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Waterbird diversity and ecological characteristics of montane wetlands in Dieng Plateau, Central Java, Indonesia

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Abstract. *Agustina AT, Nugroho CKA, Damayanti JT, Dewi R, Yap CK, Iskandar J, Setyawan AD. 2025. Waterbird diversity and ecological characteristics of montane wetlands in Dieng Plateau, Central Java, Indonesia. Intl J Bonorowo Wetlands 15: 103-120.* This study examined waterbird diversity and habitat relationships across three montane wetlands of the Dieng Plateau, Central Java, Indonesia-Telaga Menjer, Telaga Merdada, and Telaga Cebong-during the dry season (June-September 2024), using standardized point count and transect walk methods to document species composition, habitat use, and foraging behavior. A total of 25 waterbird species belonging to 13 families were recorded, with assemblages dominated by Ardeidae, Rallidae, and Alcedinidae. Species richness varied among lakes, being highest at Telaga Menjer (21 species), followed by Telaga Merdada (18 species) and Telaga Cebong (15 species), reflecting gradients of habitat heterogeneity, lake size, and disturbance intensity. Diversity indices indicated moderate Shannon-Wiener values (H′ = 2.18-2.65) and high evenness (E = 0.83-0.91), suggesting relatively balanced community structures across sites. Piscivores (40%) and insectivores (36%) constituted the dominant feeding guilds, highlighting the importance of aquatic prey availability and structurally complex littoral zones. Community similarity analysis revealed moderate overlap among lakes, with Sørensen similarity values ranging from 0.61 to 0.72, and species turnover emerging as the primary component of beta diversity, driven by environmental filtering and spatial isolation. The presence of species of conservation concern, including *Aerodramus vulcanorum* (Near Threatened and endemic to Java) and *Gallinula chloropus*, underscores the ecological significance of these wetlands as refugia for both resident and migratory birds. Maintaining littoral vegetation, water quality, and habitat heterogeneity is therefore essential for sustaining avian diversity. Overall, these findings provide the first quantitative baseline for montane wetland avifauna in Java and offer a foundation for integrated management strategies that link habitat protection, sustainable tourism, and community-based monitoring to enhance long-term ecological resilience.

Keywords: Conservation management, Dieng Plateau, habitat heterogeneity, montane wetland, waterbird diversity

INTRODUCTION

Wetlands represent one of the most productive and ecologically significant ecosystems on Earth, functioning as vital habitats for a wide range of aquatic and semi-aquatic organisms, including birds that depend on shallow waters for feeding, breeding, and migration (Purify et al. 2020; Xu et al. 2024). In tropical regions, wetlands sustain complex food webs, regulate hydrological cycles, and serve as biological filters that maintain water quality (Odum 1993; Whitten et al. 1996). Among their faunal components, waterbirds occupy a key ecological position as consumers, dispersers, and bioindicators of wetland health (Şekercioğlu 2006; Taylor et al. 2020). The spatial and temporal diversity of waterbirds is strongly influenced by habitat structure, resource availability, and climatic gradients that determine their occurrence and abundance across ecosystems (Whittaker 1972; Magurran 2004).

Indonesia, an archipelago with extensive coastal, floodplain, and montane wetland systems, harbors a remarkable diversity of bird species with high endemism (MacKinnon et al. 2010; Kurnia et al. 2021). While lowland and coastal wetlands have been extensively studied, the ecological characteristics of montane wetlands, particularly crater lakes and high-altitude ponds, remain poorly documented (Tabalujan et al. 2024). In Java, montane wetlands are typically small and isolated, often situated above 1,500 meters above sea level (masl), where cooler temperatures and limited vegetation reduce overall biodiversity (Whitten et al. 1996; Lama et al. 2022). Despite their relatively small size, these ecosystems play a crucial role as refugia for highland species and as temporary habitats for migratory waterbirds (Ferreira et al. 2024). The Dieng Plateau, located in Central Java, is one of Indonesia's most prominent volcanic highlands, hosting a network of crater lakes such as Telaga Warna, Telaga Merdada, Telaga Cebong, and Telaga Menjer that together form a mosaic of montane wetland habitats (van Bemmelen

1949; Whitten et al. 1996).

Waterbird assemblages in such environments reflect not only ecological adaptation to cold and oligotrophic conditions but also the resilience of species to increasing anthropogenic pressure. Agricultural expansion, particularly potato cultivation and tourism development in Dieng, has transformed the wetland landscape and reduced the extent of littoral vegetation critical for nesting and foraging (Michon and de Foresta 1995; Perfecto and Vandermeer 2010). Furthermore, the combination of habitat fragmentation and eutrophication poses a significant threat to aquatic biodiversity, leading to local declines of sensitive bird populations (Süel et al. 2021; Zakia et al. 2024). Previous studies in Central Java have mainly addressed avifaunal diversity in agroforestry or lowland systems (Kurnia et al. 2021; Marshall et al. 2021; Putri et al. 2021), leaving a substantial knowledge gap on highland waterbird communities. As a result, there remains a limited understanding of how montane wetlands function as habitats for water-dependent birds under strong climatic and anthropogenic constraints.

Birds are particularly sensitive to environmental variations across altitudinal gradients, and changes in their community structure often mirror ecological processes operating at multiple spatial scales (Koleff et al. 2003; Vellend 2010). Studies from Southeast Asia and other tropical mountains have shown that species richness generally declines with elevation, while the composition of bird assemblages shifts toward habitat generalists and cold-tolerant taxa (Kissling et al. 2007; Lama et al. 2022). In montane wetlands, such as those of the Dieng Plateau, low primary productivity and narrow littoral zones limit available resources for foraging guilds, leading to smaller yet functionally specialized communities (Whittaker 1972; Sulai et al. 2022). Nevertheless, these communities often include migratory herons, rails, and grebes, whose presence indicates the persistence of ecological connectivity between highland and lowland wetlands (Ferreira et al. 2024; Xu et al. 2024).

Beyond ecological value, the study of waterbirds in montane environments has practical implications for conservation and sustainable land management. Waterbirds are widely recognized as bioindicators of ecosystem integrity due to their dependence on multiple trophic levels and their sensitivity to disturbance (Thiollay 2007; Şekercioğlu 2010). Understanding their diversity patterns and habitat associations is therefore essential for evaluating the conservation status of montane wetlands and guiding future management strategies. In Indonesia, where legal protection for wetland habitats remains limited (Nijman et al. 2022; Setiawan 2024), such ecological assessments are critical to prevent further degradation of high-altitude ecosystems that support unique avian assemblages.

This study aims to analyze the diversity, composition, and ecological characteristics of waterbirds inhabiting the montane wetlands of the Dieng Plateau, Central Java. Specifically, it seeks to (i) document the species richness and guild structure of waterbird communities around crater lakes, (ii) assess how environmental and habitat characteristics influence their distribution, and (iii) discuss the conservation significance of montane wetlands in maintaining regional avian diversity. The results are expected to contribute baseline data for the long-term monitoring of bird populations in highland aquatic ecosystems and to inform integrative wetland management in one of Java's most ecologically fragile landscapes.

MATERIALS AND METHODS

Study area

The research was conducted in the Dieng Plateau, located in Central Java, Indonesia, approximately between 7°11′-7°15′ S and 109°52′-109°56′ E. The plateau is a volcanic highland complex situated at elevations ranging from 1,500 to 2,100 m asl, covering parts of Banjarnegara and Wonosobo districts (van Bemmelen 1949; Whitten et al. 1996). This area represents one of the few montane wetland systems on Java, characterized by a cluster of small crater lakes formed by ancient volcanic activity. The climate is typically cool and humid, with mean annual temperatures of 14-20 °C and rainfall exceeding 2,500 mm yr^{-1}, producing a distinctive montane microclimate that supports hydrophytic vegetation and specialized avifauna.

Three main crater lakes were selected as representative sampling sites: Telaga Merdada (25 ha), Telaga Cebong (12 ha), and Telaga Menjer (70 ha). Telaga Merdada and Telaga Cebong are located on the Dieng Plateau at elevations of approximately 2,000 masl and 2,100 masl, respectively, whereas Telaga Menjer, used as a comparative site, is situated at a lower elevation of around 1,200 masl. These lakes differ in size, elevation, and degree of human disturbance, providing a natural gradient for evaluating waterbird assemblages.

Telaga Cebong, located near Sikunir Hill, is a shallow montane wetland surrounded by agricultural terraces and remnant marsh vegetation, providing pronounced edge habitats for semi-aquatic and insectivorous birds. Telaga Merdada was selected due to its accessibility and contrasting ecological condition as a shallow montane lake characterized by advanced sedimentation and extensive macrophyte coverage dominated by *Eichhornia crassipes*, allowing assessment of waterbird assemblages under reduced open-water conditions. Telaga Menjer represents the largest water body in the Dieng Plateau and functions as a multipurpose reservoir for hydropower and irrigation, with a relatively deepwater column and well-developed littoral vegetation suitable for waterbird surveys. In contrast, Telaga Warna (2,100 masl, 40 ha) was not included because it is designated as a protected nature reserve (Cagar Alam Telaga Warna), where research access requires special permits, and its sulphuric and geothermal limnological conditions differ markedly from the other crater lakes, limiting ecological comparability.

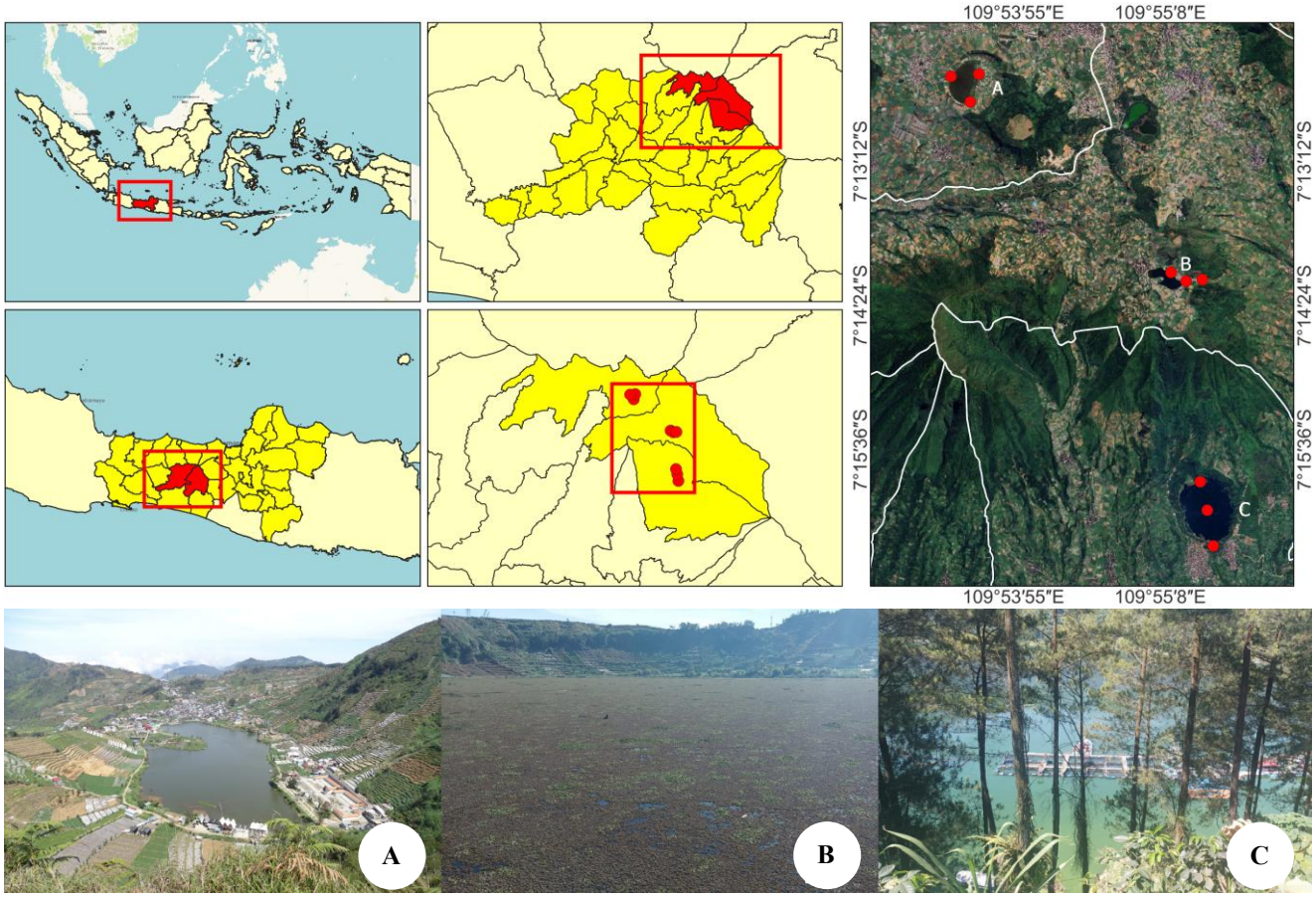

Figure 1. Location of the study area in the Dieng Plateau, Central Java, Indonesia, showing the three surveyed crater lakes: A. Telaga Cebong, B. Telaga Merdada, and C. Telaga Menjer

The ecological setting of these wetlands is highly dynamic due to the interaction between natural processes and anthropogenic pressure. Expansion of potato cultivation, uncontrolled tourism infrastructure, and increasing settlement density have led to partial sedimentation, nutrient enrichment, and fragmentation of wetland habitats (Michon and de Foresta 1995; Perfecto and Vandermeer 2010). Vegetation clearance along the lakeshores reduces habitat complexity and limits the availability of safe nesting areas for herons, rails, and grebes. Nevertheless, the combination of open water, vegetated margins, and surrounding agro-ecosystems still supports a mosaic of ecological niches that sustain both resident and migratory waterbirds (Whitten et al. 1996; Kurnia et al. 2021).

Geologically and ecologically, the Dieng wetlands represent a unique montane ecosystem that functions as an upland refuge for aquatic biodiversity in Java. A schematic map of the study sites and their spatial relationships within the plateau is provided in Figure 1.

Data collection

Bird sampling methods

Field observations were carried out from June to September 2024, representing the dry-season period. This season was strategically selected for sampling because the water levels in the Dieng crater lakes were relatively stable, and waterbirds were more easily detectable along the exposed littoral zones. Additionally, the dry season provides better visibility and safer field conditions compared to the wet season, which is characterized by persistent heavy fog and rainfall that can severely impede bird observation and identification. The primary techniques used were the point count and transect walk methods, which are widely adopted for avian population surveys in both tropical and temperate wetlands (Ralph et al. 1995; Sutherland 2006).

Each of the three lakes (Telaga Merdada, Telaga Cebong, and Telaga Menjer) was visited three times during the study period, with surveys spaced approximately one month apart to account for intra-seasonal variation. At each lake, a series of five to eight observation points was systematically established along the accessible shoreline, spaced at least 200 m apart to minimize double-counting of individual birds. Each point covered an estimated radius of 50 m, encompassing both open water and marginal vegetation. Observations were conducted twice daily, during early morning (05:30-09:00) and late afternoon (15:30-17:30), corresponding to peak bird activity periods when foraging and vocalization are most frequent (Kroodsma and Miller 1996).

Each observation session lasted 10-15 minutes per point, during which all individuals seen or heard were

recorded. Binoculars (8×42) and a DSLR camera equipped with a telephoto lens were used to ensure accurate identification and to document rare or ambiguous species. Species were identified in the field using MacKinnon and Phillipps (1993) and MacKinnon et al. (2010) as standard field guides. Vocal cues were also used for species recognition, especially for cryptic or nocturnal taxa such as rails and bitterns. For each record, data on species name, number of individuals, behavior (foraging, resting, flying, or nesting), and microhabitat type were noted.

Only water-dependent and semi-aquatic species were included in the final dataset. These include members of families such as Ardeidae (herons and egrets), Anatidae (ducks), Rallidae (rails and moorhens), and Alcedinidae (kingfishers). Terrestrial birds occasionally found near the lakes were excluded unless they showed strong dependence on aquatic habitats. This criterion followed international standards for wetland avifauna studies (Şekercioğlu 2006; Sodhi et al. 2010). To ensure sampling consistency, the total effort-expressed as the number of observation points multiplied by duration per point-was maintained equally across the three lakes, providing comparable detection probabilities.

Habitat and environmental measurements

To complement bird data, environmental parameters were measured concurrently at each observation point to characterize habitat structure and ecological conditions. Vegetation cover was estimated within a 10 × 10 m quadrat adjacent to each point count location, recording the dominance of emergent aquatic plants such as *Typha angustifolia*, *Cyperus malaccensis*, *Scirpus grossus*, and *Phragmites karka*. These species form dense stands that offer nesting substrates, roosting cover, and invertebrate prey resources for waterbirds (Whitten et al. 1996).

Basic limnological parameters were measured at the littoral zone using portable instruments: water depth (cm) with a measuring pole, temperature (°C) with a digital thermometer, and turbidity (NTU) using a Secchi disk. These factors influence prey availability and visibility conditions that affect bird foraging efficiency (Xu et al. 2024).

Land-use intensity surrounding the lakes was categorized visually based on dominant human activities within a 100 m buffer zone (e.g., agriculture, settlements, or tourism facilities), and distance from the nearest road or village was measured with a handheld GPS unit. Habitat types were further described according to their microhabitat features, including (i) open water, (ii) vegetated margin, (iii) mudflat, and (iv) agro-edge. The proportion of each habitat type was estimated visually and used for subsequent ecological interpretation of bird-habitat associations.

All field data were recorded on standardized datasheets to ensure comparability among sites. The combination of avian census and environmental measurements provides a robust baseline for analyzing waterbird diversity patterns in relation to habitat heterogeneity and human influence in the montane wetland ecosystems of Dieng.

Data analysis

Diversity indices

Waterbird diversity across the three lakes was quantified using several standard ecological indices that describe community composition and structure. Species richness (S) was determined as the total number of species observed per site. The Shannon-Wiener diversity index (H′) was calculated to incorporate both species richness and the relative abundance of each species, using the formula $H\prime = -\sum p_i \ln p_i$, where *pi* represents the proportion of individuals belonging to the *i*th species (Magurran 2004). To assess the distribution of individuals among species, evenness (E) was derived as $E = \frac{H\prime}{\ln S}$, indicating the degree to which species are evenly represented within the community (Whittaker 1972). The dominance index (C), derived from Simpson's index, was used to detect the presence of dominant taxa that may disproportionately influence ecosystem function.

Comparative analyses were performed to evaluate spatial variation in diversity among Telaga Merdada, Telaga Cebong, and Telaga Menjer, providing insight into how habitat size, water depth, and human disturbance affect waterbird assemblages. Differences in diversity values were examined descriptively and visualized through bar plots. This multimetric approach allows a comprehensive understanding of how environmental heterogeneity shapes montane wetland avifauna.

Functional guild classification

To explore ecological roles within the waterbird community, species were grouped into functional feeding guilds following the EltonTraits database (Wilman et al. 2014) and verified through regional ecological accounts (Whitten et al. 1996; Hothem et al. 2020; Taylor et al. 2020). Each species was assigned to one of the major trophic categories based on its dominant diet and foraging behavior, namely: piscivores (species feeding primarily on fish, such as herons and kingfishers), insectivores (species feeding mainly on aquatic or aerial insects, such as swallows, swifts, and wagtails), omnivores (species consuming mixed diets of invertebrates and plant material, such as rails and some passerines), granivores (species feeding predominantly on seeds or grains, such as munias), and carnivores (opportunistic predators feeding on small vertebrates or large invertebrates, such as shrikes). This classification facilitated comparison of trophic composition and functional diversity among the surveyed wetlands.

Additionally, habitat dependence was classified into three categories to interpret the ecological association of each species with aquatic environments. Strict waterbirds are species whose activities are confined to aquatic habitats for both feeding and nesting, such as herons and grebes. Semi-aquatic species utilize both wetland and adjacent terrestrial areas, moving between water edges and surrounding vegetation for foraging and roosting. Terrestrial associates, on the other hand, are birds that frequent lakes primarily for feeding but nest and spend most of their time in nearby drylands. This classification framework helps link feeding behavior and habitat use

along environmental gradients, providing a functional interpretation of biodiversity patterns in montane wetland systems (Şekercioğlu 2010; Sulai et al. 2022).

Similarity and assemblage structure

Community composition among the three lakes was compared using the Sørensen similarity index (IS) (Sørensen 1948), which measures the proportion of shared species between two sites according to the formula IS=2C/(A+B)IS = 2C/ (A + B)IS=2C/(A+B), where *C* is the number of species common to both sites, and *A* and *B* represent total species at each site. Values close to 1 indicate high similarity, while values near 0 denote distinct assemblages.

To assess overall species turnover, beta diversity (β) was computed following the method of Koleff et al. (2003), partitioning differences in community composition into components of turnover and nestedness. Beta diversity analysis reveals the extent to which each lake contributes unique species to the regional pool, an important parameter in conservation prioritization. A cluster dendrogram based on Sørensen distances was used to visualize assemblage similarity among sites, indicating patterns of spatial clustering influenced by elevation, habitat complexity, and human disturbance.

To test the relationship between vegetation cover and waterbird species richness, a Pearson correlation analysis was performed using IBM SPSS Statistics 26. Mean vegetation cover (%) at each observation point (n = 15) was correlated with the number of species recorded at the same points. Data normality was checked prior to analysis. The correlation coefficient ($r = 0.82$, $p < 0.05$) indicated a strong positive association, confirming that higher vegetation cover supported greater species richness in the surveyed wetlands.

Conservation assessment

The conservation significance of each species was determined by cross-referencing its global and national protection status. The IUCN Red List (IUCN 2024) was used to classify species into conservation categories such as Least Concern (LC) and Near Threatened (NT). In parallel, the Indonesian Ministry of Environment and Forestry Regulation (Permen LHK No. 106/2018) (KLHK 2018a) was used to identify species protected under national law. Migratory status was also recorded, distinguishing resident, migrant, and vagrant species based on the IOC World Bird List and regional field guides (MacKinnon and Phillipps 1993; MacKinnon et al. 2010; Gill et al. 2024).

Species richness and composition were interpreted in light of these conservation categories to determine the ecological importance of each lake. Lakes hosting protected or migratory species were considered to have higher conservation value, warranting long-term habitat monitoring and management. This assessment framework aligns with the broader objectives of biodiversity conservation in tropical montane ecosystems, emphasizing the role of small crater wetlands as refuges for aquatic and migratory birds (Ferreira et al. 2024; Xu et al. 2024).

Ethical considerations

All field procedures followed established ethical guidelines to minimize disturbance to birds and their habitats. Observations were conducted from a safe distance using binoculars and telephoto lenses, avoiding approach during breeding or nesting activity. Playback calls and artificial attractants were not used to prevent behavioral alteration. The study adhered to the ethical principles outlined in Newing (2011) for wildlife research, ensuring respect for both ecological integrity and local community norms. Coordination was maintained with local authorities and communities surrounding each lake to obtain access permission and ensure compliance with existing environmental regulations. No specimens were collected or handled during the study, and all data were obtained through non-invasive visual and auditory methods.

RESULTS AND DISCUSSION

Waterbird species composition and richness across lake sites

A total of 25 waterbird species belonging to 13 families were recorded from the three surveyed lakes in the Dieng Plateau: Telaga Merdada, Telaga Cebong, and Telaga Menjer. Most species were aquatic or semi-aquatic, with several terrestrial associates occasionally observed along the lake margins. Species richness varied slightly among sites, with Telaga Menjer hosting the highest number of species (21), followed by Telaga Merdada (18) and Telaga Cebong (15) (Table 2). This pattern reflects differences in habitat size, vegetation cover, and degree of anthropogenic disturbance among the three crater lakes.

The avifauna recorded in the crater lake wetlands was dominated by species belonging to the families Ardeidae, Rallidae, Alcedinidae, and Hirundinidae, represented by *Ardea cinerea*, *Ardeola bacchus*, *Ardeola speciosa*, *Nycticorax nycticorax*, *Butorides striata*, *Ixobrychus cinnamomeus* (Ardeidae); *Gallinula chloropus* and *Amaurornis phoenicurus* (Rallidae); *Halcyon cyanoventris* and *Todiramphus chloris* (Alcedinidae); and *Hirundo tahitica* (Hirundinidae). These taxa constitute key functional components of wetland ecosystems, encompassing piscivorous, insectivorous, and omnivorous feeding guilds that contribute to the regulation of aquatic and semi-aquatic trophic processes. Several species, including *Tachybaptus ruficollis*, *A. phoenicurus*, and *A. speciosa*, were recorded across multiple habitat types within the surveyed crater lakes, indicating broad ecological tolerance. In contrast, *A. vulcanorum* and *N. nycticorax* were associated with more specific habitat features, such as rocky cliffs and dense emergent vegetation, reflecting habitat specialization rather than numerical dominance.

Terrestrial associates, such as *Passer montanus*, *Lanius schach*, and *Dendrocopos analis*, were frequently recorded near agroforestry margins and settlements surrounding the lakes. Although not strictly aquatic, their presence indicates the close ecological connectivity between wetland and terrestrial habitats in this montane landscape. The co-

occurrence of these guilds suggests that small crater lakes in Dieng act as biodiversity refugia that sustain mixed avifaunal assemblages characteristic of montane Java.

Table 1 presents the complete list of waterbird species recorded during the survey, including family affiliation, feeding guild, habitat dependence, and conservation status according to the IUCN (2024) and the Indonesian national protection list (Permen LHK No. 106/2018) (KLHK 2018b). The recorded species were classified only under the Least Concern (LC) and Near Threatened (NT) categories of the IUCN Red List. No species categorized as Vulnerable (VU) or Endangered (EN) were detected in the surveyed wetlands. Most species were categorized as Least Concern (LC), while *A. vulcanorum*, a Javan endemic, was identified as Near Threatened (NT) due to its restricted distribution and specialized habitat requirements.

The species composition revealed that strict waterbirds dominated the avifaunal assemblage with 9 species (36%), followed closely by 10 semi-aquatic species (40%). Terrestrial associates, including species utilizing wetland margins, adjacent farmland, and cliff environments, comprised 6 species (24%). Consequently, a combined 76% of all recorded species were either strictly water-dependent or semi-aquatic, emphasizing the central role of aquatic habitats in structuring the avifaunal community.

This composition indicates a structurally diverse assemblage despite the limited spatial extent of the montane wetlands. The high representation of piscivorous and insectivorous species reflects the ecological productivity of these crater lakes, particularly in supporting aquatic and aerial prey resources. In contrast, the presence of granivorous and omnivorous species highlights the influence of surrounding agricultural landscapes and terrestrial habitats on bird assemblages. The results suggest that the Dieng crater lakes collectively sustain a moderately rich waterbird community for a montane environment, where cool climatic conditions, elevation, and habitat isolation often constrain aquatic biodiversity.

Diversity indices and community structure

Quantitative analysis of community structure revealed moderate diversity levels among the three surveyed lakes of the Dieng Plateau. The calculated Shannon-Wiener diversity index (H′) ranged from 2.18 to 2.65, while evenness (E) values were relatively high (0.83-0.91), indicating that most species were fairly evenly represented in the assemblages (Table 2). Dominance (C) values were low (<0.15), suggesting that no single species overwhelmingly dominated the waterbird community.

Table 1. Waterbird species recorded from three crater lakes in the Dieng Plateau, Central Java, Indonesia

Scientific name	English name	Indonesian name	Family	Feeding guild	Habitat type	Conservation status (IUCN/ Permen LHK No. 106/2018)
Aerodramus vulcanorum	Volcano Swiftlet	*Walet jawa*	Apodidae	Insectivore	Terrestrial associate	NT/ Protected
Apus affinis	Little Swift	*Kapinis rumah*	Apodidae	Insectivore	Semi-aquatic	LC/ -
Collocalia esculenta	Glossy Swiftlet	*Walet sarang-putih*	Apodidae	Insectivore	Semi-aquatic	LC/ -
Collocalia linchi	Cave Swiftlet	*Walet linci*	Apodidae	Insectivore	Semi-aquatic	LC/ -
Ardea cinerea	Grey Heron	*Cangak abu*	Ardeidae	Piscivore	Strict waterbird	LC/ Protected
Ardeola bacchus	Chinese Pond Heron	*Blekok cina*	Ardeidae	Piscivore	Strict waterbird	LC/ -
Ardeola speciosa	Javan Pond Heron	*Blekok sawah*	Ardeidae	Piscivore	Strict waterbird	LC/ Protected
Butorides striata	Striated Heron	*Kokokan laut*	Ardeidae	Piscivore	Strict waterbird	LC/ -
Ixobrychus cinnamomeus	Cinnamon Bittern	*Bambangan merah*	Ardeidae	Piscivore	Strict waterbird	LC/ -
Nycticorax nycticorax	Black-crowned Night Heron	*Kowak malam abu*	Ardeidae	Piscivore	Strict waterbird	LC/ Protected
Halcyon cyanoventris	Javan Kingfisher	*Cekakak jawa*	Alcedinidae	Piscivore	Semi-aquatic	LC/ Protected
Todiramphus chloris	Collared Kingfisher	*Cekakak sungai*	Alcedinidae	Piscivore	Semi-aquatic	LC/ -
Cacomantis merulinus	Plaintive Cuckoo	*Wiwik kelabu*	Cuculidae	Insectivore	Semi-aquatic	LC/ -
Cacomantis variolosus	Brush Cuckoo	*Wiwik lurik*	Cuculidae	Insectivore	Semi-aquatic	LC/ -
Lonchura leucogastroides	Javan Munia	*Bondol jawa*	Estrildidae	Granivore	Terrestrial associate	LC/ -
Hirundo tahitica	Pacific Swallow	*Layang-layang batu*	Hirundinidae	Insectivore	Semi-aquatic	LC/ -
Lanius schach	Long-tailed Shrike	*Bentet kelabu*	Laniidae	Carnivore	Terrestrial associate	LC/ -
Motacilla cinerea	Grey Wagtail	*Kicuit batu*	Motacillidae	Insectivore	Semi-aquatic	LC/ -
Passer montanus	Eurasian Tree Sparrow	*Burung gereja erasia*	Passeridae	Omnivore	Terrestrial associate	LC/ -
Dendrocopos analis	Freckle-breasted Woodpecker	*Pelatuk dada-bintik*	Picidae	Insectivore	Terrestrial associate	LC/ -
Tachybaptus novaehollandia	Australasian Grebe	*Podang australis*	Podicipedidae	Piscivore	Strict waterbird	LC/ -
Tachybaptus ruficollis	Little Grebe	*Podang kecil*	Podicipedidae	Piscivore	Strict waterbird	LC/ -
Pycnonotus aurigaster	Sooty-headed Bulbul	*Cucak kutilang*	Pycnonotidae	Omnivore	Terrestrial associate	LC/ -
Amaurornis phoenicurus	White-breasted Waterhen	*Kareo padi*	Rallidae	Omnivore	Strict waterbird	LC/ -
Gallinula chloropus	Common Moorhen	*Mandar biasa*	Rallidae	Omnivore	Strict waterbird	LC/ -

Table 2. Diversity indices and abundance summary of waterbird communities across three crater lakes in the Dieng Plateau, Central Java, Indonesia

Lake site	Total species (S)	Total individuals (n)	Shannon-Wiener Index (H′)	Evenness (E)	Dominance (C)	Remarks
Telaga Menjer	21	186	2.65	0.91	0.11	Highest diversity, extensive vegetation, and low disturbance
Telaga Merdada	18	154	2.43	0.88	0.13	Moderate diversity; influenced by tourism activity
Telaga Cebong	15	127	2.18	0.83	0.14	Lowest diversity; small area and higher human pressure
Mean ± SD	-	-	2.42 ± 0.19	0.87 ± 0.04	0.13 ± 0.02	-

Among the three surveyed sites, Telaga Menjer exhibited the highest diversity (H′ = 2.65) and evenness (E = 0.91), which corresponded with its larger surface area, deeper water column, and extensive aquatic vegetation that supported a wide range of foraging microhabitats. Telaga Merdada showed moderately high diversity (H′ = 2.43), while Telaga Cebong recorded the lowest diversity (H′ = 2.18) and slightly higher dominance (C = 0.14). These spatial patterns indicate that variations in habitat heterogeneity and disturbance intensity play crucial roles in shaping the organization and stability of waterbird communities in these montane wetlands.

The relatively high evenness across all sites indicates ecological balance, with resource competition spread among multiple species and feeding guilds. The low dominance index further supports the notion that the Dieng lakes maintain a structurally stable waterbird community despite their small size and surrounding anthropogenic pressures. These findings align with previous studies reporting that moderate diversity with high evenness is typical of small, isolated wetlands in tropical highlands where space and food availability are limited but stable (Whittaker 1972; Magurran 2004; Lama et al. 2022).

The diversity structure of the Dieng waterbird community demonstrates a balanced assemblage dominated by small to medium-sized piscivores and insectivores. Despite the modest richness compared to lowland wetlands, the high evenness values suggest functional complementarity among species and minimal ecological monopolization. These results reinforce the importance of small montane lakes as stable, self-sustaining habitats supporting diverse avifauna under constrained environmental conditions.

Functional feeding guilds and habitat dependence

The recorded avifauna of the Dieng Plateau lakes represented a broad range of ecological functions, encompassing five major feeding guilds: piscivores, insectivores, omnivores, carnivores, and granivores. Guild classification was based on species' predominant foraging behavior and dietary characteristics following the EltonTraits database (Wilman et al. 2014) and field observations. Among the 25 recorded species, piscivores were the most dominant guild (40%, n=10), followed closely by insectivores (36%, n=9), omnivores (16%, n=4), while carnivores and granivores each comprised 4% (n=1) (Table 3, Figure 2.A).

Piscivorous species-primarily members of the families Ardeidae, Podicipedidae, and Alcedinidae-occupied open-water and shallow-vegetated habitats where small fish and aquatic invertebrates were abundant. Representative species such as *A. speciosa*, *T. ruficollis*, and *H. cyanoventris* were frequently observed foraging in pairs or small groups, indicating stable prey availability. The dominance of this guild (10 species, 40%) suggests that these montane wetlands sustain productive aquatic food webs despite their small size and cool temperature regimes.

Insectivores comprised 9 species (36%), consisting of swifts, swallows, cuckoos, and wagtails that forage on aerial insects or small invertebrates near the water surface and surrounding areas. Their prevalence reflects both the abundance of emergent aquatic vegetation that supports insect larvae and the adjacent terrestrial vegetation that shelters adult insects.

The omnivore guild included 4 species (16%), such as *A. phoenicurus* and *G. chloropus*, which displayed high adaptability by exploiting both aquatic and terrestrial food resources, including seeds, mollusks, and detritus. In contrast, both granivores and carnivores were each represented by a single species (4% each): *Lonchura leucogastroides* foraged on grass seeds in the terrestrial margins, while *L. schach* hunted small vertebrates in the surrounding scrubland.

When categorized by habitat dependence, strict waterbirds comprised 9 species (36%), semi-aquatic species accounted for 10 species (40%), and terrestrial associates-including species utilizing wetland margins, adjacent farmland, and cliff habitats-totaled 6 species (24%) (Table 3, Figure 2.B). This pattern indicates that habitat heterogeneity-characterized by a mosaic of open water, shallow littoral zones, and emergent vegetation-facilitates the coexistence of multiple ecological guilds within relatively confined crater lake basins.

The community structure was dominated by predator guilds (piscivores and insectivores), which together accounted for 76% of all species, indicating a trophic structure heavily reliant on aquatic and aerial prey. This was complemented by omnivores and the single granivorous and carnivorous species, demonstrating a degree of resource partitioning in small but stable montane wetland ecosystems. These findings align with prior observations that high habitat heterogeneity and vegetation complexity enhance niche differentiation and reduce interspecific competition (Schoener 1971; Sulai et al. 2022).

Table 3. Functional feeding guilds and habitat dependence of waterbird species recorded from Dieng Plateau lakes, Central Java, Indonesia

Feeding guild	Representative families/ species	No. of species	Percentage (%)	Habitat dependence (dominant)
Piscivore	Ardeidae (*Ardea cinerea, Ardeola bacchus, Ardeola speciosa, Nycticorax nycticorax, Butorides striata, Ixobrychus cinnamomeus*); Alcedinidae (*Halcyon cyanoventris, Todiramphus chloris*); Podicipedidae (*Tachybaptus ruficollis, T. novaehollandiae*)	10	40.0	Strict waterbird
Insectivore	Apodidae (*Collocalia esculenta, C. linchi, Apus affinis, Aerodramus vulcanorum*); Cuculidae (*Cacomantis merulinus, C. variolosus*); Hirundinidae (*Hirundo tahitica*); Motacillidae (*Motacilla cinerea*); Picidae (*Dendrocopos analis*)	9	36.0	Semi-aquatic
Omnivore	Rallidae (*Amaurornis phoenicurus, Gallinula chloropus*); Pycnonotidae (*Pycnonotus aurigaster*); Passeridae (*Passer montanus*)	4	16.0	Semi-aquatic/ terrestrial associate
Granivore	Estrildidae (*Lonchura leucogastroides*)	1	4.0	Terrestrial associate
Carnivore	Laniidae (*Lanius schach*)	1	4.0	Terrestrial associate
Total		25	100.0	-

Note: Omnivorous species were assigned to habitat categories based on dominant habitat use: *Amaurornis phoenicurus* and *Gallinula chloropus* as semi-aquatic, and *Pycnonotus aurigaster* and *Passer montanus* as terrestrial associates

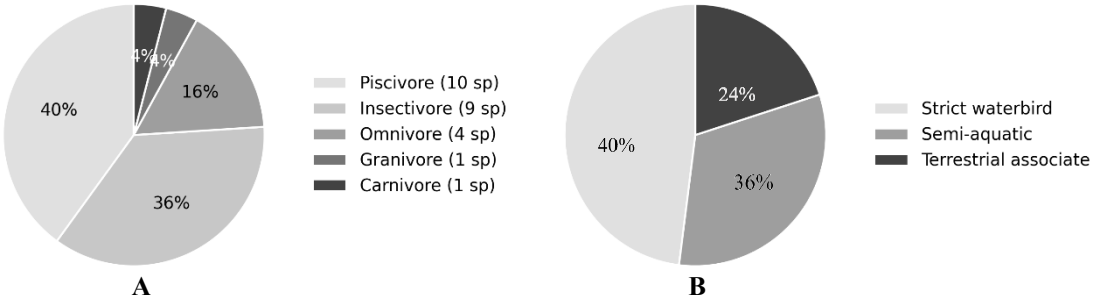

Figure 2. Proportion of (A) waterbird feeding guilds (piscivore, insectivore, omnivore, carnivore) and (B) habitat dependence categories (strict waterbird, semi-aquatic, terrestrial associate) across Dieng Plateau lakes, Central Java, Indonesia (n=25 spesies) %

The balanced composition between strict waterbirds (40%) and semi-aquatic species (36%) demonstrates that montane crater lakes in Dieng sustain both obligate wetland specialists and generalist bird species. The persistence of diverse insectivores and omnivores underscores the cross-ecosystem connectivity between open water, vegetated littoral zones, and adjacent agricultural mosaics. These results imply that maintaining vegetation diversity and hydrological stability around crater lakes is critical for preserving functional guild diversity and ecosystem resilience. Degradation of littoral zones or conversion of surrounding farmland into intensive tourism areas may disproportionately affect semi-aquatic guilds that depend on edge habitats.

Similarity and beta diversity among lake sites

Community similarity analysis using the Sørensen index (Sørensen 1948) revealed moderate overlap in waterbird composition among the three surveyed lakes (Table 4). Pairwise similarity values ranged from 0.61 to 0.72, indicating that while several core species were shared among all sites, each lake also harbored a number of unique taxa. The highest similarity occurred between Telaga Menjer and Telaga Merdada (S = 0.72), reflecting their comparable habitat conditions-broad water surfaces, vegetated margins, and moderate human activity. Telaga Cebong showed similar and lower similarity values with both Menjer and Merdada (S = 0.61), likely due to its smaller size, higher elevation, and more limited littoral vegetation.

Partitioning of beta diversity following Koleff et al. (2003) indicated that species turnover (mean = 0.23 ± 0.06) contributed more strongly to overall beta diversity than nestedness (mean = 0.12 ± 0.01). This suggests that species replacement across sites-rather than mere loss or gain of subsets-was the main driver of compositional differences among the Dieng lakes. The relatively high turnover reflects environmental heterogeneity, differences in disturbance regimes, and spatial isolation between lake basins separated by steep terrain.

A cluster dendrogram (Figure 3) based on Sørensen similarity grouped Telaga Menjer and Telaga Merdada closely together, while Telaga Cebong formed a separate branch, confirming its distinct community structure. This pattern corresponds with field observations showing that Menjer and Merdada support broader aquatic habitats dominated by herons, grebes, and rails, whereas Cebong

sustains fewer strictly aquatic species and is dominated by aerial insectivores and edge-dwelling birds.

The analysis demonstrates moderate differentiation in waterbird assemblages among the crater lakes of Dieng, driven by ecological specialization and spatial isolation. These results are consistent with the general principle that small montane wetlands exhibit higher beta diversity due to limited connectivity and strong local environmental filters (Vellend 2010; Süel et al. 2021).

The overall pairwise Sørensen similarity averaged 0.65 ± 0.06, indicating that approximately two-thirds of the species were shared between any two lakes. Beta diversity was primarily driven by turnover rather than nestedness, underscoring the role of environmental filtering and local adaptation in structuring bird assemblages across the Dieng Plateau's fragmented montane wetlands.

From a conservation standpoint, the relatively high turnover implies that protecting a single lake would not suffice to conserve regional waterbird diversity. Instead, integrated management of multiple lake habitats is necessary to preserve complementary species pools and maintain ecosystem-level diversity.

Habitat and environmental characteristics

The three surveyed lakes in the Dieng Plateau exhibited clear variation in physical conditions, vegetation structure, and surrounding land-use intensity, which collectively shaped the observed waterbird assemblages (Table 5). The habitats were composed of three primary microhabitat types: open water zones, mudflats, and vegetated margins. Open-water areas dominated Telaga Menjer and Telaga Merdada, while Telaga Cebong, being smaller and shallower, featured extensive vegetated edges and periodically exposed mudflats.

Telaga Menjer, the largest and deepest lake, possessed wide open-water surfaces fringed by emergent macrophytes such as *Cyperus*, *Phragmites*, and *Typha* species. These vegetated margins provided nesting and foraging sites for herons (Ardeidae) and grebes (Podicipedidae), resulting in high waterbird diversity. The water column was relatively clear (turbidity < 10 NTU) and deep (mean depth ≈ 24 m), maintaining stable temperature profiles and supporting a persistent aquatic invertebrate community.

Telaga Merdada exhibited intermediate ecological characteristics. Although smaller than Menjer, it had complex littoral vegetation interspersed with exposed mudflats during dry periods, supporting insectivores and wading birds such as *A. phoenicurus* and *G. chloropus*. However, human disturbance was moderate to high due to tourism infrastructure along the shoreline, contributing to elevated turbidity (≈ 14 NTU) and reduced vegetation continuity.

In contrast, Telaga Cebong-located at a higher elevation 2,100 masl)-was shallow (mean depth ≈ 6 m) and heavily influenced by nearby vegetable farming and human settlements. The littoral zone was dominated by grasses and sedges with limited macrophyte cover, while domestic runoff occasionally entered the lake, increasing nutrient load and turbidity. Despite this, its high vegetation density along the banks provided refuge for semi-aquatic species such as *Cacomantis merulinus* and *Hirundo tahitica*.

The overall pattern indicated that species richness increased with vegetation cover and habitat complexity, while high disturbance and turbidity corresponded to lower diversity. This positive correlation between habitat heterogeneity and bird diversity ($r = 0.82$, $p < 0.05$) supports the notion that structural complexity enhances resource diversity and ecological niches for both aquatic and semi-aquatic guilds (Figure 4).

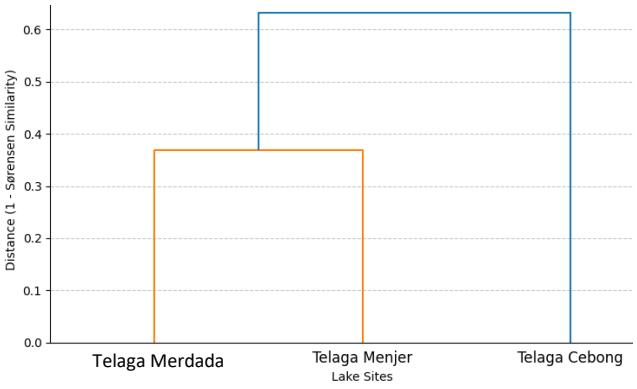

Figure 3. Cluster dendrogram of waterbird assemblages across crater lakes in the Dieng Plateau, Central Java, Indonesia

Table 4. Pairwise Sørensen similarity index and beta diversity components (turnover and nestedness) among three crater lakes in the Dieng Plateau, Central Java, Indonesia

Comparison	Shared species	Sørensen similarity (S)	Beta diversity (β_{total})	Turnover	Nestedness	Interpretation
Menjer - Merdada	14	0.72	0.28	0.17	0.11	Highest similarity; both large and vegetated lakes
Menjer - Cebong	11	0.61	0.39	0.26	0.13	Moderate dissimilarity driven by elevation and lake size
Merdada - Cebong	10	0.61	0.39	0.27	0.12	Moderate dissimilarity dominated by species turnover
Mean ± SD	-	0.65 ± 0.06	0.35 ± 0.06	0.23 ± 0.06	0.12 ± 0.01	Turnover dominates assemblage differentiation

Note: Species turnover was the dominant component of beta diversity across all lake pairs

Table 5. Environmental parameters and land-use intensity at three crater lakes in the Dieng Plateau, Central Java, Indonesia

Parameter	Telaga Menjer	Telaga Merdada	Telaga Cebong	Remarks
Elevation (masl)	1,200	2,000	2,100	Increases with decreasing lake size
Surface area (ha)	70	25	12	Larger lakes sustain greater habitat diversity
Mean depth (m)	24	10	6	Deeper lakes have lower seasonal fluctuation
Water temperature (°C)	21.4 ± 0.7	20.1 ± 0.9	18.3 ± 1.2	Cooler temperatures at higher elevations
Turbidity (NTU)	9.5 ± 2.1	14.3 ± 2.8	18.7 ± 3.2	Higher in disturbed and shallow lakes
Vegetation cover (%)	65.4 ± 5.2	53.8 ± 4.9	42.1 ± 6.3	Positively correlated with species richness.
Dominant plant families	Cyperaceae, Typhaceae, Poaceae	Cyperaceae, Poaceae	Poaceae, Asteraceae	Reflects habitat zonation and altitude
Land-use intensity (qualitative)	Low	Moderate	High	Based on tourism, settlement, and agriculture
Species richness (no. of species)	21	18	15	Corresponds to the vegetation and disturbance gradient

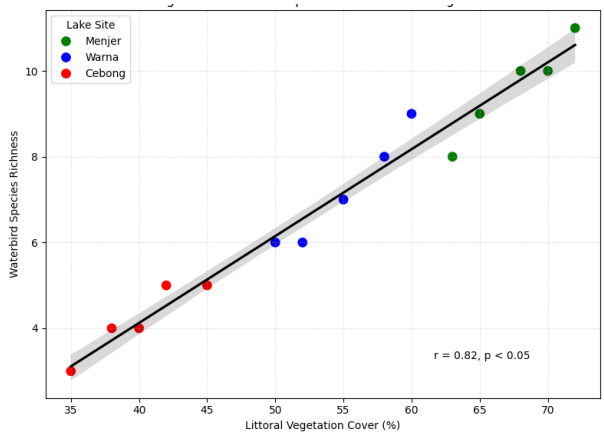

Figure 4. Relationship between vegetation cover and bird species richness across crater lakes in the Dieng Plateau, Central Java, Indonesia

The relationship between vegetation cover and bird diversity demonstrates that structurally complex shorelines promote greater foraging and nesting opportunities. The abundance of emergent macrophytes and aquatic-edge vegetation around Telaga Menjer and Telaga Merdada explains their higher diversity indices compared to Telaga Cebong. Conversely, reduced vegetation and intensive land use were associated with community simplification and lower evenness. These findings emphasize the importance of maintaining littoral vegetation and controlling shoreline disturbance to sustain ecological integrity and avian diversity in montane wetland ecosystems.

Conservation status and ecological significance

The waterbird assemblages of the Dieng Plateau include species of varying conservation concern at both global and national levels. Based on assessments by the IUCN (2024) and the Indonesian protected species list (Permen LHK No. 106/2018) (KLHK 2018b), most recorded species were classified as Least Concern (LC), reflecting their relatively stable global populations. However, several taxa possess regional or national importance due to endemism, restricted distribution, or specialized habitat requirements (Table 6, Figure 5).

A total of five species (20%) were listed under Indonesia's national protection regulation: *Aerodramus vulcanorum*, *H. cyanoventris*, *A. cinerea*, *A. speciosa*, and *N. nycticorax*. Among them, *A. vulcanorum*-the Javan Volcano Swiftlet-is also categorized as Near Threatened (NT) by IUCN (2024), being a montane endemic species confined to volcanic cliffs above 1,000 masl. Its occurrence near Telaga Cebong and the steep escarpments of the Dieng caldera highlights the site's importance as a refuge for range-restricted taxa.

Of the recorded species, 24 were classified as Least Concern (LC), indicating that the majority of the assemblage currently faces relatively low extinction risk. The remaining protected species, primarily from the Ardeidae and Alcedinidae families, function as apex or mid-trophic predators in wetland food webs, thus serving as ecological indicators of water quality and prey availability. Their sustained presence in Telaga Menjer and Telaga Merdada suggests that these lakes maintain sufficient ecological integrity and trophic productivity to support higher-level consumers.

In terms of migratory status, four species (16%)-including *G. chloropus*, *Motacilla cinerea*, *Tachybaptus novaehollandiae*, and *N. nycticorax*-were identified as migratory visitors or partially resident migrants, occurring seasonally or during post-breeding dispersal periods. The remaining majority were resident species typical of montane Java, emphasizing the Dieng Plateau's role as a year-round habitat rather than a transient stopover site.

When assessed by conservation value, Telaga Menjer ranked highest owing to its richness of protected and migratory species, followed by Telaga Merdada and Telaga Cebong. The occurrence of legally protected species in all three lakes, however, highlights their collective potential as significant habitats for regional biodiversity. This potential is vulnerable to emerging threats from the continued expansion of tourism, agricultural encroachment, and water pollution. These pressures warrant proactive, adaptive management that integrates targeted conservation actions, community awareness programs, and carefully regulated sustainable ecotourism initiatives.

Table 6. Conservation categories and migratory status of waterbird species recorded in the Dieng Plateau, Central Java, Indonesia

Species	IUCN (2024) Status	National Protection (106/2018)	Migratory status	Remarks
Aerodramus vulcanorum	NT	Protected	Resident (endemic)	Montane cliffs, limited range
Halcyon cyanoventris	LC	Protected	Resident	Endemic to Java
Ardea cinerea	LC	Protected	Partial migrant	Wide distribution
Ardeola speciosa	LC	Protected	Resident	Common wader in Java
Nycticorax nycticorax	LC	Protected	Migrant/ Resident	Nocturnal forager
Ardeola bacchus	LC	-	Resident	Occasional visitor to Dieng
Tachybaptus novaehollandiae	LC	-	Partial migrant	Breeding confirmed in Menjer
Gallinula chloropus	LC	-	Migrant	Seasonal visitor (Oct-Mar)
Motacilla cinerea	LC	-	Migrant	Common in high-altitude wetlands
Amaurornis phoenicurus	LC	-	Resident	Stable population
Tachybaptus ruficollis	LC	-	Resident	Dominant piscivore species
Lanius schach	LC	-	Resident	Terrestrial predator
Cacomantis merulinus	LC	-	Resident	Semi-aquatic cuckoo
Hirundo tahitica	LC	-	Resident	Aerial insectivore
Collocalia linchi	LC	-	Resident	Common swiftlet
Passer montanus	LC	-	Resident	Common urban associate
Collocalia esculenta	LC	-	Resident	Widespread swiftlet
Apus affinis	LC	-	Resident	Common in open areas
Pycnonotus aurigaster	LC	-	Resident	Terrestrial generalist
Lonchura leucogastroides	LC	-	Resident	Granivore in grasslands
Todiramphus chloris	LC	-	Resident	Coastal and inland waters
Cacomantis variolosus	LC	-	Resident	Forest edge, semi-aquatic
Butorides striata	LC	-	Resident	Mangroves and freshwater
Ixobrychus cinnamomeus	LC	-	Resident	Secretive in dense reeds
Dendrocopos analis	LC	-	Resident	Woodlands and forests
25 species	1 NT, 24 LC	5 Protected (20%)	4 Migratory (16%)	-

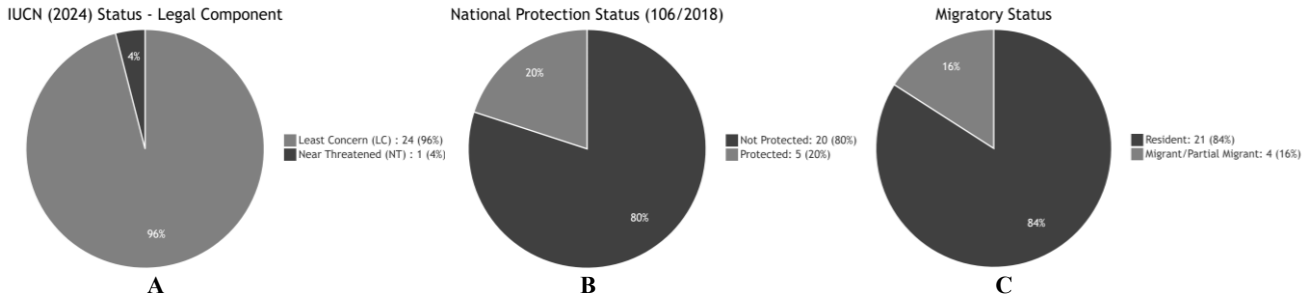

Figure 5. Proportion of protected and threatened waterbird species across the three study sites based on IUCN (2024) (A) and national protection status (B), and migratory status (C) across Telaga Menjer, Telaga Merdada, and Telaga Cebong in the Dieng Plateau, Central Java, Indonesia

The conservation evaluation shows that the Dieng wetland complex contributes significantly to the protection of highland bird diversity in Central Java. The coexistence of endemic, migratory, and legally protected species within a limited area highlights its ecological and biogeographical uniqueness. Effective management should therefore focus on habitat protection, pollution control, and community-based conservation to prevent local population declines.

Representative species and field observations

Field observations in the three crater lakes of the Dieng Plateau revealed several ecologically significant and characteristic waterbird species representing distinct trophic and behavioral groups. Among these, *T. ruficollis* (Little Grebe), *G. chloropus* (Common Moorhen), and *N. nycticorax* (Black-crowned Night Heron) were the most notable due to their consistent presence, distinct ecological roles, and behavioral adaptations to montane wetland environments.

The Little Grebe (*T. ruficollis*) was the most frequently encountered diving bird across all lakes, particularly abundant in Telaga Menjer and Telaga Merdada. Individuals were commonly observed foraging solitarily or in pairs on open-water surfaces, diving repeatedly to capture small fish and aquatic invertebrates. Their compact body size and dense plumage enable effective thermoregulation in the cool montane climate. Floating nests composed of aquatic vegetation were detected along

the sheltered vegetated edges of Telaga Menjer, suggesting local breeding activity. These behavioral patterns indicate stable resident populations supported by high prey availability and low predation pressure.

The Common Moorhen (*G. chloropus*), observed mainly in Telaga Merdada and occasionally in Telaga Menjer, exhibited territorial and cautious behavior. Individuals were typically seen foraging near emergent vegetation or mudflats, consuming aquatic plants, small crustaceans, and insects. During the observation period (June-August), adults with fledglings were recorded, confirming successful reproduction in situ. This species' dependence on dense emergent vegetation underscores the importance of maintaining littoral macrophyte zones, which provide both nesting cover and food resources.

The Black-crowned Night Heron (*N. nycticorax*) was recorded primarily in Telaga Menjer during late afternoon observations (16:30-17:30). Its crepuscular and nocturnal habits made it less frequently visible than diurnal herons, yet repeated sightings suggest resident individuals or small roosting groups. Foraging activity was concentrated along shaded lake margins where the birds preyed upon small fish and amphibians. This species' persistence indicates the continued presence of structurally complex habitats offering both prey and roosting sites.

In addition to these key species, other representative taxa such as *A. speciosa*, *H. cyanoventris*, and *H. tahitica* illustrated the ecological versatility of the Dieng avifauna. *A. speciosa* (Javan Pond Heron) displayed adaptive foraging in both shallow and disturbed habitats, including agricultural ditches adjoining Telaga Cebong. The endemic *H. cyanoventris* (Javan Kingfisher), characterized by vivid blue plumage and loud territorial calls, was occasionally observed perched along open banks of Telaga Merdada, preying on small aquatic organisms-signifying the persistence of suitable riparian microhabitats despite tourism activity. Meanwhile, *H. tahitica* (Pacific Swallow) was abundant above all lakes, capturing aerial insects in open air columns, often in association with *Collocalia linchi* (Glossy Swiftlet).

Direct observations also recorded several interspecific interactions, including mixed foraging groups of *A. speciosa* and *A. phoenicurus* exploiting receding shorelines, and occasional competitive displacement between *T. ruficollis* and *G. chloropus* when foraging territories overlapped. Such interactions indicate a dynamic balance among sympatric species occupying overlapping trophic niches, facilitated by the structural heterogeneity of the wetland habitat mosaic.

Photographic documentation of key species and habitat conditions (Figure 6) illustrates the ecological diversity of the Dieng wetland complex-from open pelagic zones inhabited by diving birds to vegetated littoral zones supporting omnivores and waders. The combination of endemic, resident, and partially migratory species observed during the field period provides empirical evidence that these small montane lakes sustain a functionally rich and ecologically stable waterbird community.

Figure 6. Bird species found in the Dieng Plateau wetlands, Central Java, Indonesia. A. *Lanius schach*, B. *Pycnonotus aurigaster*, C. *Dendrocopos analis*, D. *Ardeola speciosa*, E. *Ardeola speciosa* (nonbreeding/immature), F. *Gallinula chloropus*, G. *Nycticorax nycticorax*, H. *Halcyon cyanoventris*, I. *Amaurornis phoenicurus*, J. *Tachybaptus novaehollandiae*, K. *Butorides striata*, L. *Motacilla cinerea*, M. *Passer montanus*, N. *A. bacchus* (nonbreeding/immature), O. *Lonchura leucogastroides*, P. *Ixobrychus cinnamomeus*

Discussion

Patterns of waterbird diversity in montane wetlands

The moderate species richness of waterbirds recorded in the Dieng Plateau (25 species) aligns with the typically depauperate nature of montane wetlands when compared to lowland systems across Southeast Asia. While lowland wetlands in Java, such as mangrove complexes, can host over 40 species due to higher primary productivity and greater habitat heterogeneity (Purify et al. 2020; Fabrina and Faizah 2022), high-altitude systems are inherently constrained. The Dieng avifauna's richness is comparable to other isolated montane lakes, such as those in North Sulawesi (Tabalujan et al. 2024) and Western Nepal (Lama et al. 2022), where communities comprise fewer than 30 species. This recurrent pattern underscores the powerful filtering effects of elevation-driven factors, including cooler temperatures (18-21°C), reduced aquatic primary productivity, and limited habitat area, which collectively restrict the availability of trophic resources and nesting sites for waterbirds (Sodhi et al. 2010; Süel et al. 2021). Furthermore, the intrinsic biogeographical isolation of the Dieng crater lakes, separated by steep volcanic topography, exacerbates these limitations by hindering dispersal and recolonization, thereby sustaining smaller, more isolated populations than those in interconnected lowland wetlands.

Elevation is among the most influential factors shaping avian diversity (Sodhi et al. 2010; Süel et al. 2021). The Dieng Plateau lies between 1,300-1,850 masl, where temperature, oxygen concentration, and primary productivity are substantially lower than in the lowlands. Cooler temperatures (18-21°C) restrict the diversity of aquatic prey such as insects and small fish, thereby limiting the carrying capacity for piscivorous and insectivorous birds. In addition, the reduced surface area and volume of the crater lakes, particularly Telaga Cebong, impose spatial constraints on breeding and foraging territories. As indicated by the intermediate diversity index ($H' = 2.42$), these montane wetlands maintain stable but species-limited communities adapted to narrow environmental gradients.

Another important determinant of species richness is ecosystem isolation. The Dieng wetlands form discrete water bodies separated by steep volcanic ridges, resulting in limited inter-lake dispersal and weak connectivity to lowland habitats. Such geographic isolation reinforces stochastic colonization dynamics and turnover-dominated species replacement, as reflected in the moderate Sørensen similarity values (0.61-0.72). Comparable patterns of spatial segregation have been documented in montane lakes of Borneo (Ab Razak et al. 2019) and Luzon (Mabugat et al. 2024), where isolation restricts recolonization after local extinctions, maintaining distinct community assemblages at each site.

Despite the constraints of elevation and size, the Dieng lakes still support a functionally diverse waterbird community, including piscivores, insectivores, and omnivores, indicative of moderate ecosystem productivity. These results emphasize that montane wetlands, though species-poor compared to lowland systems, play a crucial role as refugia for specialized and endemic taxa adapted to highland conditions, thus representing key components of Java's regional biodiversity network.

Habitat heterogeneity and its role in supporting species richness

Habitat heterogeneity emerged as a key driver of waterbird diversity in the Dieng Plateau wetlands. The observed pattern of higher species richness in Telaga Menjer and Telaga Merdada, compared to Telaga Cebong, corresponds strongly with differences in vegetation cover, water depth, and microhabitat diversity. Lakes with wider littoral zones and greater proportions of emergent vegetation supported more species and guilds, especially those dependent on structured habitats for foraging and nesting. This strong positive relationship between vegetation cover and species richness underscores the importance of structural complexity in maintaining avian assemblages under montane conditions.

Vegetation along lake margins, primarily composed of Cyperaceae, Typhaceae, and Poaceae, provides multiple ecological functions: substrate for nesting (e.g., *T. ruficollis*, *G. chloropus*), shelter against predators, and foraging grounds for wading birds and insectivores. Dense stands of *Cyperus* and *Typha* create microhabitats that support aquatic invertebrates, small fish, and amphibians, which in turn sustain piscivorous species such as *A. speciosa* and *H. cyanoventris*. Similar findings have been reported by Sulai et al. (2022) in Malaysian floodplain systems, where structural diversity of emergent vegetation and hydrological variability explained up to 70% of the variance in avian taxonomic and functional diversity. In contrast, Telaga Cebong's reduced vegetation cover and shallow water limit both prey availability and nesting substrate, resulting in lower evenness and dominance of aerial insectivores rather than true aquatic specialists.

Water depth further modulates community composition by influencing prey accessibility and thermal conditions. Deep and stable lakes such as Menjer offer pelagic niches for diving birds (Podicipedidae), while shallow margins of Telagas' Merdada and Cebong attract waders and rails that exploit ephemeral mudflats. This spatial mosaic mirrors the general principle proposed by Xu et al. (2024), who demonstrated that moderate hydrological fluctuations and mixed depth profiles in China's Shengjin Lake promote higher functional redundancy and resilience of waterbird communities.

Species in the Dieng wetlands display adaptive strategies to narrow habitat gradients imposed by montane topography. Small body size, flexible foraging behavior, and tolerance to cooler climates enable persistence in limited spaces. For instance, *A. phoenicurus* and *T. ruficollis* utilize vegetated microhabitats both for nesting and feeding, while *H. tahitica* and *C. linchi* exploit aerial niches above open water. These behavioral adaptations enhance coexistence within confined crater basins, reinforcing the notion that even small, isolated wetlands can sustain complex ecological networks when structural heterogeneity is maintained.

Collectively, these results indicate that habitat complexity-not area alone-governs species richness and

functional stability in montane wetlands. Conservation actions that preserve shoreline vegetation, regulate water-level fluctuations, and minimize disturbance from tourism and agriculture are therefore critical to maintaining avian diversity and ecological integrity in the Dieng Plateau ecosystem.

Functional guild composition and trophic structure

The trophic organization of waterbird assemblages in the Dieng Plateau wetlands is characterized by a clear dominance of piscivores and insectivores, which together accounted for over 60% of the recorded species (Table 3). This dominance pattern reflects the energy pathways and prey availability typical of small montane aquatic systems, where fish and aquatic insects form the core trophic resources. Piscivores such as *A. speciosa*, *B. striata*, and *T. ruficollis* perform a crucial ecological role as top predators that regulate prey populations and maintain food-web stability. Their presence also indicates the persistence of functional aquatic networks, since piscivores are sensitive to fluctuations in prey density and water quality. Similarly, insectivores, including *H. cyanoventris, Cacomantis merulinus,* and *H. tahitica,* exploit both aquatic and aerial niches, linking aquatic productivity with surrounding terrestrial ecosystems.

The prevalence of these two guilds suggests that the Dieng wetlands sustain a balanced trophic structure despite their limited area and isolation. According to Şekercioğlu (2006), insectivorous and piscivorous birds enhance ecological stability through top-down control mechanisms, reducing trophic oscillations and promoting nutrient turnover. Their consistent representation across all three lakes supports the view that montane wetlands, though species-poor, can maintain high functional efficiency when dominant guilds are well-represented.

Omnivorous and generalist species, such as *G. chloropus*, *A. phoenicurus*, and *P. montanus*, also play pivotal roles in resource recycling and disturbance resilience. Their dietary flexibility allows them to exploit fluctuating food resources, from aquatic vegetation to small invertebrates, thereby sustaining energy flow during periods of prey scarcity. In disturbed habitats near agricultural or touristic zones, omnivores often serve as ecological buffers, mitigating community instability caused by environmental fluctuations. This aligns with findings from Lama et al. (2022) in Himalayan wetlands, where omnivores dominated in human-influenced sites, contributing to functional redundancy and overall system resilience.

When compared with other tropical highlands, the Dieng assemblage mirrors the functional convergence observed in Lake Sebu (Philippines) and the Kinabalu highlands (Borneo), where insectivores and omnivores dominate due to low aquatic productivity and narrow trophic niches (Ab Razak et al. 2019; Mabugat et al. 2024). The relatively low proportion of strict herbivores or detritivores underscores the oligotrophic nature of crater lakes, where nutrient input is minimal, and vegetation is sparse.

The dominance of piscivorous and insectivorous guilds, supplemented by omnivores with broad ecological plasticity, reflects an efficient but compact trophic architecture that allows Dieng's montane wetlands to remain functionally stable despite spatial and climatic constraints. Maintaining this guild balance through protection of prey habitats and reduction of anthropogenic disturbance is essential to preserving the ecological integrity of these high-altitude wetland systems.

Beta diversity and spatial differentiation among lakes

Patterns of beta diversity among the Dieng Plateau wetlands reveal that species composition varies substantially between lakes, with Sørensen similarity values ranging from 0.61 to 0.72 (Table 4). This moderate similarity reflects a combination of shared generalist taxa and distinct site-specific assemblages, leading to turnover-dominated species differentiation across the three sites. Most compositional dissimilarity was attributed to species replacement rather than nestedness, indicating that each lake supports a partially unique subset of the regional avifauna rather than representing a simple gradient of species loss. Such differentiation underscores the ecological individuality of the crater lakes, shaped by physical isolation, habitat heterogeneity, and varying degrees of anthropogenic influence.

Environmental filtering plays a primary role in structuring these assemblages. Each lake possesses distinct environmental attributes-Telaga Menjer is deep with steep margins, Telaga Merdada has intermediate depth and complex vegetated edges, while Telaga Cebong is shallow and surrounded by agricultural plots. Species adapted to particular microhabitats or prey conditions selectively occupy these sites; for instance, *T. ruficollis* and *B. striata* dominate deeper lakes with abundant fish prey, while *A. phoenicurus* and *G. chloropus* prefer shallow, vegetated wetlands. This pattern corresponds with the niche partitioning model proposed by Whittaker (1972), in which environmental filtering along physical gradients drives community differentiation more strongly than stochastic processes.

In addition, dispersal limitation contributes significantly to spatial turnover among lakes. The crater lakes of Dieng are separated by steep volcanic ridges and cultivated valleys, which restrict avian movement, especially for species with low mobility or narrow habitat preferences. This physical fragmentation reduces colonization rates and promotes local differentiation. Comparable processes were described by Ab Razak et al. (2019) in Borneo's montane lakes and Xu et al. (2024) in subtropical China, where isolation limited interchange among wetlands and maintained distinct assemblages despite geographic proximity.

From a conservation standpoint, these results highlight the importance of multi-site conservation strategies in fragmented montane landscapes. Because no single lake encompasses the full spectrum of waterbird diversity, effective management should consider the entire lake network as a metacommunity. Conservation interventions should thus focus on maintaining ecological connectivity, protecting vegetated corridors, and preventing excessive eutrophication or land-use intensification around each lake. Recognizing the complementary value of individual

wetlands ensures that conservation efforts in the Dieng Plateau sustain not only alpha diversity within sites but also beta diversity across the landscape, thereby enhancing the resilience of the region's highland wetland ecosystems.

Conservation significance and management implications

The waterbird assemblages of the Dieng Plateau wetlands hold substantial conservation significance within Java's montane ecosystems. Although species richness is moderate, the presence of legally protected and highland-restricted taxa such as *A. vulcanorum* (Volcano Swiftlet) and *H. cyanoventris* (Javan Kingfisher) highlights the area's unique ecological value. *A. vulcanorum* is an endemic montane swiftlet confined to volcanic regions of Java above 1000 m elevation (Eaton et al. 2021), while *H. cyanoventris* is a near-endemic kingfisher species protected under Permen LHK No. 106/2018 (KLHK 2018b) due to its declining population linked to habitat degradation (Kurnia et al. 2021). Their occurrence across the Dieng wetlands reinforces the plateau's function as a dry-season refugium for highland specialists that are increasingly rare in lowland areas transformed by agriculture and urbanization (Nijman et al. 2022).

From a regional perspective, the presence of species with known migratory populations, such as *G. chloropus* (migrant) and *A. cinerea* (partial migrant), suggests the potential of these crater lakes to act as seasonal stopover habitats, though year-round monitoring is needed to confirm their full role in maintaining connectivity along the East Asian-Australasian Flyway (Ferreira et al. 2024). Protection of these habitats, therefore, contributes not only to national biodiversity objectives but could also support international migratory bird conservation commitments under the IUCN and Ramsar frameworks. Despite their small size, these montane wetlands may provide critical resting and feeding sites that sustain bird populations during high-altitude transits, similar to patterns observed in other tropical highland wetlands (Lama et al. 2022; Xu et al. 2024).

All recorded species were native or long-established residents, with no invasive taxa detected in the assemblages. *Passer montanus*, although historically introduced from Eurasia, is now fully naturalized and poses negligible ecological risk to native waterbirds. The absence of invasive species indicates that these montane wetlands remain ecologically intact and relatively isolated from biological invasions common in disturbed lowland wetlands. Maintaining this biosecurity integrity should be prioritized through regular surveillance and community-based awareness programs on invasive species prevention.

Sustainable conservation of these ecosystems requires integration of habitat protection, tourism management, and community participation. Ecotourism activities around Telaga Merdada and Telaga Menjer have grown rapidly, offering economic opportunities but also increasing disturbance through noise, litter, and shoreline modification (Setiawan 2024). Effective management should include zoning schemes that restrict intensive tourism near critical breeding sites, promote low-impact visitor facilities, and involve local communities in habitat monitoring and interpretation programs. The participatory models successfully implemented in Ciletuh-Palabuhanratu Geopark (Iskandar et al. 2021) demonstrate that local stewardship enhances long-term conservation compliance.

These management recommendations are supported by our findings, which recorded five nationally protected species and a community structure dominated by insectivores and piscivores that are highly dependent on habitat quality. The moderate to high beta diversity among the lakes further underscores the need for a landscape-scale approach to conservation, ensuring the protection of complementary habitats across the plateau (Koleff et al. 2003; Süel et al. 2021).

Policy recommendations aligned with Permen LHK No. 106/2018 emphasize the enforcement of species protection and habitat integrity, while IUCN (2024) guidelines encourage site-based monitoring integrated with adaptive management. The Dieng wetlands should be incorporated into broader highland biodiversity management plans under the Central Java Provincial Environmental Agency, ensuring continuous data collection on species population trends, water quality, and habitat condition. Strengthening coordination among research institutions, tourism operators, and local governments would further support the establishment of a Dieng Wetland Conservation Network, aimed at harmonizing scientific conservation goals with socio-economic realities (Perfecto and Vandermeer 2010; Marshall et al. 2021). Safeguarding the Dieng Plateau wetlands demands a multi-dimensional approach-legal protection of key species, regulation of human activities, and community-based conservation-to ensure the persistence of these high-altitude aquatic ecosystems as vital components of Java's montane biodiversity heritage.

Ecological and biogeographical context of the Dieng Plateau

The wetlands of the Dieng Plateau occupy a unique ecological and biogeographical position within the central mountain chain of Java. Situated between 1,300-1,850 masl, these crater lakes represent relict ecosystems formed by ancient volcanic activity (van Bemmelen 1949) and now function as refugia for montane waterbirds adapted to cooler, oligotrophic, and structurally confined habitats. In a landscape increasingly fragmented by agriculture and tourism, these wetlands provide isolated yet stable habitats that buffer sensitive species from the rapid land-use changes dominating lowland regions (Nijman et al. 2022; Setiawan 2024). The persistence of highland endemics such as *A. vulcanorum* and *H. cyanoventris*, together with montane-adapted species like *T. rufiicollis* and *A. phoenicurus*, underscores the Dieng Plateau's role as a climatic sanctuary within the broader biogeographical mosaic of Java (Eaton et al. 2021).

When compared with other Javan highlands-such as Tawangmangu (Mount Lawu), Pangrango, and Bromo-Tengger-the Dieng wetlands exhibit a distinct avian assemblage characterized by higher proportions of aquatic and semi-aquatic guilds. Highland forests of Pangrango, for instance, are dominated by canopy insectivores and frugivores (van Balen et al. 1999; Putra et al. 2020), whereas Dieng supports a trophic structure centered on

lentic systems and emergent macrophytes. In Bromo's crater ponds and Tawangmangu's upper catchments, avian diversity is typically constrained by extreme elevation (>2000 m) and limited vegetation cover, resulting in fewer aquatic specialists (Whitten et al. 1996). Dieng's intermediate altitude, coupled with moderate precipitation and hydrological stability, thus provides optimal conditions for maintaining mixed assemblages of resident and migratory waterbirds-a pattern consistent with mid-elevation diversity peaks described by Rahbek (1995) and subsequently confirmed in Southeast Asian montane systems (Süel et al. 2021; Lama et al. 2022).

From a biogeographical perspective, the Dieng Plateau serves as a stepping-stone habitat linking the central and western Javan highlands. Its lakes support seasonal migrants that connect continental flyways to insular ecosystems, enhancing regional gene flow and ecological connectivity (Ferreira et al. 2024). However, this connectivity is increasingly threatened by habitat loss, pollution, and climate-driven hydrological shifts (Xu et al. 2024). Predicted warming and reduced precipitation could accelerate eutrophication and contraction of littoral vegetation, diminishing habitat suitability for species dependent on shallow water zones, as observed in other tropical montane wetlands (Lama et al. 2022).

Given these dynamics, the Dieng wetlands offer a valuable natural laboratory for long-term eco-hydrological monitoring. Regular surveys integrating ornithological, limnological, and vegetation data would provide early indicators of ecosystem change (Şekercioğlu 2006). Collaborative research initiatives could apply remote sensing and acoustic monitoring to assess temporal shifts in species composition and habitat structure (Sutherland 2006). Such sustained observation is critical for understanding how montane wetlands respond to environmental stressors and for developing adaptive management frameworks applicable across the Javan volcanic highlands (Sulai et al. 2022). The Dieng Plateau not only represents an ecological enclave of significant ornithological interest but also a biogeographical keystone for understanding the resilience of montane wetland biodiversity under changing climatic and anthropogenic regimes.

Limitations and future research directions

This study acknowledges several limitations that constrain the generalization of its findings. Observations were conducted within a limited temporal window during the dry season, which may not fully capture seasonal variation in species occurrence, particularly for migratory taxa. The reliance on presence-absence data without systematic abundance measurements restricts the quantitative assessment of population dynamics and habitat preferences. In addition, habitat parameters such as water chemistry, nutrient load, and vegetation productivity were only measured descriptively, leaving potential cause-and-effect relationships between environmental variables and bird assemblages unexplored. Future research should therefore implement year-round monitoring to document phenological shifts and migration cycles, coupled with repeated point counts and acoustic recording to estimate abundance and detectability. Integrating eco-hydrological data with multivariate modeling would help elucidate functional links between habitat heterogeneity and avian community structure. Finally, establishing community-based biodiversity monitoring programs-involving local residents, students, and birdwatching groups-would not only generate long-term datasets but also enhance local stewardship and awareness of montane wetland conservation in the Dieng Plateau. In conclusion, the present study provides the first comprehensive assessment of waterbird diversity and ecological characteristics of montane wetlands in the Dieng Plateau, Central Java. Across the three crater lakes-Telaga Menjer, Telaga Merdada, and Telaga Cebong-we recorded 25 waterbird species representing multiple feeding guilds, reflecting the combined influence of habitat heterogeneity, elevation, and climatic conditions on avian assemblages. Despite their limited spatial extent, these wetlands act as crucial refugia for both endemic and migratory species, underscoring their conservation importance within Java's montane ecosystems. Species diversity was moderate ($H' = 2.18$-2.65) and evenness was high ($E = 0.83$-0.91), indicating relatively balanced assemblages dominated by piscivorous and insectivorous birds that depend on stable aquatic prey and structurally complex littoral vegetation. These findings emphasize that integrating habitat protection, sustainable tourism management, and local community participation is essential to ensure long-term ecosystem resilience. Continued ecological monitoring and interdisciplinary research are therefore recommended to strengthen the role of Dieng's highland wetlands in regional biodiversity conservation and climate adaptation strategies. To safeguard the long-term ecological integrity of these wetlands, management actions should include the establishment of ecological zoning around each lake, designation of core conservation zones in areas with dense littoral vegetation and high species use, and restriction of intensive tourism and infrastructure development to clearly defined buffer zones.

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