns are inconsistent with short-term aggregation, rather suggesting enhanced local habitat quality and resource availability.

Species-specific population trajectories

Numbers of nearly three-quarters of 40 species increased, including 17 with strong annual growth rates (> 5% annually). Among threatened species, Malagasy Pond Heron, Madagascar Grebe and Malagasy Sacred Ibis showed strong increases, whilst the Madagascar Jacana and Sakalava Rail remained stable. Only one, the critically endangered Madagascar Fish Eagle, showed an uncertain trend, probably because of the difficulty of monitoring a low-density, territorial species (Steenweg *et al.* 2017). Increases in Malagasy Pond Heron and Malagasy Sacred Ibis numbers are particularly notable given their sensitivity to wetland degradation and disturbance (BirdLife International 2023). The slow declines recorded for Whiskered Tern and Common Moorhen did not trigger alerts for concern for these two species.

Conservation-driven site management and species recovery

The timing and consistency of positive trends in Mandrozo Lake waterbird numbers and diversity between 2009 and 2023 coincided with the implementation of conservation and management measures after 2008. The introduction of legal protection, community co-management and regulated resource use appears to have been central to reducing disturbance and improving ecological conditions at the lake, mirroring recoveries in tropical wetlands where long-term protection and disturbance reduction were effectively implemented (Kingsford & Porter 2009).

Regulation of fishing activities, limited to *c.* 200 fishermen for a seven-month period (May–November), governed by the traditional "*Teabony*" system managed by the "*Tompondrano*" (local guardian of the water), has reduced human disturbance during critical breeding and roosting periods and enhanced fish recruitment and invertebrate availability. Seasonal fishing closures elsewhere have shown increased aquatic prey biomass, benefiting piscivorous and omnivorous waterbirds (Welcomme 2001; Kolding & van Zwieten 2011). Reduced human presence during closed periods is particularly beneficial to colonial-nesting and disturbance-sensitive taxa, as repeated human intrusion can lower nest attendance, increase predation risk and reduce breeding success (Burger 1981; Gill *et al.* 2001; Carney & Sydeman 1999; Steven *et al.* 2011).

Conservation of surrounding forests has limited erosion and sedimentation, enhancing wetland productivity and aquatic vegetation structure (Mitsch & Gosselink 2015). Protection of emergent and floating macrophytes has preserved nesting, roosting and refuge habitats, particularly for rallids, herons and dabbling ducks. Numerous studies have demonstrated that the structural complexity of aquatic vegetation is a strong predictor of waterbird diversity and abundance in freshwater ecosystems (Elmberg *et al.* 1994; Ma *et al.* 2010). Expansion of reedbed islets used as nesting sites at Mandrozo has further improved breeding habitat quality.

Community-based co-management through the Transfer of Natural Resource Management (TGRN) framework has strengthened compliance and local

stewardship, consistent with evidence that participatory systems enhance the maintenance of tropical wetland biodiversity and conservation outcomes (Ostrom 1990; Berkes 2004; Oldekop *et al.* 2016). At Mandrozo, such governance has likely contributed to the long-term effectiveness and social acceptance of conservation measures, reducing illegal exploitation and habitat degradation.

The progressive increases in waterbird abundance and diversity following protection in 2008 show the gradual and sustained delayed response typical of wetland restoration (Zedler & Kercher 2005; Moreno-Mateos *et al.* 2012). Overall, the breadth and duration of the positive trends present strong evidence for conservation-driven recovery of an important tropical freshwater ecosystem which still provides vital ecosystem services to local human communities.

International importance and conservation value

Six species exceeded 1% of their global populations – *i.e.* the threshold for designation of Ramsar sites and IBAs – confirming Mandrozo's global significance for waterbirds. The regular presence of multiple threatened Malagasy endemics further underlines the lake's vital role in sustaining island-restricted populations, especially given the deteriorating conditions at other Madagascan wetlands.

Management implications and research needs

Mandrozo represents a rare case of sustained ecological integrity in a region marked by wetland degradation (Davidson 2014). Continued support for local community governance, adaptive management of hydrology, fire and invasive species, and also long-term monitoring, will be essential to maintain this trajectory.

Future research should examine drivers of species-specific responses, particularly for threatened endemics and rapidly increasing taxa and guilds (*e.g.* diving birds). Integrating breeding success, habitat dynamics and landscape-scale connectivity into monitoring frameworks will allow a more predictive understanding of population changes (Lindenmayer & Likens 2010).

Finally, improving collaboration with national and international conservation networks may help secure long-term funding and technical support, ensuring that Mandrozo remains a flagship site for wetland and bird conservation in Madagascar.

Conservation implications and future perspectives

Despite the encouraging trends at Mandrozo, other Madagascan wetlands remain vulnerable to the same threats – *i.e.* agricultural expansion, overfishing, invasive species and hydrological change. Continued monitoring is essential, especially for cryptic and low-density species with uncertain trends in abundance. Long-term waterbird monitoring programmes are already being implemented at several internationally important wetlands, notably the Manambolomaty and Bemanevika Ramsar Sites, where regular surveys have contributed to improved understanding of population dynamics and site management. However, many other important wetlands in Madagascar still lack consistent long-term ecological monitoring, particularly smaller

and remote sites outside protected-area networks. Strengthening community-based protection, management of water levels, and control of key threats such as fire, fishing and disturbance in general could help achieve such gains elsewhere.

Further research should explore the drivers behind the observed increases. For instance, changes in land-use patterns within the watershed, the impacts of climate variability, or regional species movements may all influence local dynamics. It is also essential to improve knowledge on breeding success, survival rates and connectivity between wetlands to ensure conservation actions are targeted and effective.

Conclusion

After 15 years of monitoring, Mandrozo Lake stands out as an important example for waterbird conservation in Madagascar. Significant increases in species richness and abundance, particularly among endemic and globally threatened species, highlight effectiveness of community-based management in safeguarding the ecological value of a site. These positive population trends contrast sharply with the widespread declines in waterbird populations in other wetlands across Madagascar and the African continent. However, some rare, local and sensitive species, such as the Madagascar Fish Eagle, remain vulnerable to ecological or anthropogenic disturbance. On-going monitoring and adaptive management will be crucial to sustaining these gains, integrating breeding success and habitat dynamics, and to strengthen partnerships at national and international levels. Mandrozo offers a promising model of sustainable wetland conservation, but its long-term success will depend on the commitment to maintaining and enhancing these gains in the face of ongoing environmental pressures.

Acknowledgements

We thank The Peregrine Fund for providing financial support for this study. We also thank the Madagascar Biodiversity Fund (FAPBM), for additional funding for ecological waterbird surveys at Mandrozo Lake. We are grateful to The Peregrine Fund's field technicians at the Mandrozo site for their assistance with data collection. We also acknowledge the valuable support and collaboration of local communities during field activities. Two anonymous referees made helpful comments on an earlier draft of the text.

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