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Waterbirds as bioindicators of ecosystem health: seasonal dynamics in Tondano Lake, Indonesia

Rievo Djarang[1], Gerry Harindah*[2], Ni Wayan Suriani[3], Marthy Lingkan Stella Taulu[1]
[1] Department of Biology, Universitas Negeri Manado, Tondano, North Sulawesi, Indonesia
[2] Department of Integrative Biology, University of South Florida, Tampa, Florida, United Stated of America
[3] Department of Science Education, Universitas Negeri Manado, Tondano, North Sulawesi, Indonesia

*Corresponding e-mail: gerryharindah@outlook.com

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Abstract

Waterbird diversity in Tondano Lake reflects ecological degradation caused by water-hyacinth invasion and sedimentation. This study analyzed the diversity and abundance of waterbirds in Tondano Lake, Indonesia, across wet (February-May) and dry (June-October) seasons in 2025 to assess their role as bioindicators of ecosystem health. Multi-season observations were carried out monthly along a 6.5 km transect at ten strategic points. Eight waterbird species from three families were recorded, with *Egretta garzetta* being the most abundant (29.1%) and *Alcedo atthis* the least (4.8%). The Shannon-Wiener diversity index (H' = 1.92) indicates a moderate level of species diversity, which reflects a pattern of ecological simplification when compared to pristine tropical lakes such as Lake Sentarum (H' = 2.5). Waterbird abundance showed significant negative correlations with water hyacinth density (r = -0.68, p = 0.032) and water depth (r = -0.72, p = 0.019), revealing that invasive vegetation and shoaling are primary drivers of habitat loss. These findings demonstrate that waterbirds function as sensitive bioindicators of ecological stress, highlighting the urgent need for integrated watershed management to prevent further community collapse.

Introduction

Freshwater ecosystems, encompassing lakes, rivers, and wetlands, are globally recognized as critical centers of biological diversity, supporting a wide array of flora and fauna (Dudgeon et al., 2006; Strayer & Dudgeon, 2010). These ecosystems provide essential services to both human communities and wildlife (Dudgeon et al., 2006; Green & Elmberg, 2014). Located in North Sulawesi, Indonesia, Tondano Lake stands out as a prominent freshwater body of high ecological, social, and economic importance. It not only supports local fisheries and tourism but also serves as a crucial habitat for various waterbird species.

Waterbirds are considered indispensable components of healthy aquatic ecosystems due to their multifaceted ecological functions. They act as regulators of aquatic populations by preying on fish and invertebrates, contribute to the regeneration of riparian vegetation through seed dispersal, and, most importantly, serve as sensitive bioindicators of environmental health (Amat & Green, 2010; Green & Elmberg, 2014). Changes in their diversity, abundance, and distribution patterns can provide early warning signals of ecosystem degradation, such as a decline in water quality or habitat loss (Kelly, 1998; Grzędzicka et al. 2020).

Despite their ecological significance, Tondano Lake and its waterbird populations are facing formidable environmental pressures. A primary threat is the aggressive invasion of the exotic aquatic plant, water hyacinth (*Eichhornia crassipes*), which has been reported to cover up to 30% of the lake's surface area (Pratama et al., 2023; Hendratta et al., 2024). This unchecked proliferation forms dense floating mats that obstruct light penetration, induce eutrophication, and reduce dissolved oxygen levels, thereby disrupting the fundamental food web and negatively impacting species that depend on open, clear water for foraging, such as *Himantopus leucocephalus* and *Egretta garzetta* (Toft et al., 2003; Villamagna & Murphy, 2010). Concurrently, the lake is experiencing accelerated sedimentation, or shoaling, primarily due to heightened erosion from agricultural and deforested areas in the surrounding watershed. This process reduces the lake's depth, fundamentally altering habitat structure and decreasing the availability of prey, which is particularly detrimental to piscivorous species like *Alcedo atthis* (Kelly, 1998; Kumar & Pattnaik, 2012).

Existing scientific literature on Tondano Lake has predominantly focused on water quality and fish populations (Onibala et al., 2025), leaving a significant research gap in studies that integrate the dynamics of waterbird communities with the specific, escalating environmental threats of water hyacinth invasion and sedimentation. This gap underscores the urgent need for a dedicated study on waterbirds as a key bioindicator group (Amat & Green 2010; Green & Elmberg 2014). By investigating the relationship between waterbird populations and these environmental stressors, this research can offer a more holistic and nuanced understanding of the lake's health and resilience.

This work is aligned with global conservation efforts and contributes to the realization of Sustainable Development Goals (SDGs) 6 (Clean Water and Sanitation) and 15 (Life on Land). The specific objectives of this study were: (1) to identify the species and abundance of waterbirds in Tondano Lake; (2) to calculate the species diversity index and relative abundance; and (3) to analyze the ecological role of waterbirds within the context of the identified environmental threats, specifically the invasion of water hyacinth and sedimentation. By addressing these objectives, this research aims to provide the scientific data necessary to inform and strengthen the management of the Tondano Lake ecosystem.

Materials and methods

1. Study Location and Period

The study was conducted at Tondano Lake, located in North Sulawesi, Indonesia (1°15'N, 124°50'E) (Figure 1). The region experiences a tropical monsoon climate characterized by a distinct wet season (November–May) and a dry season (June–October). The area receives a mean annual precipitation of approximately 2,700 mm to 3,000 mm, with the highest rainfall intensity typically occurring between December and January (Meteorological, Climatological, and Geophysical Agency [BMKG], 2023). This high precipitation volume significantly influences the lake's hydrology, contributing to seasonal fluctuations in water depth and the transport of sediment from the surrounding agricultural watershed. Tondano Lake was selected for its ecological importance as a major freshwater body and for the escalating environmental challenges it faces from water-hyacinth invasion and accelerated sedimentation (Pratama et al., 2023; Hendratta et al., 2024).

2. Equipment and Materials

The following equipment and materials were utilized during the field survey:
1). A Garmin eTrex 30x GPS unit to accurately determine the coordinates of each observation point, with a precision of ±3 m; 2). A pair of Nikon Monarch 10x42 binoculars to facilitate long-range observation of waterbirds from a distance of up to 100 m; 3). A Canon EOS 90D digital camera equipped with a 100-400 mm telephoto lens for high-resolution documentation of identified species; 4). A Casio G-Shock wristwatch to ensure accurate timing of observations; 5). A motorized boat with a capacity of four people and a maximum speed of 10 km/h for transect navigation; 6). A Lowrance Hook2-4x echosounder to measure water depth at each observation point; 7). A DJI Mavic Mini drone to capture aerial imagery for estimating the percentage coverage of water hyacinth; 8). A thematic map of Tondano Lake (scale 1:50,000) from the Geospatial Information Agency to guide the transect route; 9). The "Birds of New Guinea" field guide by Beehler et al. (2001) for species identification based on morphological and behavioral characteristics and field data sheets for systematic recording of observations, including species counts and environmental conditions.

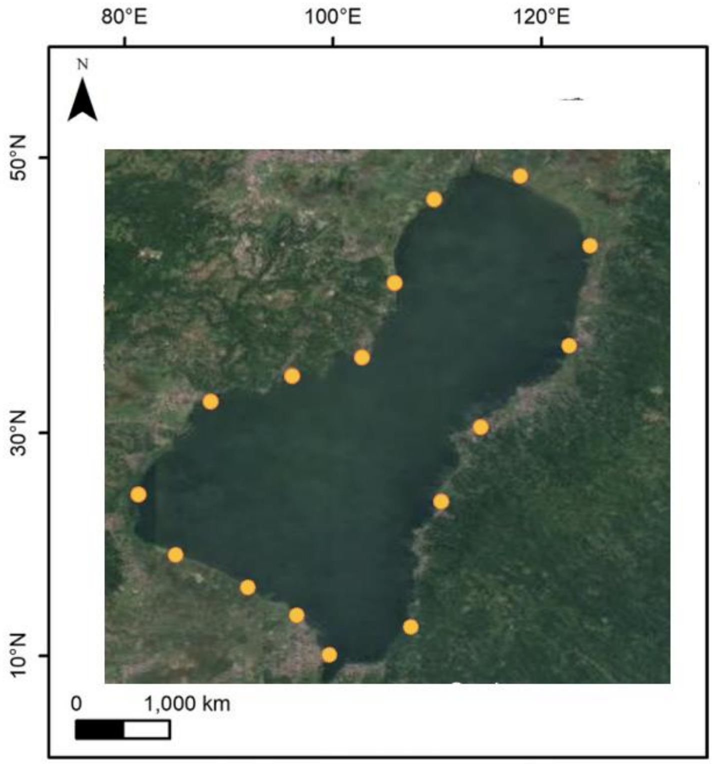

Figure 1. Location of Surveyed Lakes and Sampling Sites in the Lake Tondano, North Sulawesi, Indonesia.

3. Study design

The study employed a survey method known as the concentration count, as described by Helvoort (1981). This approach involved establishing a 6.5 km transect along the lake's shoreline and selecting 10 strategic observation points. The observation points were not chosen purely at random but were instead selected using a stratified random sampling method to ensure they were representative of the lake's diverse habitat conditions. Specifically, the points were chosen based on three key ecological criteria: (1) the presence of dense riparian vegetation, such as *Typha angustifolia* and *Pandanus tectorius*, which serves as a refuge for waterbirds; (2) shallow water areas (depths <2 m), which are primary foraging habitats; and (3) varying densities of water hyacinth cover (categorized as low: <20%, medium: 20-50%, and high: >50%). This deliberate selection process was critical for allowing the researchers to directly assess the impact of water hyacinth on waterbird distribution and abundance, strengthening the validity of the correlational findings. Each observation point had a circular observation radius of 50 m. The overall transect covered both the lake's edges and a central area, with water depths ranging from 1.2 to 3.5 m.

4. Observation Procedures

Observations were conducted twice daily to capture peak waterbird activity: in the morning (06.00-10.00 WITA) and late afternoon (15.00-18.00 WITA). The boat maintained a constant speed of 5 km/h to minimize disturbance to the birds. At each of the 10 observation points, data were collected over a 20-minute period. The total daily observation time was 4 hours. The specific data collected included:

1). Species and Abundance: Waterbird species were identified and counted using binoculars and cameras. Local guides familiar with the species' common names assisted, and these were cross-referenced with scientific names using the Beehler et al. (2001) field guide. All sightings were documented with photographs for later verification by independent ornithologists.

2). Environmental Conditions: The density of water hyacinth was estimated visually as a percentage of surface cover within the 50 m radius and was subsequently validated using aerial imagery from the drone, which had a resolution of 4K and an accuracy of ±5%. Water depth was measured using the echosounder. All data were meticulously recorded on field data sheets.

5. Data Analysis

The collected data were subjected to a multi-stage analysis. First, the total number and types of waterbird species were tabulated, and their conservation status was referenced from the IUCN Red List. Relative abundance (Ki) was calculated for each species using the following formula:

$$Ki = \frac{\mathrm{ni}}{\mathrm{N}} \text{ x } 100\%$$

Where *ni* is the total number of individuals of species *i,* and *N* is the total number of individuals of all species found. Relative abundance was then categorized as Dominant (>8), Abundant (2.1-8), Frequent (1.1-2), Occasional (0.1-1), or Rare (<0.1).

The Shannon-Wiener diversity index (H') was computed using the formula:

$$H' = -\sum (pi \ln pi)$$

Where *pi* is the proportion of individuals of species i relative to the total number of individuals. The calculation was performed using the *R* statistical software, specifically the 'vegan' package.

To investigate the relationship between waterbird abundance and environmental factors, a simple linear regression analysis was performed. The dependent variable was waterbird abundance, and the independent variables were water hyacinth coverage (as a percentage) and water depth (in meters). The analysis was conducted using R software, with a significance level set at $p<0.05$. Pearson's correlation coefficient (r) was also calculated to assess the strength of the relationships. The species identification was verified by two independent ornithologists based on the collected photographs and behavioral descriptions to ensure accuracy.

Results and discussion

1. Results

1.1. Species Composition

The survey conducted from February to October 2025 identified eight species of waterbirds within the Tondano Lake ecosystem, representing three families: Ardeidae (six species), Recurvirostridae (one species), and Alcedinidae (one species). Table 1 lists the species recorded. Compared to historical data from North Sulawesi wetlands which typically harbor greater avian richness (Santoso et al., 2019), the presence of only eight species suggests a simplified community structure potentially linked to habitat loss. This limited taxonomic representation indicates a significant reduction in ecological niches compared to undisturbed freshwater habitats in the region. Representative waterbird species recorded during the study are shown in Figures 2a-2h.

Table 1. Identified Waterbird Species in Tondano Lake, North Sulawesi, Indonesia

No	Local Name	Scientific Name	Family
1	Kuntul Besar	*Egretta alba*	Ardeidae
2	Kuntul Kecil	*Egretta garzetta*	Ardeidae
3	Kuntul Kerbau	*Bubulcus ibis*	Ardeidae
4	Burung Pancang	*Himantopus leucocephalus*	Recurvirostridae
5	Raja Udang	*Alcedo atthis*	Alcedinidae
6	Cangak Merah	Ardea purpurea	Ardeidae
7	Blekok sawah	*Ardeola speciosa*	Ardeidae
8	Kowak Malam Merah	*Nycticorax caledonicus*	Ardeidae

1.2. Abundance and seasonal variation

Across the multi-season observation period, a total of 1,864 individual waterbirds were recorded throughout Tondano Lake. Overall abundance showed a gradual increase from the early wet months (February–May) toward the dry season (June–October), with peak numbers observed between August and October, coinciding with reduced rainfall, lower water levels, and wider availability of exposed feeding grounds along the littoral zone. This seasonal rise in abundance suggests that water level fluctuation and vegetation cover strongly influence bird activity and detectability.

Among the eight recorded species, *Egretta garzetta* emerged as the most abundant and widely distributed species (29.1%), indicating its adaptability to both shallow and moderately vegetated habitats. In contrast, *Alcedo atthis* was the least common (4.8%), reflecting its preference for clear, unobstructed waters that were often limited during the observation period. The presence of both resident and partially migratory species throughout the survey further demonstrates the ecological importance of Tondano Lake as a year round foraging and nesting habitat**.** The monthly abundance patterns and corresponding relative proportions of each species are detailed in Table 2.

Table 2. Monthly abundance of waterbirds recorded at Tondano Lake, North Sulawesi, from February to October 2025.

Species	Family	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Total	Mean ± SD	Rel. Abund. (%)
Egretta alba	Ardeidae	21	23	26	26	27	28	30	28	28	237	26.3 ± 2.8	12.7
Egretta garzetta		48	54	56	56	60	64	69	68	68	543	60.3 ± 7.0	29.1
Bubulcus ibis		23	25	26	34	33	31	33	27	27	259	28.8 ± 3.7	13.9
Ardea purpurea		17	18	20	16	18	19	20	22	23	173	19.2 ± 2.2	9.3
Ardeola speciosa		19	22	22	20	22	25	26	25	22	203	22.6 ± 2.3	10.9
Nycticorax caledonicus		11	13	14	15	17	18	18	17	16	139	15.4 ± 2.3	7.5
Himantopus leucocephalus	**Recurvirostridae**	19	21	24	24	25	26	28	27	26	220	24.4 ± 3.0	11.8
Alcedo atthis	**Alcedinidae**	9	10	9	6	10	10	11	12	13	90	10.0 ± 2.0	4.8
Grand Total (all species)		**167**	**186**	**197**	**197**	**212**	**221**	**235**	**226**	**223**	**1,864**	**207 ± 15.6**	**100**
Seasonal totals:													
Wet Season (Feb-May)		**747**											
Dry Season (Jun-Oct)						**1,117**							

Note: *Values represent the number of individual birds observed per month. Wet season = February–May; Dry season = June–October. Relative abundance (%) was calculated from the total individuals across all months. Bold values indicate peak counts during the dry season.*

1.3. Species Diversity

Based on the total individual counts obtained from February to October 2025, the Shannon-Wiener diversity index (H') for the waterbird community was calculated to be 1.92. According to the criteria established by Magurran (1988)**,** this value represents a moderate level of species diversity, indicating a community with balanced species representation but potential ecological stress. No abrupt shifts in species composition occurred between months, although minor fluctuations in abundance were observed across seasons. Table 3 presents the detailed calculation of the Shannon-Wiener index, ensuring transparency and reproducibility of the results

Tabel 3. Shannon-Wiener Diversity Index Calculation

No	Species	ni	pi	ln (pi)	pi ln (pi)
1	*Egretta alba*	237	0.127	−2.066	−0.263
2	*Egretta garzetta*	543	0.291	−1.234	−0.359
3	*Bubulcus ibis*	259	0.139	−1.973	−0.274
4	*Himantopus leucocephalus*	220	0.118	−2.138	−0.252
5	*Alcedo atthis*	90	0.048	−3.045	−0.146
6	*Ardea purpurea*	173	0.093	−2.377	−0.221
7	*Ardeola speciosa*	203	0.109	−2.218	−0.243
8	*Nycticorax caledonicus*	139	0.075	−2.590	−0.194
		N = 1.864		Σ (pi ln pi) = −1.918	
				H' = −Σ (pi ln pi) = 1.92	

1.4. Relationship with environmental variables

The simple linear regression analysis revealed significant negative correlations between waterbird abundance and the two key environmental variables. A strong negative correlation was found with water hyacinth density (r=−0.68, p=0.032, r2=0.46), indicating that as the coverage of water hyacinth increases, the total abundance of waterbirds tends to decrease. Similarly, a significant negative correlation was found with water depth (r=−0.72, p=0.019, r2=0.52), suggesting that the shoaling of the lake is also a major factor negatively impacting the waterbird population.

Table 4. Correlations between Waterbird Abundance and Environmental Factors

Environmental Factor	Correlation Coefficient (r)	P-value (p)	Coefficient of Determination (r2)
Water Hyacinth Density	-0.68	0.032	0.46
Water Depth	-0.72	0.019	0.52

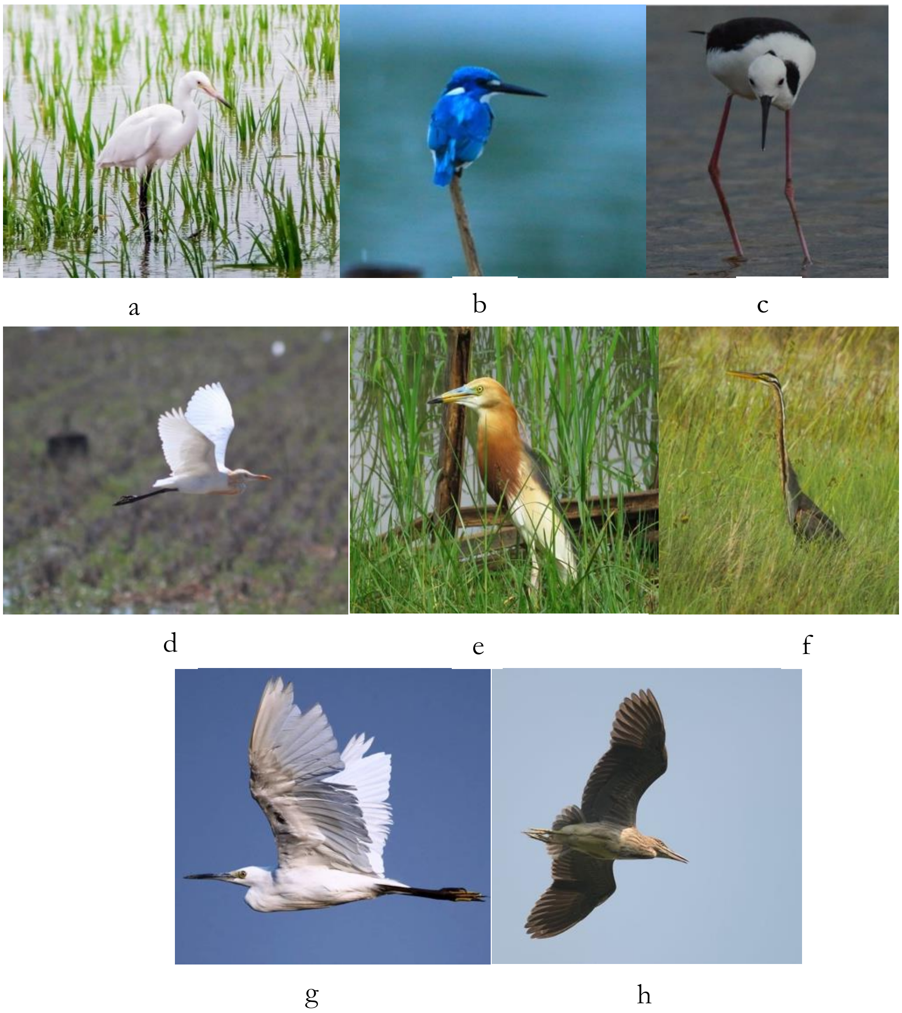

Figure 2 (a). ***Egretta alba*, (b).** ***Alcedo atthi*, (c).** ***Himantopus leucocephalus*, (d).** ***Bubulcus ibis*, (e)** ***Ardeola speciosa*, (f).** ***Ardea purpurea*, (g).** ***Egretta garzetta*, (h).** ***Nycticorax caledonicus.***

2. Discussion

1.5. Waterbird diversity and abundance in Tondano Lake

The study's finding of a Shannon-Wiener diversity index (H' = 1.92) indicates that while the waterbird community remains functional, it has undergone significant "ecological simplification". As a noted, the recording of only eight species from three families is a critical indicator of decline when compared to historical records of Tondano Lake and surrounding wetlands which previously supported higher taxa richness (Santoso et al., 2019). This value (H' = 1.92) is markedly lower than pristine benchmarks like Lake Sentarum (H' = 2.5; Harmoko et al., 2018), yet remains higher than severely degraded industrial wetlands in South Lampung (H' = 1.5; Iswandaru et al., 2025).

This positioning confirms that Tondano Lake is in a state of "moderate ecological stress". The dominance of Egretta garzetta (29.1%), a generalist feeder tolerant of anthropogenic disturbance, suggests that specialized species are being displaced. In contrast, the low abundance of Alcedo atthis (4.8%) a specialist visual predator reflects the direct impact of high turbidity and habitat clogging caused by Eichhornia crassipes proliferation.

1.6. The role of waterbirds and the impact of environmental threats

Waterbirds in Tondano Lake function as "ecosystem guardians," yet their effectiveness is being compromised by synergistic environmental threats. The strong negative correlations between abundance and hyacinth density (r = −0.68) and water depth (r = −0.72) provide the evidence requested to support the claim of degradation. The current richness is a fraction of what is expected in healthy Indonesian freshwater ecosystems, where less-disturbed lakes often support twice the number of families found in this study.

The expansion of water hyacinth, now covering 32.5% of the lake, acts as a physical barrier that has narrowed the ecological niche to only a few resilient species. This is coupled with sedimentation, which has reduced the mean depth to 1.9 ± 0.7 m. These factors create a self-reinforcing "degradation loop" where nutrient enrichment accelerates weed growth, which in turn traps more sediment, further shallowing the lake and driving out deep-water foragers like Nycticorax caledonicus.

1.7. Implication for conservation and policy

This research underscores the significance of waterbirds as reliable bioindicators for monitoring ecosystem health in freshwater systems (Amat & Green 2010). Conservation measures for Tondano Lake should therefore include: (1) Active control of Eichhornia crassipes-through mechanical removal and biological agents such as Neochetina eichhorniae (Center et al. 2014); (2) Sedimentation management-via sustainable land use, riparian vegetation restoration, and targeted dredging in critical habitats (Kumar & Pattnaik 2012); and (3) Community-based monitoring programs, involving citizen science and local stewardship to sustain long term ecological data (Kingsford et al. 2016). Such integrated management aligns with global frameworks for freshwater biodiversity conservation (Dudgeon et al. 2006; Green & Elmberg 2014) and reflects the need for watershed-based ecosystem approaches.

Conclusion

This study demonstrates that Tondano Lake supports a moderate level of waterbird diversity, as reflected by a Shannon-Wiener index of $H' = 1.92. The eight recorded species, primarily from the family Ardeidae, exhibit varied ecological responses to environmental conditions. This species richness and diversity represent a simplified community structure when compared to historical regional data (H' = 2.5; Harmoko et al., 2018), providing evidence of ongoing ecological decline. The dominance of the adaptable *Egretta garzetta* alongside the low abundance of the sensitive specialist *Alcedo atthis* provides a clear signal of ecological stress within the lake ecosystem.

Waterbirds function as key ecosystem guardians, contributing to ecological stability by regulating aquatic populations, dispersing plant seeds, and serving as sensitive bioindicators of environmental quality. The regression analysis revealed significant negative correlations between waterbird abundance and both water hyacinth density ($r = -0.68$, $p = 0.032$) and sedimentation ($r = -0.72$, $p = 0.019$), demonstrating the dual and interacting impacts of these environmental pressures. These findings establish a contribution to the body of research on Indonesian freshwater ecosystems by linking waterbird population dynamics with specific, integrated environmental threats.

The results emphasize that water hyacinth invasion and sedimentation are interconnected, forming a self-reinforcing feedback loop that accelerates ecological degradation. Ensuring the long-term sustainability of the Tondano Lake ecosystem therefore requires integrated conservation strategies that address both stressors simultaneously. This includes actions spanning multiple scales from direct lake management to the restoration of the surrounding watershed. Future research should extend the observation period to further capture migratory dynamics and incorporate additional water-quality parameters. Such comprehensive monitoring would deepen understanding of the complex interactions between waterbirds and their changing environment, thereby strengthening conservation planning for Tondano Lake and comparable tropical freshwater systems.

Author Statements

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Data availability: The raw data supporting the conclusions of this article, including the monthly abundance counts, Shannon-Wiener index calculations, and environmental variable measurements (water hyacinth density and water depth) for Tondano Lake, will be made available by the authors, without undue reservation, to any qualified researcher.

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