Aquatic bird species richness and distribution in relation to reservoirs' limno-chemistry in Tigray National Regional State, northern Ethiopia

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Abstract

Summary 1. Knowledge of the relationship between biodiversity and environmental factors provides insight into patterns of species richness and distribution in limnetic ecosystems. To this end, this study was conducted to test the effect of limnological characteristics of reservoirs on bird species richness and distribution along an age gradient of limnetic ecosystems in Tigray National Regional State. 2. To evaluate the relationship between limnological characteristics of reservoirs and patterns of bird species richness and distribution, six physicochemical variables, three morph-edaphic and biological variables were recorded for 35 reservoirs and analyzed by multivariate statistical techniques. Species richness data was subjected to a multiple regression analysis at limnological variables, biological variables and age of the reservoirs in order to investigate the most important explanatory factors influencing avian species richness and their distribution using Redundancy analysis (RDA). 3. 85 bird species from 54 genera, 25 families and 15 bird orders were recorded, with mean species richness 14.23?6.72 (mean ? standard deviation) per reservoir. Five of these species are near threatened (NT) while other two species fall under critically endangered (CR) and vulnerable (VU) conservation status designations, respectively. Bird species richness was positively correlated with surface area of reservoirs. The RDA analysis identified two significant RDA axis and 34.4% of the variation in species richness is explained by environmental variation (R2adj = 0.34375; P < 0.001). Generally, water chemistry appears to play only a minor part in affecting bird species richness in reservoir in Tigray, Northern Ethiopia. However, chemical variables may be helpful to distinguish between used and unused sites for some species. 4. The result provides an important insight on the ecological relationship between waterbirds species richness and limnological characteristics of reservoirs. And plays a role towards strengthening our knowledge on aquatic bird ecology and natural history of African Eurasian Migratory waterbirds.

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Running headline : reservoirs' bird species richness

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Key words : Abdim's Stork; *Bostrychia carunculata* ;*Numida meleagris* ; Reservoirs; Tigray; Waterbirds

Introduction

Globally, there are approximately 10928 species of birds distributed in 40 orders, 250 families and 2322 genera of the class Aves (Gill & Donsker 2020). Ornithologists have studied the geographic distribution, local and regional diversity and variation in birds for many years (Roth 1976; Hoyer & Canfield 1990; Clavel, Julliard & Devictor 2011; Dinesen *et al.* 2019). Many factors including geographic location, habitat condition and climatic factors affect bird species richness and abundance (MacArthur, MacArthur & Preer 1962; MacArthur 1964; González-Gajardo, Sepúlveda & Schlatter 2009; Moritz & Agudo 2013; Guevara *et al.* 2021). Studies have indicated that birds globally are at risk because of human growth, forest destruction, fragmentation and loss of suitable habitats (Brown & Dinsmore 1986; Jokimäki & Suhonen 1993; Chace & Walsh 2006). Ecologists have long been interested in how human induced ecological and environmental factors affect the abundance and distribution of communities in limnetic ecosystems. For over six decades a positive correlation between species richness and habitat area and cover have been established for terrestrial ecosystems (MacArthur, MacArthur & Preer 1962; MacArthur 1964; Venier & Fahrig 1996; González-Gajardo, Sepúlveda & Schlatter 2009; Cardinale *et al.* 2018). Furthermore, factors like wetland area, water surface, water level, habitat productivity and heterogeneity have been positively related to species richness, bird abundance and species guild (Mark & Daniel 1990; Edwards & Otis 1999; Babbitt 2000). However, which factors are most important remains unresolved. What is more, despite the growing recognition of wetlands as important environments for birds worldwide, wetland ecosystems are being altered and reduced at an increasing rate by human activities (Dugan 1990). Unfortunately, despite the value of wetland biodiversity, wetlands are still declining locally and regionally as a result of human pressure at global level (Ramsar Convention Bureau 2006; Sebastián-González, Sánchez-Zapata & Botella 2010).

Unlike this global situation, of decreasing and loss of wetlands, over the past two to three decades, wetlands have been created as a result of the construction of manmade reservoirs in Tigray (Asmelash 2009). The construction of such reservoirs has created a sizeable wetlands downstream and induced positive microclimate change in the surrounding areas (Haileselasie & Teferi 2012). However, majority of the research conducted on these limnetic ecosystems involves limnoilogical characteristics (Dejenie et al. 2008), Phytoplankton community structure (Asmelash 2009), fisheries (Teferi et al. 2013) and colonization of these reservoirs by the water flea-*Daphnia*(Haileselasie et al. 2018). There is little information on the avian fauna of these limnetic ecosystems since their construction for irrigation, livestock and household water consumption purposes. Globally there are a few studies that compared the diversity and composition of waterbird functional traits between natural, restored, and artificial wetlands (Almeida et al. 2020). But to the best of my knowledge, there is no study that examined the factors that affect bird population in limnetic ecosystems of Ethiopia in general and Tigray regional state in particular. Furthermore, it is not known whether modified habitats such as reservoirs, constructed wetlands could act as alternative habitats to attract and sustain bird communities and conserve regional species diversity. This study is focused on bird species richness as an indicator of biodiversity gain triggered by construction of reservoirs and has the following specific objectives: 1) to assess avian species richness in an age gradient of limnetic ecosystem constructed for irrigation, livestock and household water consumption in Tigray. 2) To investigate the effect of ecological and environmental variables of reservoirs on bird species richness and distribution in reservoirs of Tigray, Northern Ethiopia.

Materials and methods

Study area

Tigray is one of the nine autonomous National Regional States of the Federal Democratic Republic of Ethiopia (FDRE, Fig. 1A). It is divided into seven administrative zones namely: Western zone, North-western zone (NW), Central zone, Eastern zone, South-eastern zone (SE), Southern zone and Mekelle special zone which are further divided into more 47 administrative districts (Fig. 1B). The region has several agro-ecological zones that fall under three major biomes namely: Sudan-Guinea Savanna biomes; Afrotropical Highlands biomes and Somali-Masai biomes (Fishpool & Evans 2001; Haileselasie & Teferi 2012). It has four traditional agro-ecological classifications: The "Qhola" (below 1500 m a.s.l), "Weyna Degu'a" (1500-2300 m a.s.l), "Degu'a" (2300-3200 m a.s.l), and "Wurch/Alelama" (above 3200 m a.s.l). The highest mountain range in the region is the "Tsibet Sky Island" with its highest peak reaching 3960 m a.s.l, located in the Southern Zone of Tigray National Regional State and the lowest point is around 500 m a.s.l in the Tekeze valley, western Tigray.

Here, 35 reservoirs of varying age were included in a study of avifauna of the limnetic aquatic ecosystem of the region (see Appendix S1 in supporting information). These reservoirs were purposively selected because of previous experience to each site (Haileselasie & Teferi 2012; Teferi et al. 2013; Haileselasie et al. 2018). The reservoirs have different age from the youngest Mihtsab Azmati reservoir (MAZ; 5 years) to oldest Bokoro reservoir (BOK; 44 years). They also vary in elevation (range: 1512– 2747), water surface (range: 1.78– 45.41 ha) and water depth (range: 1– 13.7 m). To evaluate the relationship between limnological characteristics of reservoirs and patterns of bird species richness and distribution, we selected nine variables: reservoir area, water depth, elevation, pH, nutrient concentration (Total Nitrogen & Total Phosphate), water turbidity, water temperature and electrical conductivity that are known to influence ecological processes and species abundance in freshwater wetlands and lakes (Hoyer & Canfield 1994; Seymour & Simmons 2008; Rajpar & Zakaria 2010; van der Valk 2012). Ecological variables such as: presence and absence of fish, emergent vegetation, presence and absence of forest edge and/or downstream wetland were recorded and coded into an appropriate format for analysis. Limnological characteristics of each reservoir: reservoir's morphometry (altitude, area and maximum depth) and water chemistry variables: water temperature (°C), pH, electrical conductivity (EC, µS/cm) were measured in the field using portable pH/EC/ multi-meters. Whereas integrated water samples were collected and brought to Aquatic Ecology Laboratory (Mekelle University, Tigray) for determination of Total Phosphorus (TP, µg/l) and Total Nitrogen (TN, µg/l) in the laboratory using standard methods stated in Nelson and Sommers (1975).

Bird surveys

Data for this study were obtained by counting birds that were observed during a survey of 35 reservoirs (see Fig. 1). Birds observed utilizing limnetic ecosystems were recorded by observers who motored around each reservoir in a small boat and/or by walking along the perimeters of the reservoir depending on the size of the water body. Birds were identified to a species level based on bird's field guide for East Africa; birds of sub-Sahara and country specific checklists (Urban & Brown 1971; Sinclair & Ryan 2003; Ash &

Atkins 2009). Species richness in this article's context is defined as the total number of bird species observed throughout the entire sampling period in the region (as gamma diversity) and number of bird species recorded in each reservoir (as alpha diversity). Here no attempt has been made to calculate annual bird abundance (birds/area) for each reservoir. English names and Taxonomy of birds reported here, follows the International Ornithological Congress (IOC) standard format (Gill & Donsker 2020).

Data analysis

Differences in limnological variables between reservoirs are visualized by Principal Component Analyses on residuals of full limnological data set. Principal components were extracted from covariance matrices using the function rda in vegan package of the R software (R Development Core 2014). The Eigenvalues and % of variance for each axis were used to retain number of significant PC axis for further analysis. And the Euclidean distance after standardizing the variables, followed by Ward clustering is used to display plot of the first two PC axis of limnological components.

To partition gamma diversity into its alpha (α) and beta (β) components; gamma (γ) diversity of birds as species richness with q=0, is equated as multiplicative (i.e. $\alpha*\beta= \gamma$) relationship. As a result beta (β) diversity is calculated as gamma diversity divided by mean alpha diversity, with all samples being equally weighted as applied in the R-software package vegetarian (Jurasinski, Retzer & Beierkuhnlein 2009).

To explore relationships among environmental variables (ENV) and geographic location (SPACE) of the reservoirs and bird species richness, redundancy analysis ordination (RDA) is performed. Species richness data was submitted to a multiple regression analysis at limnological variables (ENV), biological variables (BV) and age of the reservoirs in order to investigate the most important explanatory factors influencing avian species richness and their distribution. The Monte Carlo Permutation test of 999 permutations is used to test statistical significance of the relationship. Pearson's correlation coefficients is used to examine correlations between the variables and to reduce the number of explanatory factors.

Besides, the scores of species (alpha diversity) and environmental variables resulting from the ordination is used to build a bi-plot that illustrates the relationships between environment and bird species richness. To describe the environmental preferences of particular species, Redundancy Analysis ordination (RDA) in R software (R Development Core 2014) was applied. The function partitions the variation-varpart in vegan R package (Oksanen *et al.* 2013) using adjusted *R-squared* (R^2_{adj}) in redundancy analysis ordination (RDA) is used to disentangle the effect of these variables: in species - environment - space - age variation partitioning by partial regression.

Results

Limnological characteristics

Limnological characteristics varied among the sampled reservoirs (see Appendix S1 in supporting information). Principal component analysis (PCA) identified three major axes of limnological variation (axes that explain more than 10 % of the variation). PCA reduced the data set to three components that explained 64.27% of the variance in the original variables. The first and second axis of the PCA explained 51.07% of the total variation observed. PC1 explained 28.69% of the variation and can be interpreted as a measure of altitude, surface area, total nitrogen (TN) and total phosphorus (TP) (Fig. 2). PC2 explained 22.38% of the limnological variation and was loaded heavily by electrical conductivity, pH and depth. PC3, which explained 13.2% of the variation, was loaded mostly by Temperature and transparency. As can be seen in Fig. 2 three major clusters of reservoirs is created based on the PCA components. Cluster 1 is composed of 6 lowland reservoirs and cluster 2 is composed of 12 highland reservoirs while cluster three is composed on 17 reservoirs of mixed elevation but mostly with high nutrient concentration (Fig. 2; see Appendix S2 in supporting information).

Taxonomic Richness

Avian fauna associated with limnetic aquatic ecosystem, waterbirds, from 35 reservoirs of varying age is presented in Table 1. A total (γ-diversity) of 85 bird species from 54 genera, 25 families and 15 bird orders were recorded during the study period (Tables 1 and 2). When the seven species that are not listed as waterbirds in a strict sense, by ornithologists, are excluded the total ornithological richness of waterbirds of the surveyed reservoirs (γ-diversity) is 78 species from 48 genera, 22 families and 11 orders. Most of the waterbirds (60%) recorded are all-year residents and 4.71% (n=4 bird species) are intra-African migrants and visitors. Thirty of the waterbirds (35.29%) recorded are Palaearctic migrants/winter visitors (see Appendix S3 in supporting information). Out of the total bird species recorded five of species: Black-Tailed Godwit (*Limosa limosa),* Ferruginous Duck (*Aythya nyroca*), Lesser Flamingo (*Phoeniconaias minor),*Maccoa Duck (*Oxyura maccoa)* and Pallid Harrier (*Circus macrourus)* fall under the near threatened (NT) IUCN conservation status designations. Two species: Hooded Vulture (*Necrosyrtes monachus*) and Common Pochard (*Aythya ferina*) fall under critically endangered (CR) and vulnerable (VU) conservation status designations, respectively. While the rest (91.8%) birds recorded are of least concern (LC) under the IUCN conservation status designations (Table 2).

Charadriiformes had the highest number of recorded taxa (7 families, 15 genera, 27 species) followed by Pelecaniformes (4 families, 9 genera, 15 species) (Tables 1 and 2). Within the recorded Charadriiformes, the Scolopacidae (Sandpipers and allies) was the most widespread family of that order (12 species). Of all the families recorded, Anatidae (order: Anseriformes) was the family with the most recorded genera (7 genera; 15 species; including geese, ducks, teals), followed by the Scolopacidae (order: Charadriiformes) (6 genera; 12 species; including sandpipers and snipes). The Ardeidae (herons and egrets), Ciconiidae (storks) and Accipitridae (raptors) were the next in number of families recoded with 8, 7 and 5 species per family, in that respective order (Fig. 3).

The alpha (α) diversity of reservoirs varies from 3 to 32 with 14.23±6.72 (mean ± standard deviation) birds per reservoir. Mai Nigus (n= 32 species) and Tsinkanet (n= 26 species) had the highest bird species recorded, followed by Mai Gassa I reservoir (n= 23 species) and Haiba reservoir (22 species) (Fig. 4A). Two spatial distribution pattern of species richness (α- diversity) of waterbird population are clearly detected. The first pattern is within Northern cluster where the central reservoirs have a higher alpha diversity while northern reservoirs have relatively lower alpha diversity when plotted along the geographic location of reservoirs (Fig. 4B). The second pattern is within the southern Tigray where higher alpha diversity is observed in the center while reservoirs in the peripheries have lower alpha diversity (Fig. 4B). The second pattern becomes clearly visible after removing Haiba reservoir from the data set which is connected to Meala reservoir.

Frequency of occupancy of the reservoirs varies from 1 to 35 birds (Table 2). From the 35 reservoirs sampled, the highest frequency of occupancy have been recorded for Egyptian Goose (*Alopochen aegyptiaca*) followed by: Common Sandpiper (*Actitis hypoleucos*) and Grey Heron (*Ardea cinerea*) recorded from 28 and 26 reservoirs, respectively (Table 2 and see Appendix S3 in supporting information). Three of the Near-threatened birds recorded in this study were from a single reservoir while the two other birds in this category status: Ferruginous Duck (*Aythya nyroca*) and Maccoa Duck (*Oxyura maccoa*) are recorded from two and five reservoirs, respectively (Table 2). The spatial distribution of the two endemic species recorded was also different. The Wattled Ibis (*Bostrychia carunculata)* is recorded from nine reservoirs whereas Spot-breasted Lapwing (*Vanellus melanocephalus*) is recorded from Mai Nigus reservoir only (Table 2 and see Appendix S3 in supporting information). The spatial distribution of the four intra-African migrants recorded: African Openbill (*Anastomus lamelligerus*), Southern Pochard (*Netta erythrophthalma*), Abdim's Stork (*Ciconia abdimii*) and Pied Avocet (*Recurvirostra avosetta*) did not show a uniform pattern. The first two species were recorded from a single reservoir each while Abdim's Stork and Pied Avocet were recorded from seven and three reservoirs, respectively (Table 2 and see Appendix S3 in supporting information).

Relationship between bird species richness and limnological variables

The redundancy analysis (RDA) identified two significant RDA axis and 34.4% of the variation in species richness of the reservoirs is explained by environmental variation ($R^2_{adj} = 0.34375$; $P < 0.001$). Four variables were selected as the best factors explaining the variation in bird species richness observed: elevation, water depth, pH and nutrients. A clear association between the occurrence of specific bird species and several of the measured environmental variables was detected. A strong relationship between species richness and size of reservoir is detected but not the depth. That is bigger reservoirs did support a higher number of bird species (see Appendix S4 in supporting information).

The RDA indicates that a significant portion of the variation in species composition is explained by both biological variables (BV) and environmental variables (ENV) ($R^2_{adj} = 0.18$, $p<0.001$). If only environmental and biological variables are used in the RDA, environmental variation explained 9.5% of the variation in species composition ($R^2_{adj} = 0.0953$, $p<0.001$), whereas the biological variables (BV) explains about 8.9% of the variation in species composition ($R^2_{adj} = 0.089$, $p<0.001$; Fig. 5A). Among the environmental variables, elevation, depth, pH, transparency and TP contributed significantly to explaining the variation in species composition in the studied reservoirs. In a partial RDA analysis, the complete model (ENV [?] BV) accounted for about 18% of the variation in species composition ($R^2_{adj} = 0.1799$, $p<0.001$; Fig. 5A) with environmental variables ($R^2_{adj} = 0.091$, $p<0.001$) being most important. But significant portion of the variation in species composition was also explained by pure biological variables ($R^2_{adj} = 0.085$, $p<0.01$), while shared environmental and biological variables contributed less than 1% (Fig. 5A and see Appendix S5 in supporting information). A large part of the variation in species composition, however, remained unexplained ($R^2_{adj} = 0.82$; Fig. 5A).

Including age of reservoirs (AGE) as an independent variable in the partial RDA did change the percentage of variation explained by environmental variables ($R^2_{adj} = 0.107$, $p< 0.001$; Fig. 5B) and biological variables ($R^2_{adj} = 0.074$, $p< 0.001$) differently. It did, reduce the variation explained by biological descriptors (BV), and the pure effect of BV is down to 7.4% ($R^2_{adj} = 0.074$, $p< 0.001$; Fig. 5B). The combined effect of ENV, AGE and BV ($R^2_{adj} = 0.203$) was higher than that of the effect without age. The pure effect of AGE was small but statistically significant ($R^2_{adj} = 0.023$, $p < 0.05$; Fig. 5B) and its effect was also confounded with BV effects (Fig. 5B; see also appendix S5 in supporting information). Only a small fraction of the variation was shared among BV descriptors and environmental heterogeneity ($R^2_{adj} = 0.005$, $p< 0.001$; Fig. 5B).

The global model, using ENV, BV, AGE and geographic location of each reservoir (SPACE) as an independent variables in the partial RDA did not change the percentage of variation explained by environmental variables ($R^2_{adj} = 0.107$, $p< 0.001$; Fig. 5B) and biological variables ($R^2_{adj} = 0.074$, $p< 0.001$). However, the model indicated the marginal effect of SPACE on the bird species richness to be 5.6%. Out of these, 4% is pure effect of SPACE and 1.6% is confounded with effect of AGE and BV variables (see Appendix S5 in supporting information).

Discussion

The 35 reservoirs investigated present a mixture of contrasting age gradient and structural heterogeneity of habitat in terms of differences in size, elevation and liminological characteristics, among others. I show here that these reservoirs are an important repositories for birds including species designated as Near Threatened (NT), Vulnerable (VU), Critically Endangered (CR) under the International Union for Conservation of Nature (IUCN) conservation status (IUCN 2019) and endemic birds. In the face of an unprecedented habitat loss and degradation of natural wetlands, it can be argued that such artificial waterbodies can play an important role for waterbird conservation. These reservoirs and its associated wetlands, have the capacity to maintain high avian diversities. In line with results presented here, other studies have likewise indicated that urban reservoirs and artificial ponds harbor waterbird communities and act as refugia for waterbirds (Hale *et al.* 2019; Almeida *et al.* 2020; Tatiane *et al.* 2020).

Studies elsewhere indicated that wetland area and habitat heterogeneity as being the most important features that affect aquatic bird species richness and abundance (Roth 1976; Hoyer & Canfield 1994; Scheffer *et al.* 2006; Kortz & Magurran 2019). According to the continental species area relationship (SAR-hypothesis, (MacArthur & Wilson 1967), large reservoirs are expected to contain more species (i.e. higher taxonomic richness). In line with the long established theory of island biogeography (MacArthur & Wilson 1967; Losos & Ricklefs 2009), a significant difference in species richness between large and small reservoirs investigated is observed in this study. Community ecology and population genetic studies have indicated that spatial variation in species/clonal composition is the result of environmental sorting, dispersal limitation and historical factors at different temporal scales (Rossetto *et al.* 2008; Orsini *et al.* 2013; Haileselasie *et al.* 2016). Here, I have reported that highly significant variation in bird species richness attributed to environmental variables and a small but significant effect of age of reservoir is also observed. This result is in agreement with previous research that showed that pattern of beta diversity are sensitive to environmental and historical factors (Haileselasie *et al.* 2016) where high *Daphnia* clonal richness was observed in an age gradient of ponds/lakes created by glacial retreat in Greenland. The small but significant effect of age of reservoirs on bird species richness is also in line with long established meta-population theory which argue with an increase in age there will be an increase in the heterogeneity of habitat (Hanski 1998). Thus, providing different resources for nesting, foraging and roosting habitats for different bird species (MacArthur 1964; Brown & Dinsmore 1986; Hoyer & Canfield 1994; Edwards & Otis 1999; Almeida *et al.* 2020).

Despite the fact the fact that positive correlations between habitat cover, habitat area and species richness have long been established (Murphy, Kessel & Vining 1984; Murphy & Dinsmore 2018); what drives patterns of species composition in a landscape, however, remained debatable. For example, Merckx, Miranda & Pereira (2019) argued that habitat amount not patch size drives species richness against the long established island biogeography (MacArthur & Wilson 1967; Losos & Ricklefs 2009). In addition, to the contrary of the theory of island biogeography some studies have suggested that small habitat size and isolation promotes species richness in shallow lakes and ponds (Scheffer *et al.* 2006). While others have argued that larger habitats (or islands) accumulate a higher number of species (MacArthur & Wilson 1967; Losos & Ricklefs 2009). In favor of this argument, studies have indicated that wetland area, vegetation cover, and structural heterogeneity of habitat are the most important features that affected wetland bird richness and abundance (Guevara *et al.* 2016; Dinesen *et al.* 2019). The result of this study provides an additional evidence in favor of the later argument. However, the mere size is not significant but possible presentation of large sized habitat accompanied by an increase in habitat heterogeneity does supporting greater species richness. In contrast to a previous positive relationship between bird richness and lake depth (Guevara *et al.* 2016) this study did not support the positive relationship between reservoirs' depth and bird species richness. This could be due to the effect of reservoir depth being species specific (Guevara *et al.* 2021).

With regard to the distribution of the waterbirds two patterns are apparent in this study. Some species are widely distributed water specialist birds while others are restricted in their distribution but also non-specialist or opportunist. Such pattern of distribution has been reported previously elsewhere (Hoyer & Canfield 1990). Some of the bird species, recorded in this study, occurred in almost all the reservoirs thus are generalists. While others are reported from single reservoir with specific habitat features such as presence of settlements, large wetland forest downstream or in the near proximity of the reservoir. Some reservoirs are very close to residential areas (example Bokoro and Mai Sessela) or have very large wetlands downstream (example Meskebet reservoir). This might be responsible for the presence of Eastern Grey Plantain-eater (*Crinifer zonurus*), Long-crested Eagle (*Lophaetus occipitalis*) and Rose-ringed Parakeet (*Psittacula krameri*) in Meskebet reservoir. The presence of these birds in Bokoro, Mai Seyie, and Meskebet reservoirs could likely be due the presence of housing and plantation very close to the reservoirs and also the positive influence of shrub density on species richness via the provision of nesting, foraging and roosting habitats for different bird species for example Kites, Eagles and Vulture. Generally, bird abundance has been reported to increase in response to increase in degree of urbanization (Chace & Walsh 2006) and this increase has been attributed to the availability of food subsidies and the reduction of predation pressure. Nonetheless, the presence of these birds should be interpreted with caution and only in terms of conditions stated in this study. There could be a possibility of seeing these birds outside the study area covered here. This calls for further investigation into larger areas and/or more reservoirs than studied here. For example Long-crested Eagle and Rose-ringed Parakeet are recorded only from Meskebet reservoir not in any of the reservoirs investigated here. However, Rose-ringed Parakeet has been recorded from Mereb river irrigation farms which is 10 km west of Mihtsab Azmati reservoir (Haileselasie & Teferi 2012). Another surprising finding is the absence of Cape Shoveler (*Anas smithii*). A preliminary study by Asmelash *et al* . (2007) reported the presence of Cape Shoveler in 10 reservoir. Unfortunately, I have not seen any Cape Shoveler during the field campaigns in the 35 reservoirs including reservoirs where it was reported to have been seen previously. This could possibly be a typical example of local extinction of the species. Previous studies have suggested that human interference could lead to locally extinct (Hassall & Anderson 2015). Besides, globally, 14% of the known bird species are threatened with extinction (IUCN, 2019). This clearly indicates a worrying development and there might even be a higher risk of loss of biodiversity of aquatic birds in particular because aquatic habitats are highly sensitive ecosystems that are also threatened by global trend of climate change, agricultural expansion and intensifications (Johnson *et al.* 2013; Newbold *et al.* 2015).

In conclusion, the patterns of distribution in birds depended on the level of limnological characteristic, age and biotic components in the studied reservoirs. In this study bird species richness was only significantly influenced by area which is in line with previous studies elsewhere (Murphy & Dinsmore 2018). Nevertheless, the strength of these correlations was only moderate, indicating there are other habitat variables important to species richness that were not measured in this study.

Waterbirds play key functional roles in many aquatic ecosystems and can be effective bio-indicators of change in aquatic ecosystems (Green & Elmberg 2014). There is a clear consensus that waterbirds are good biological indicator but when using waterbirds as indicators, a thorough knowledge of their ecology is essential monitoring program. It is my strong believe there is dire need for more research into the status and ecology of these essential ecosystems and their role towards strengthening our knowledge on aquatic bird ecology and natural history of African Eurasian Migratory waterbirds. These reservoirs investigated forms a gradient of many ecological variables (Teferi et al. 2014) and different degree of eutrophication which vary with season (Asmelash *et al.* 2007; Asmelash 2009) and could be an excellent experimental macrocosms to study many ecological questions.

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Data Accessibility Statement

All data generated and/or analyzed during this study are included in this published article and its supplementary information files

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List of tables

Table 1. Taxonomic richness of waterbirds from an age gradient of reservoirs in Tigray National Regional State. ++ row number for each bird order adapted from the International Ornithological Congress (IOC) World Bird List (10.1) (Gill & Donsker 2020) and SS number of reservoirs the bird order was recorded from

IOC-row++	Bird order	Family	Genus	Species	§number
7123	Accipitriformes	2	6	6	6
1261	Anseriformes	1	7	15	35
5427	Charadriiformes	7	15	27	35
6663	Ciconiiformes	1	4	7	16
8972	Coraciiformes	1	3	3	4
3451	Cuculiformes	1	1	1	1
232	Galliformes	1	1	1	1
4852	Gruiformes	1	1	2	15
12253	Passeriformes	1	1	2	3
6829	Pelecaniformes	4	9	15	32
5416	Phoenicopteriformes	1	1	1	1
9558	Piciformes	1	1	1	1
5340	Podicipediformes	1	2	2	25
11220	Psittaciformes	1	1	1	1
6699	Suliformes	1	1	1	4
Total	Total	25	54	85	

Table 2. Details of waterbird species recorded across 35 reservoirs during the study period in Tigray National Regional State. + Common names follow that of IOC format; * species recorded in/at the perimeter of the reservoirs thus are not water specialist birds; § number of reservoirs the species was recorded from; ++ conservation status designation by the International Union for Conservation of Nature (IUCN): Near Threatened (NT), Vulnerable (VU), Critically Endangered (CR) and Least Concern (LC) (IUCN, 2019)

	English name+	Zoological name	Family	Order	§Occupancy	
1	Abdim's Stork	*Ciconia abdimii*	Ciconiidae	Ciconiiformes	7	L
2	African Fish Eagle	*Haliaeetus vocifer*	Accipitridae	Accipitriformes	1	L
3	African Grey Woodpecker*	*Dendropicos goertae*	Picidae	Piciformes	1	L
4	African Open-billed Stork	*Anastomus lamelligerus*	Ciconiidae	Ciconiiformes	1	L
5	African Pied Wagtail	*Motacilla aguimp*	Motacillidae	Passeriformes	1	L
6	African Sacred Ibis	*Threskiornis aethiopicus*	Threskiornithidae	Pelecaniformes	12	L
7	African Snipe	*Gallinago nigripennis*	Scolopacidae	Charadriiformes	1	L
8	African Spoonbill	*Platalea alba*	Threskiornithidae	Pelecaniformes	2	L
9	African Wattled Lapwing	*Vanellus senegallus*	Charadriidae	Charadriiformes	6	L
10	Black Stork	*Ciconia nigra*	Ciconiidae	Ciconiiformes	3	L
11	Black-headed Heron	*Ardea melanocephala*	Ardeidae	Pelecaniformes	1	N
12	Black-tailed Godwit	*Limosa limosa*	Scolopacidae	Charadriiformes	1	L
13	Black-winged Lapwing	*Vanellus melanopterus*	Charadriidae	Charadriiformes	1	L
14	Black-winged Stilt	*Himantopus himantopus*	Recurvirostridae	Charadriiformes	18	L
15	Cattle Egret	*Bubulcus ibis*	Ardeidae	Pelecaniformes	11	L
16	Collared Pratincole	*Glareola pratincola*	Glareolidae	Charadriiformes	1	L
17	Common Greenshank	*Tringa nebularia*	Scolopacidae	Charadriiformes	20	L
18	Common Pochard	*Aythya ferina*	Anatidae	Anseriformes	11	V

	English name[+]	Zoological name	Family	Order	[§]Occupancy
19	Common Redshank	*Tringa totanus*	Scolopacidae	Charadriiformes	1
20	Common Sandpiper	*Actitis hypoleucos*	Scolopacidae	Charadriiformes	28
21	Common Snipe	*Gallinago gallinago*	Scolopacidae	Charadriiformes	3
22	Curlew Sandpiper	*Calidris ferruginea*	Scolopacidae	Charadriiformes	1
23	Eastern Grey Plantain-eater*	*Crinifer zonurus*	Musophagidae	Cuculiformes	1
24	Egyptian Goose	*Alopochen aegyptiaca*	Anatidae	Anseriformes	35
25	Egyptian Plover	Pluvianus aegyptius	Pluvianidae	Charadriiformes	1
26	Eurasian Coot	*Fulica atra*	Rallidae	Gruiformes	9
27	Eurasian Teal	*Anas crecca*	Anatidae	Anseriformes	2
28	Eurasian Wigeon	*Mareca penelope*	Anatidae	Anseriformes	1
29	Ferruginous Duck	*Aythya nyroca*	Anatidae	Anseriformes	2
30	Fulvous Whistling Duck	*Dendrocygna bicolor*	Anatidae	Anseriformes	1
31	Gadwall	*Mareca strepera*	Anatidae	Anseriformes	1
32	Garganey	*Anas querquedula*	Anatidae	Anseriformes	1
33	Giant Kingfisher	*Megaceryle maxima*	Alcedinidae	Coraciiformes	1
34	Glossy Ibis	*Plegadis falcinellus*	Threskiornithidae	Pelecaniformes	2
35	Goliath Heron	*Ardea goliath*	Ardeidae	Pelecaniformes	2
36	White-breasted Cormorant	*Phalacrocorax lucidus*	Phalacrocoracidae	Suliformes	4
37	Great Crested Grebe	*Podiceps cristatus*	Podicipedidae	Podicipediformes	14
38	Great Egret	*Egretta alba*	Ardeidae	Pelecaniformes	4
39	Great White Pelican	*Pelecanus onocrotalus*	Pelecanidae	Pelecaniformes	4
40	Green Sandpiper	*Tringa ochropus*	Scolopacidae	Charadriiformes	3
41	Grey Heron	*Ardea cinerea*	Ardeidae	Pelecaniformes	28
42	Gull-billed Tern	*Sterna nilotica*	Sternidae	Charadriiformes	7
43	Hamerkop	*Scopus umbretta*	Scopidae	Pelecaniformes	8
44	Helmeted Guineafowl*	*Numida meleagris*	Numididae	Galliformes	1
45	Hooded Vulture*	*Necrosyrtes monachus*	Accipitridae	Accipitriformes	2
46	Lesser Flamingo	*Phoeniconaias minor*	Phoenicopteridae	Phoenicopteriformes	1
47	Little Egret	*Egretta garzetta*	Ardeidae	Pelecaniformes	15
48	Little Grebe	*Tachybaptus ruficollis*	Podicipedidae	Podicipediformes	23
49	Little Tern	*Sterna albifrons*	Sternidae	Charadriiformes	1
50	Long-crested Eagle*	*Lophaetus occipitalis*	Accipitridae	Accipitriformes	1
51	Maccoa Duck	*Oxyura maccoa*	Anatidae	Anseriformes	5
52	Malachite Kingfisher	*Alcedo cristata*	Alcedinidae	Coraciiformes	1
53	Marabou Stork	*Leptoptilos crumenifer*	Ciconiidae	Ciconiiformes	1
54	Marsh Sandpiper	*Tringa stagnatilis*	Scolopacidae	Charadriiformes	3
55	Northern Pintail	*Anas acuta*	Anatidae	Anseriformes	5
56	Northern Shoveler	*Anas clypeata*	Anatidae	Anseriformes	19
57	Osprey	*Pandion haliaetus*	Pandionidae	Accipitriformes	1
58	Pallid Harrier	*Circus macrourus*	Accipitridae	Accipitriformes	1
59	Pied Avocet	*Recurvirostra avosetta*	Recurvirostridae	Charadriiformes	3
60	Pied Kingfisher	*Ceryle rudis*	Alcedinidae	Coraciiformes	2
61	Pink-backed Pelican	*Pelecanus rufescens*	Pelecanidae	Pelecaniformes	14
62	Purple Heron	*Ardea purpurea*	Ardeidae	Pelecaniformes	5
63	Red-billed Teal	*Anas erythrorhyncha*	Anatidae	Anseriformes	2
64	Red-knobbed Coot	*Fulica cristata*	Rallidae	Gruiformes	14
65	Rose-ringed Parakeet*	*Psittacula krameri*	Psittacidae	Psittacifprmes	1
66	Ruff	*Calidris pugnax*	Scolopacidae	Charadriiformes	2
67	Senegal Thick-knee	*Burhinus senegalensis*	Burhinidae	Charadriiformes	6
68	Southern Pochard	Netta erythrophthalma	Anatidae	Anseriformes	1

	English name[+]	Zoological name	Family	Order	[§]Occupancy
69	Spot-Breasted Lapwing	*Vanellus melanocephalus*	Charadriidae	Charadriiformes	1
70	Spotted Thick-knee	*Burhinus capensis*	Burhinidae	Charadriiformes	1
71	Spur-winged Lapwing	*Vanellus spinosus*	Charadriidae	Charadriiformes	20
72	Terek Sandpiper	*Xenus cinereus*	Scolopacidae	Charadriiformes	1
73	Three-banded Plover	*Charadrius tricollaris*	Charadriidae	Charadriiformes	21
74	Tufted Duck	*Aythya fuligula*	Anatidae	Anseriformes	2
75	Water Thick-knee	*Burhinus vermiculatus*	Burhinidae	Charadriiformes	1
76	Wattled Ibis	*Bostrychia carunculata*	Threskiornithidae	Pelecaniformes	9
77	White Stork	*Ciconia ciconia*	Ciconiidae	Ciconiiformes	10
78	White Wagtail	*Motacilla alba*	Motacillidae	Passeriformes	2
79	White-winged Tern	*Chlidonias leucopterus*	Sternidae	Charadriiformes	4
80	Wood Sandpiper	*Tringa glareola*	Scolopacidae	Charadriiformes	10
81	Woolly-necked Stork	*Ciconia episcopus*	Ciconiidae	Ciconiiformes	1
82	Yellow Billed Duck	*Anas undulata*	Anatidae	Anseriformes	10
83	Intermediate Egret	*Egretta intermedia*	Ardeidae	Pelecaniformes	3
84	Yellow-billed Kite*	*Milvus aegyptius*	Accipitridae	Accipitriformes	3
85	Yellow-billed Stork	*Mycteria ibis*	Ciconiidae	Ciconiiformes	6

Figure Legends

Figure 1. Map of Ethiopia with Tigray National Regional State highlighted in grey (A). Districts of Tigray National Regional State with location of the reservoirs sampled from each district indicated in star (B). Names of reservoirs: MES = Meskebet; MDI = Mai-Dimu; MAZ = Mihtsab Azmati; Laelay Maichew Cluster (LMC): Mai Nigus (MNG) and Mai Seye (MSY); MSS = Mai Sessela; DBD = Dibdibo; AAS = Adi Asma'e; Ganta-afeshum Cluster (GAC): Bokoro (BOK), Dibla (DIB) and Enda Gabriel (EGA); TSI = Tsinkanet ; RUF = Ruba Feleg; TEG = Teg'hane; Wukro cluster (WUC): Laelay Wukro (LWK) and Korir (KOR); MLE = Mai Leba; GBE = Gereb Beati ; HWC = Hintalo Wajerat Cluster (HWC): AGE = Adi Gela; AKE = Adi Kenafiz; BET = Betequa; DAM = Dur Anbasa; GMI = Gereb Mihiz; GSE = Gum Selassa; HAI = Haiba; MDE = Mai Delle; MGI = Mai Gassa I; MGII = Mai Gassa II; MEA = Meala; SHI = Shilanat IV and Enderta Cluster (EDC): HAS = Hashenge; ADA= Adi Amharay; HWD = Hizaeti Wedi Cheber; EQU = Era Quihila; GAW = Gereb Awso

Figure 2. Principal components analysis biplot of the reservoirs characteristics with overlaid clustering results. MES = Meskebet; MDI = Mai-Dimu; MAZ = Mihtsab Azmati; MNG = Mai Nigus; MSY = Mai Seye; MSS = Mai Sessela; DBD = Dibdibo; AAS = Adi Asma'e; BOK = Bokoro; DIB = Dibla; EGA = Enda Gabriel; TSI = Tsinkanet ; RUF = Ruba Feleg; TEG = Teg'hane; LWK = Laelay Wukro; KOR = Korir; MLE = Mai Leba; GBE = Gereb Beati ; AGE = Adi Gela; AKE = Adi Kenafiz; BET = Betequa; DAM = Dur Anbasa; GMI = Gereb Mihiz; GSE = Gum Selassa; HAI = Haiba; MDE = Mai Delle; MGI = Mai Gassa I; MGII = Mai Gassa II; MEA= Meala; SHI = Shilanat IV; HAS = Hashenge; ADA = Adi Amharay; HWD = Hizaeti Wedi Cheber; EQU = Era Quihila and GAW = Gereb Awso

Figure 3. Avian taxonomic richness of waterbirds from 35 reservoirs in Tigray National Region state. Solid shaded black bars indicate number of genera per family while striped-bars indicate species richness per family. Families along the X-axis are arranged according to their, English ABC, alphabetical order.

Figure 4. Specie richness (α diversity) of the respective reservoir investigated during the study period (A) and the pattern of species richness of waterbird populations inhabiting reservoirs sampled in Tigray (B). The species richness with respect to geographic location of the reservoirs is plotted along X-Y coordinates; the size of the circle is proportional to species richness of each reservoir

Figure 5. Venn diagram illustrating the results of variation partitioning from the partial redundancy analysis (pRDA) of the bird species composition of along an age of gradient of reservoirs in Tigray National Regions State, Northern Ethiopia. The pRDA shows the unique and shared contribution of biological descriptors (BV), environmental heterogeneity (ENV), and approximate age (AGE) of reservoir (AGE) to the variation in bird species composition observed in the reservoirs. A) Results of the pRDA based on two variables; B) pRDA with three variables: ENV, BV and AGE as independent variables. The numbers in the Venn diagram represent the fraction of variation in species composition that is explained by each independent variable. Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05

Figure 1

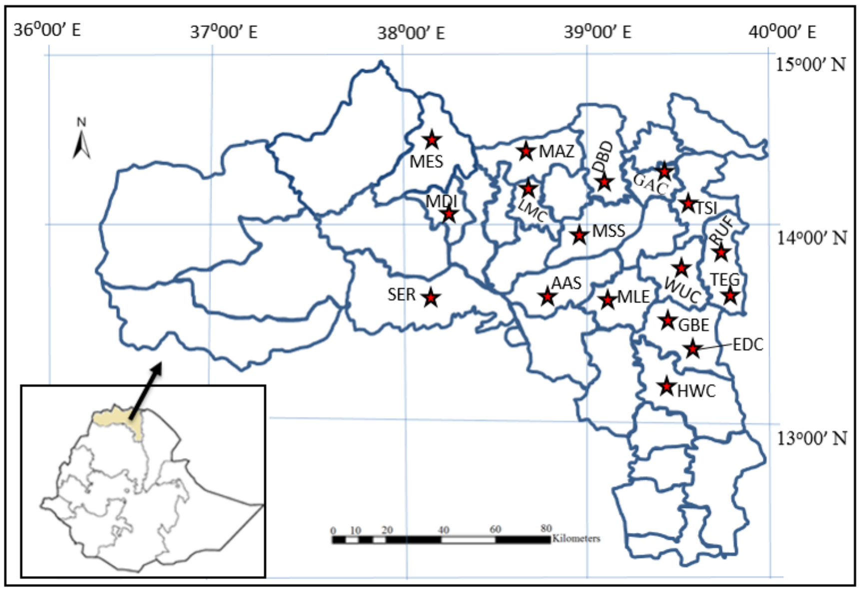


Figure 2

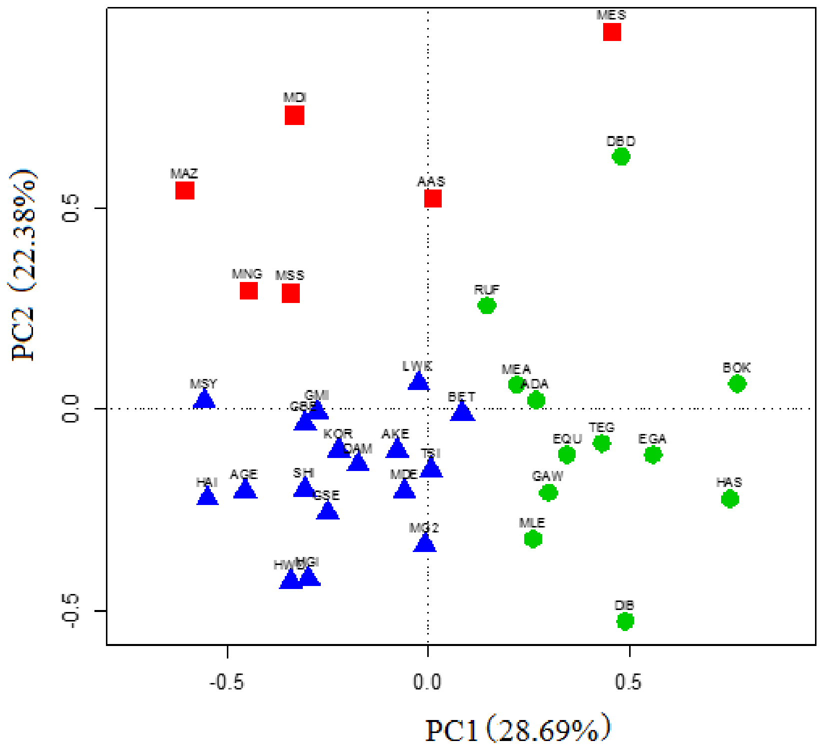


Figure 3

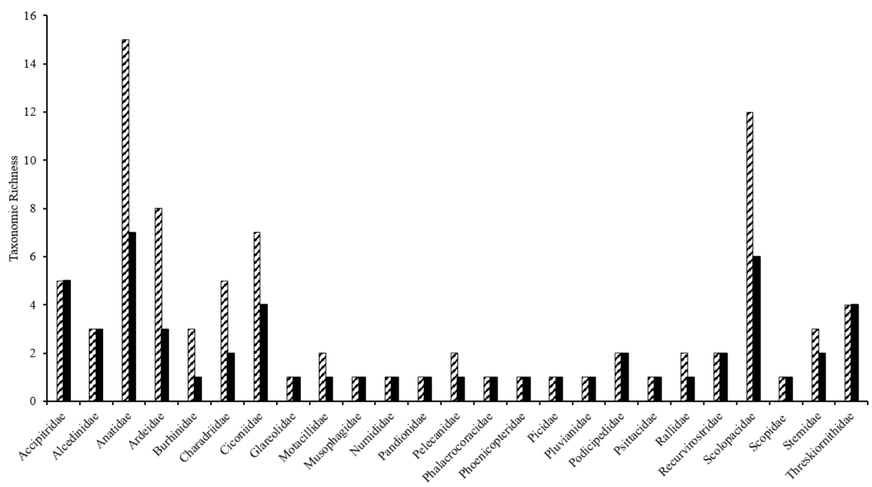
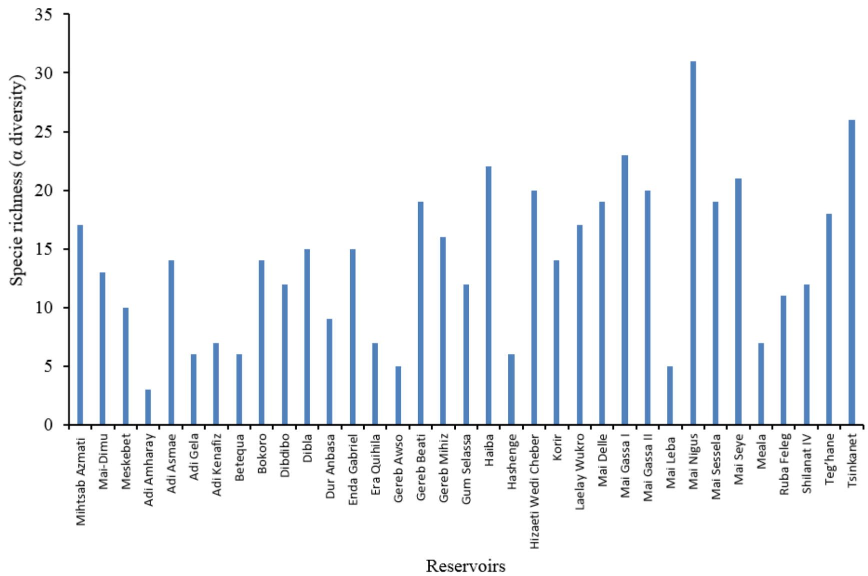
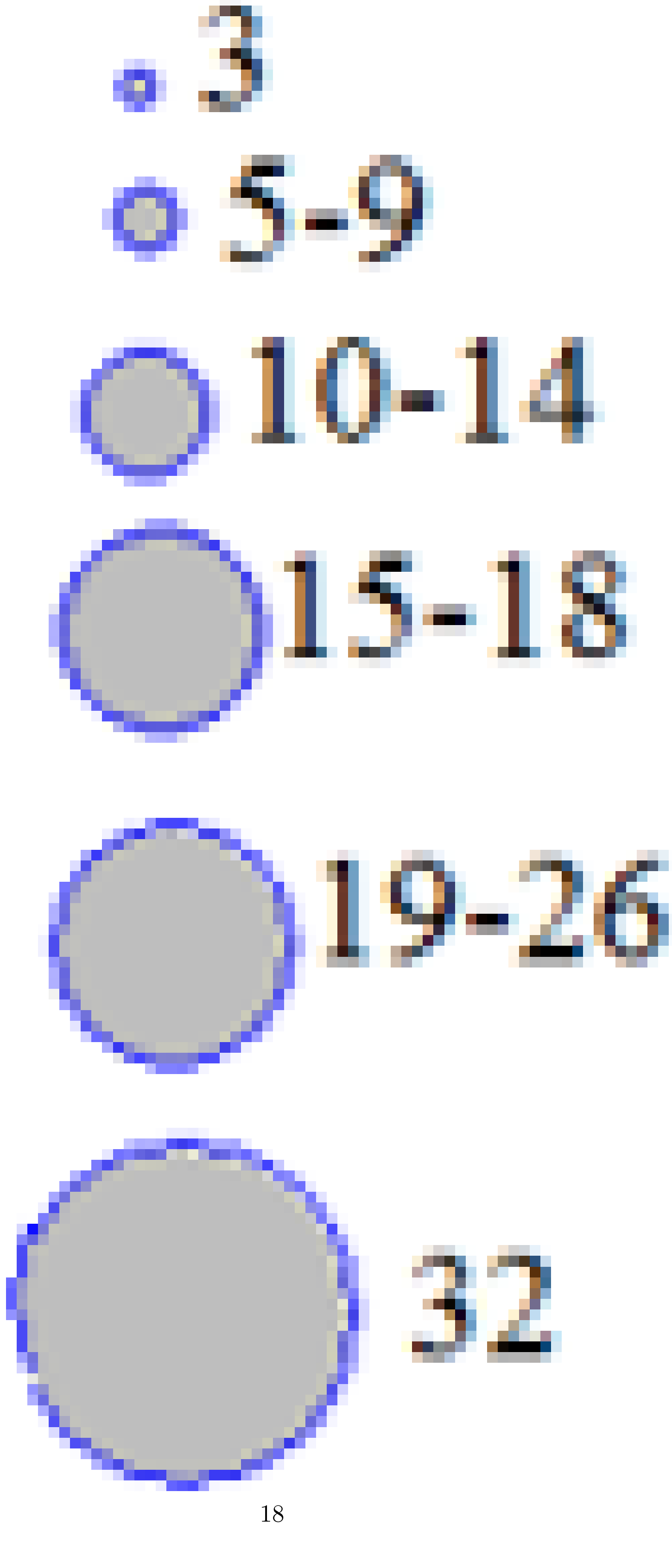


Figure 4


Specie richness (α diversity)
35
30
25
20
15
10
5
0
Mihtsab Azmati
Mai-Dimu
Meskebet
Adi Amharay
Adi Asmae
Adi Gela
Adi Kenafiz
Betequa
Bokoro
Dibdibo
Dibla
Dur Anbasa
Enda Gabriel
Era Quihila
Gereb Awso
Gereb Beati
Gereb Mihiz
Gum Selassa
Haiba
Hashenge
Hizaeti Wedi Cheber
Korir
Laelay Wukro
Mai Delle
Mai Gassa I
Mai Gassa II
Mai Leba
Mai Nigus
Mai Sessela
Mai Seye
Meala
Ruba Feleg
Shilanat IV
Teg'hane
Tsinkanet
Reservoirs


3
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10-14
15-18
19-26
32

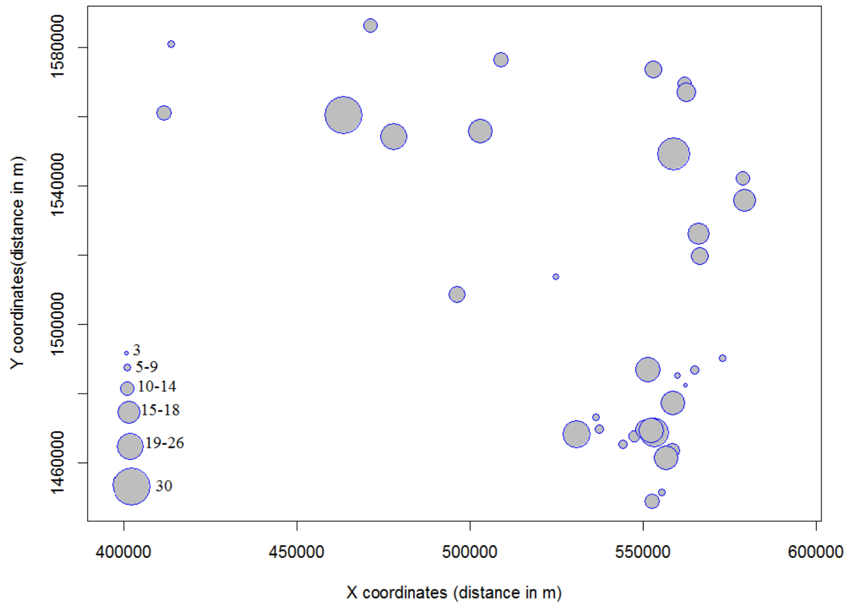

Figure 5

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`image8.emf` available at https://authorea.com/users/566287/articles/613010-aquatic-bird-species-richness-and-distribution-in-relation-to-reservoirs-limno-chemistry-in-tigray-national-regional-state-northern-ethiopia