

Sustainability and avian biodiversity tensions in wastewater management in arid zones

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ABSTRACT

Biodiversity is increasingly threatened by anthropogenic and climatic changes around the globe. Many animals lose the habitats where they can settle and reproduce successfully or are affected in their migratory movements due to disturbance and a lack of stop-over sites. For instance, wetlands are declining worldwide with strong impacts on millions of resident and migratory birds relying on them. Artificial wetlands, such as wastewater treatment ponds can serve an important role in meeting habitat needs of wetland and water-dependent birds. Yet these sites are also altered by technological upgrades geared to more efficient water usage, with largely unknown consequences for avian biodiversity. Here, we systematically determine the relationship between wastewater treatment plants (WTPs) and avian biodiversity across various levels of technological WTP advancement, along the Nile in Egypt, which is a major bird migration flyway. We show that WTPs host large numbers of resident and migratory birds, however the most advanced treatment technologies have significantly lower abundance, species richness and species diversity compared to less advanced WTPs. In contrast, lower-technology WTPs with water availability and spill-over ponds and with a presumably higher water quality displayed higher species diversity. WTP type also affected the avian community composition, with smaller and less diverse species communities in the technologically most advanced WTPs with no open water surface. The results underscore ecological trade-offs associated with water-saving technologies, especially in arid regions where natural wetlands are limited or absent. We advocate for a balanced approach to wastewater management that integrates human resource efficiency and biodiversity conservation. Our findings have broader implications for trade-offs in resource management, emphasizing the need for multi-stakeholder involvement and nature-based scientific approaches. Our study lays the groundwork for establishing wastewater treatment policy that meets both the needs of humans and of wildlife, and more broadly, how wastewater treatment can contribute to biodiversity conservation and meeting sustainable development goals.

1. Introduction

Around the globe, biodiversity is increasingly threatened by a changing climate as well as through direct anthropogenic changes to natural habitats, including urbanization, agricultural expansion, and recreational activities (Butchart et al., 2010; Oliver et al., 2015; IPBES, 2019; Lees et al., 2022). While some changes to local habitats only affect resident species, others can cause drastic and widespread disruption of global animal movements - for example if they affect habitat connectivity, or if they lead to a loss of habitats as stop over sites in migratory

animals (Doherty et al., 2021; Xu et al., 2019, 2022).

For instance, millions of birds rely on wetlands every year to complete their migration and breeding cycle successfully (Newton, 2010). Wetland availability is a key factor for a successful migration (Merken et al., 2015) as wetlands function as stopover sites on migration flyways, and local environmental conditions of these sites thus are important to sustain migration movements. However, natural wetland areas are declining and deteriorating rapidly. Over 50 % of natural wetlands have disappeared during the last century (Fraser and Keddy, 2005). Losses in natural wetland habitat make birds increasingly dependent on artificial

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wetlands (Guillemain et al., 2000; Ma et al., 2004; Anika and Parasharya, 2013; Giosa et al., 2018), urging the necessity to determine their importance for bird communities. Thus, while anthropogenetic environmental changes typically cause a decline in species diversity (Vitousek et al., 1997; Sala et al., 2000; Rockström et al., 2009; IPBES, 2019) and affect behavior of individual animals (Marzluff et al., 2012; Plummer et al., 2013), such artificial wetlands may help to maintain biodiversity by partially compensating for loss of natural wetlands (Čehovská et al., 2022). Artificial wetlands indeed could become avian hotspots in increasingly human-dominated landscapes (Cheng and Ma, 2023). For instance, species diversity and richness in artificial wetlands with low disturbance are similar to that in natural wetlands on Cyprus (Giosa et al., 2018). Therefore, artificial wetlands have the potential to become an integral part of convivial conservation programs integrating wildlife and human activities (Büscher and Fletcher, 2019).

According to the Ramsar convention, wastewater treatment plants (WTPs) are one of man-made artificial wetlands potentially having a particular importance in bird ecology and their integration with human activities (The Ramsar Convention, Iran, 1971). Yet, WTPs often are not considered in studies on the role of artificial landscapes for biodiversity (Cheng and Ma, 2023), even though they are widespread and usually less disturbed by immediate human activities. WTPs commonly show high concentrations of nutrients, which make them an apparent suitable and attractive habitat for many bird species (Guillemain et al., 2000; Hamilton et al., 2005; Murray and Hamilton, 2010). Thus, given that WTPs attract large numbers of birds, it is crucial to enhance our understanding of the types of WTPs in use and their specific effects on avian ecology. Yet, few studies on bird usage of WTPs (Murray and Hamilton, 2010) exist and they are limited to usually a single local WTP, lacking a wider temporal and spatial perspective. We therefore need a better understanding of the role of WTPs for waterbirds, especially in developing countries where demand on sanitation services is very high to lift people out of poverty (Giné Garriga and Pérez Foguet, 2013). Moreover, there is little scientific evidence to guide the construction of WTPs in a way that also considers bird conservation, which yet is important to generate a fact-based understanding of benefits and risks by WTP on waterbirds (Murray and Hamilton, 2010).

There are three levels of wastewater treatment used in WTPs, after wastewater is received via sewage pipes from municipal areas. In primary WTPs, treatment is being done by mechanical filtration of solid and suspended material of wastewater and is stagnated for breakdown by microorganisms. As a result, it requires additional water ponds as a treatment component and these water ponds can have many features which also occur in natural wetlands. In secondary WTPs, biological treatment of wastewater removes organic matter and suspended solids through aeration and filtration. In this case, water ponds are very limited in the WTP's area and, even if present, are not permanent. Advanced treatments by e.g. ion exchange or reverse osmosis, and purifications are known as tertiary treatment, where water exposure to air is very limited and additional water ponds are absent (Malik et al., 2015). The number, distribution, and conditions of these different levels of treatment of WTPs vary substantially throughout the world, depending on national development plans. For example, in the European Union, according to the European Environment Agency (EEA, 2019), primary WTPs are rare and concentrated mainly in Southern and Eastern Europe. Instead, most common are secondary and tertiary WTPs which usually lack additional permanent water treatment ponds. In North Africa, all types of WTPs are present with primary WTP with additional unmanaged water ponds being very frequent. Yet, these primary WTPs are targeted to be upgraded to secondary and tertiary WTPs to optimize water usage, an important consideration in semi-arid and arid circumstances (Mafuta, 2021; Asaad and Suleiman, 2023). Since the Western palearctic bird migration between Europe and Africa occurs through these largely arid landscapes, however, WTPs can play a crucial role not only with local impact on resident birds but also as potential stopover sites for trans-continental migratory birds. WTPs thus could have an impact on

global bird ecology.

Wastewater treatment plants, and their resulting water discharge bodies in arid landscapes, indeed form a very special habitat for birds and other forms of wildlife (Murray et al., 2012; Anika and Parasharya, 2013; Dean et al., 2015). Bird ecology and conservation status in those sites are not well understood. Since the construction and upgrading WTPs are development requirements according to the sustainable development goals (SDGs) (Malik et al., 2015), many more WTPs are planned to be constructed, and existing primary ones are planned to be transformed to meet national and international development and environment protection guidelines. These developments can have major impacts on local and global bird ecology, as changes in the spatial distribution, configuration, and local conditions of WTPs can be expected to dramatically influence bird migration. To be able to assess the role of WTPs for resident and migratory birds, more information is needed on bird abundance, species diversity and community composition to determine the value of WTPs for both resident and migratory birds.

Here, we focus on bird abundance, species richness, species diversity, and community composition in WTPs in the trans-African migration flyway along the Nile in Egypt. Western Palearctic birds migrate through the arid Northern African landscape where human population growth and urbanization concentrate mainly around natural wetlands (Mossad et al., 2024). In Egypt, for example, over 95 % of the human population lives in <5 % of the country's area along the Nile Valley (Bohannon, 2010). The Northern African Sahara (over 9 million km²) is part of both, the Black Sea/Mediterranean flyway and West Asian-East African Flyway. Egypt hosts migration flyways for about 350 species, travelling southwards to their wintering grounds in autumn and northwards to their breeding grounds in spring. The rarity of suitable wetlands as stopover sites constrains migratory birds to complete their migration compared to less arid regions and this can apply to short - as well as long-distance migrants (Senner et al., 2019), also as the Nile River itself and the irrigated agricultural fields in the Nile valley are not suitable for many species. Accordingly, even though WTPs are often small wetlands of typically a few hundred m², and located near human settlements, their spatial connectivity across the Saharan barrier could play a critical role in the bird migration network. Likewise high disturbance levels along the highly populated Nile valley, make the commonly less disturbed WTPs also potentially important habitats for resident species. Moreover, Egypt with its high human population density produces a high amount of wastewater which is estimated to be over seven billion m³ annually (AbuZeid and Elrawady, 2014). Only half of that water is treated, while the rest is either pumped into freshwater bodies or discharged into neighboring desert spaces (Ayoub, 2018). As a consequence, Egypt is planning to expand its wastewater recycling capacity (AbuZeid and Elrawady, 2014), so that more primary WTPs will be upgraded to secondary and tertiary WTPs, with an expected impact on the wetland availability for resident and migratory birds.

In order to determine the value of WTPs along this major flyway along the Nile, we here quantify bird abundance, species richness, and community composition of WTPs along the Nile in Egypt. We conducted a cross-seasonal bird census in 25 WTPs at regular intervals along the Nile between Aswan and Cairo during summer to quantify the resident species and during winter to quantify also the migratory species that use WTPs as wintering sites which typically are suited as stopover sites. We predicted higher bird abundance and species diversity in winter as we expected more migratory birds in addition to residents. As a result, we also predicted different community compositions in summer and winter. We further predicted high abundance and diversity as well as different community compositions in primary WTPs compared to WTPs with more advanced wastewater treatment. Moreover, we expected that WTPs that have associated wetlands habitats, generated by spillover water that is pumped into the surroundings, host higher abundance and diversity and distinguishable communities.

2. Methods

2.1. Study area

The study area spans a stretch of the Nile Valley of over 800 km, from Aswan ($24^{\circ}05'23.7''\text{N}$ $32^{\circ}54'00.1''\text{E}$) up to Cairo ($30^{\circ}02'49.2''\text{N}$ $31^{\circ}14'09.5''\text{E}$) (Fig. 1). Our sampling strategy was implemented to include various types of WTP's treatment types, with several observations for each type (Fig. 1); type A, primary WTP with an associated unmanaged water pond, $N = 8$; type B, primary WTP without unmanaged water ponds (just concrete ponds but often with an overall large water surface area), $N = 8$; type C, secondary WTP with an associated unmanaged water pond, $N = 4$; type D, secondary WTP without water pond (mechanical steering facilities, $N = 5$), as explained in more detail in the next section. We followed the course of the river Nile, as this is where urban expansion predominantly occurs, and where WTPs are constructed along the river's banks. 25 WTPs along the river Nile were selected in a systematic random method with respect to their latitude. Starting at the course of Nile at $24^{\circ} 00' 00'' \text{ N}$ in Aswan, we systematically selected 25 points on the river, one point for every 0.15 latitude degrees toward the North as in the following sequence, $24^{\circ} 15' 00'' \text{ N}$ -

$24^{\circ} 30' 00'' \text{ N}$ - $24^{\circ} 45' 00'' \text{ N}$ - $25^{\circ} 00' 00'' \text{ N}$, etc.. Then we selected the nearest WTP site to each of the selected points. Because the types of WTPs are non-randomly distributed in Egypt, with more advanced WTPs in the North, it was not possible to collect data from an equal number of WTP along the latitudinal gradient along the Nile. Most of the WTPs sites are located in the suburbs of villages and cities (Fig. 1).

2.2. Wastewater treatment types and categories

Each site sampled in this study represents an official wastewater treatment plant (WTP). The WTPs were initially classified into two main categories based on their treatment processes: stabilization ponds and mechanical treatment ponds. Moreover, within each category, WTPs were further subcategorized based on their capacity to treat incoming wastewater, resulting in a total of four types. These range from type A (least advanced) to type D (most advanced) (Fig. 2).

For stabilization ponds, type A represents a stabilization WTP with low treatment capacity, which cannot handle the full volume of received wastewater. The untreated excess water flows to adjacent unmanaged ponds, often characterized by sloping banks and vegetated areas, and, sometimes, large trees, resembling natural wetlands. In contrast, type B

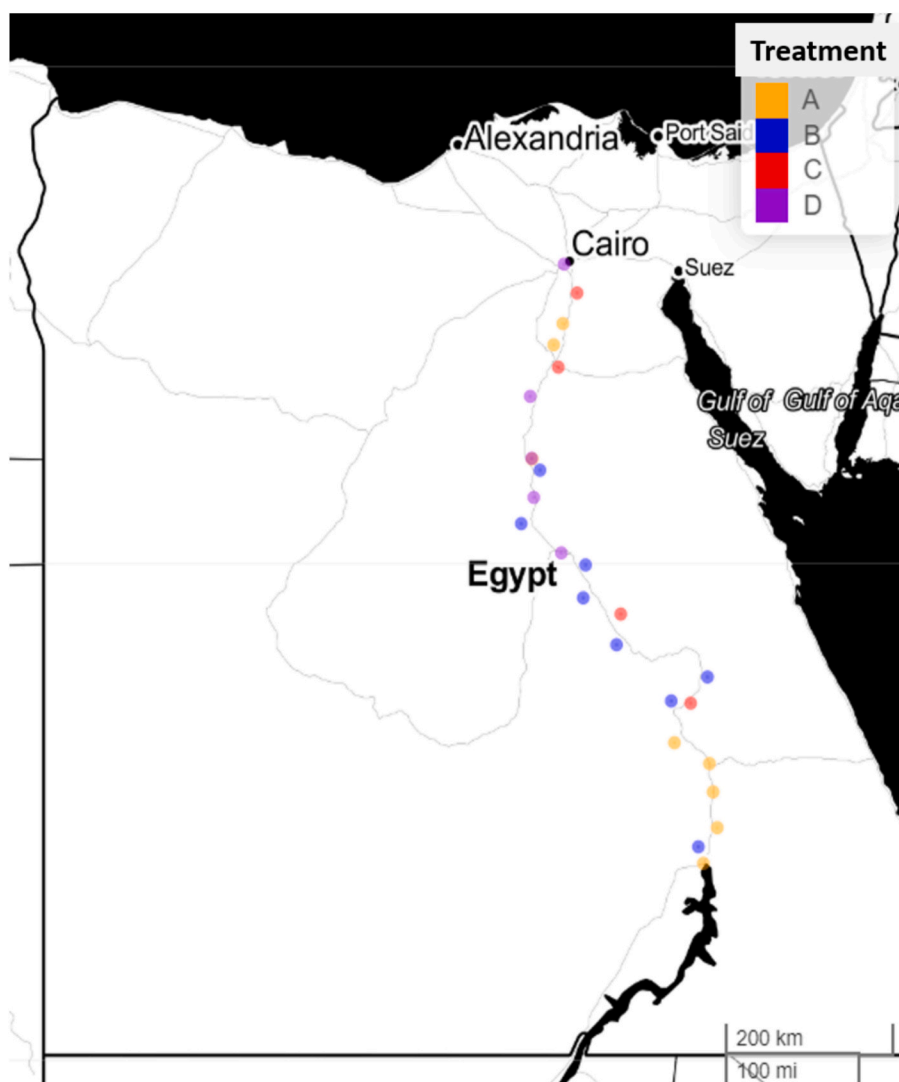


Fig. 1. Map of the study area showing the distribution of the sampled WTPs along the Nile. The sample WTP treatment types are indicated by different colors: A, B, C, and D. A, primary WTP with an associated unmanaged water pond; B, primary WTP without an associated unmanaged water ponds (just concrete ponds); C, secondary WTP with a stirring mechanical facility and an associated unmanaged water pond; secondary WTP with a stirring mechanical facility, without water pond, but open sludge pools (mechanical steering facilities).

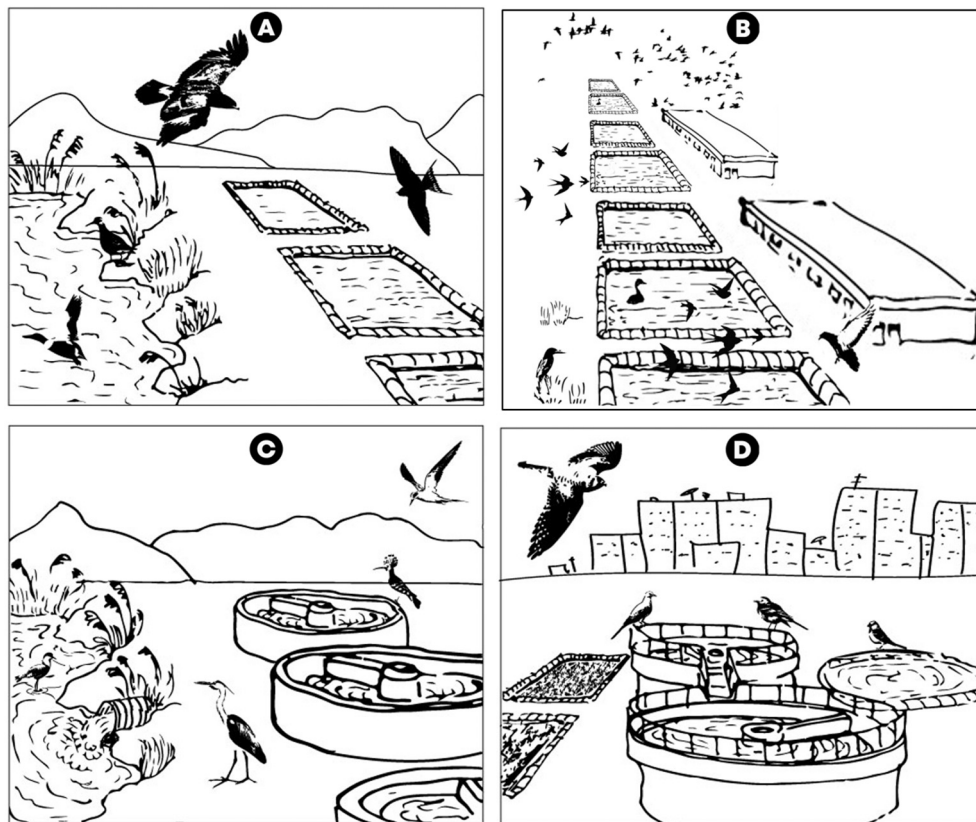


Fig. 2. Illustrations of each of the WTPs treatment types. A, primary WTP with an associated unmanaged water pond; B, primary WTP without an associated unmanaged water ponds (just multiple concrete ponds); C, secondary WTP with a stirring mechanical facility and an associated unmanaged water pond; D, secondary WTP with a stirring mechanical facility, without open water surface or additional water pond, but with merely open sludge pools.

represents stabilization WTPs with sufficient capacity to treat all received wastewater without creating unmanaged ponds. These WTPs often feature a larger surface area of treated water compared to WTP type A. These concrete ponds typically have an abundance of zooplankton, as the water is retained in the ponds for a relatively longer duration, allowing solid waste to settle at the bottom.

Mechanical treatment ponds (type C) include WTPs with low capacity, leading to spillover water that creates unmanaged ponds adjacent to the facility. These unmanaged ponds exhibit similar bird habitats to those of type A, but they are smaller in size and have cleaner water than type A due to the advanced treatment processes of type C systems. Finally, type D includes mechanical WTPs with high treatment capacity and no unmanaged ponds. These facilities are also characterized by utilizing open sludge pools but no open water. WTPs of type D have the highest level of technological advancement among the sampled WTPs as they incorporate advanced biochemical and biological processes for secondary treatment. They are most effective in recycling water for human use and also offer the potential for excess treated water to be recycled for reuse or discharged into fresh water canals or streams where the water can be used by agriculture.

2.3. Data collection

We collected the data during two seasonal surveys to account for the variation in bird communities between summer (resident birds) and winter (resident plus migratory birds). The winter survey was conducted from January 1 to January 25, 2021, moving from South to North to avoid potential double counting resulting from birds tending to move south during winter disturbance (unpublished observation). The summer survey was conducted between June 1 and June 25, 2021, proceeding from North to South for the same reason, as observations

suggested that disturbed birds tend to move north then. This directional approach thus was adopted to align with the seasonal movement patterns of birds during disturbances events and reduced the likelihood of double counting.

Depending on the nature, topography, size, and accessibility of each site, one to 15 vantage points were used to record all bird species and their abundance. Because the sewage ponds with additional unmanaged water ponds had more complex structures, including vegetation, those WTP thus required more vantage points to enable a full scan of the area to have the same quality of data as for the WTPs without additional water ponds. The area of each WTP site was calculated using ESA WorldCover Project 2020 data available on the GEE platform ([Google Earth Engine, n.d.](#)). This calculation included the total area of the official infrastructure, which consist mainly of the treatment ponds, combined with the area of unmanaged associated ponds (as in types A and C). This total area represents the scope within which the vantage points were located for each site. WTP with additional unmanaged ponds (WTP A and C) were larger than those without additional unmanaged ponds and the secondary sewage ponds type D was substantially smaller than the other WTPs (type A, $11.9 \pm 2.6 \text{ km}^2$, type B $6.4 \pm 0.5 \text{ km}^2$, type C $19.1 \pm 4.5 \text{ km}^2$, type D $0.6 \pm 0.1 \text{ km}^2$).

The counting duration was fixed at 10 to 15 mins at each vantage point. Bird surveys were conducted between 09:00 and 11:00 in winter and between 06:00 and 08:00 in summer to avoid counts being affected by birds sheltering during high mid-day summer temperatures. Two highly qualified bird observers were equipped with $10\times$ binoculars and $60\times$ telescopes and conducted both summer and winter surveys. We identified all bird species according to the IOC World Bird List, version 12.1. ([Gill et al., 2020](#)). We recorded only those birds which we could identify visually and were clearly utilizing the habitats of the site.

2.4. Statistical analysis

Bird abundance at each point represented the cumulative count of individuals across all recorded species within the site. We determined species richness by the count of unique species observed within each site. Species diversity was quantified using the Shannon-Wiener Index (H'), which integrates measures of species richness and abundance data (Krebs, 1985).

To test whether bird abundance, species richness, and species diversity differed across seasons and WTP types, we used linear mixed models (LMMs, in R (RStudio 2023.12.1 Build 402) for each dependent variable. These models included treatment type (four levels), season (summer and winter), their interaction, size of the WTP site area and latitude as predictors as well as site as random effect. For the linear mixed model on bird abundance, the abundance data were log transformed to meet assumptions of the model. We checked the residuals of the models using Q-Q plots and residual vs. fitted value plots to verify the assumptions of normality and homoscedasticity, confirming the appropriateness of the models. We then applied ANOVAs to the output of each model to assess the significance of the predictors. When WTP treatment was significant, we further conducted pairwise comparisons

through post hoc Tukey tests to determine differences between WTP types. We used the *lme4* package for fitting linear mixed models, the *car* package for conducting ANOVA on model outputs, and the *emmeans* package for performing post-hoc pairwise comparisons to analyse the effects of treatment, season, and their interaction on bird abundance, species richness, and diversity.

In subsequent analyses we used Canonical Correspondence Analyses (CCA) (Ter Braak, 1986), in Canoco5 software, to capture the effect of treatment type on bird community composition, applied separately for summer and winter bird community data. CCA is a multivariate technique that relates species data to environmental gradients, allowing to identify how different WTP treatment types are related to the community composition of bird species and its distribution along the treatment gradients. In case of the different WTP types, the treatment gradient represents an imaginary landscape gradient, ranging from the more diverse habitats provided by WTP types A and C with their unmanaged ponds, to the less diverse habitats, represented by the concrete ponds of types B, and lowest diversity habitats of type D. To do so, we plotted the effect of WTPs treatment type in summer and winter on a constrained ordination axis plot and on a binominal plot to examine to what extent bird community composition can be distinguished based on the WTP

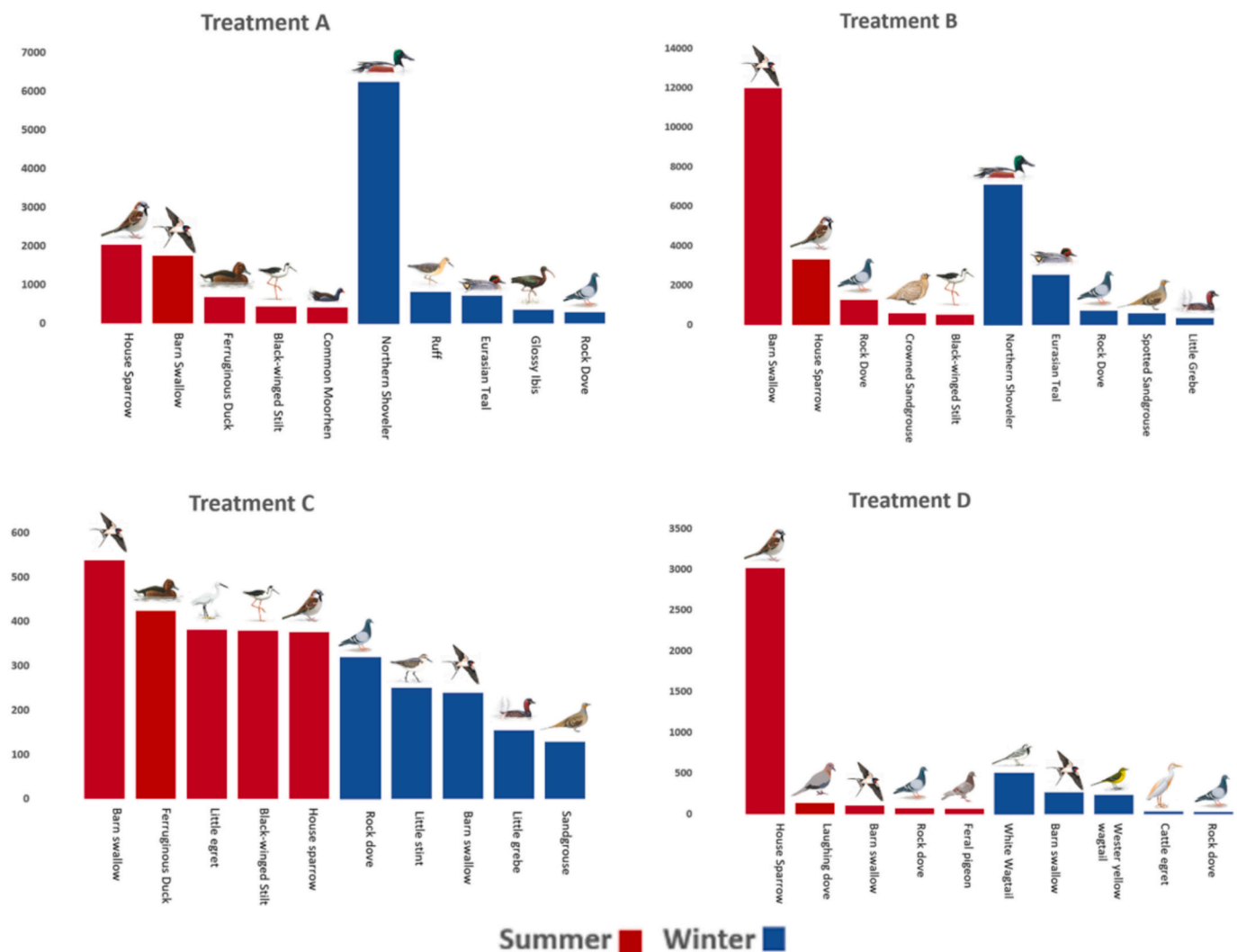


Fig. 3. The most abundant five bird species observed in each treatment group of WTPs during summer and winter survey. The sample WTPs are indicated by different colors: A, primary WTP with an associated unmanaged water pond; B, primary WTP without an associated water ponds (just concrete ponds); C, secondary WTP with a stirring mechanical facility and an associated unmanaged water pond; D, secondary WTP with a stirring mechanical facility, but without water pond, but with open sludge pools. Note that the Y axis differs in scale for each of the different treatment to make the differences within in treatment more visible. Differences in total abundance are shown in Fig. 4.

treatment type. We here followed a similar approach as in (Kati et al., 2009), where we used the WTP treatment types as the only constrained ordination for avian community distribution.

3. Results

In winter we observed a total 26,736 individuals from 82 bird species, and in summer we observed a total of 32,446 individuals from 63 species. There was substantial variation in abundance for different species. The Northern shoveler (*Spatula clypeata*) emerged as the most abundant species in winter, with 13,436 sightings, constituting 50.3 % of total bird abundance during this season. In contrast, the barn swallow (*Hirundo rustica*) was the most frequently observed species in summer, numbering 14,784 individuals, or 45.6 % of total bird abundance (Fig. 3).

Bird abundance varied significantly across WTP types ($\chi^2_3 = 12.51$, $p = 0.006$, Fig. 4a), with treatment B having significantly higher abundance compared to treatment D (B-D estimate = 3.04, $p = 0.012$; all other comparisons $p > 0.16$, Fig. 4a). Season ($\chi^2_1 = 2.88$, $p = 0.090$) showed a tendency for more birds in summer than in winter while size of the area and latitude were not significant (area, $\chi^2_1 = 0.886$, $p = 0.35$, latitude $\chi^2_1 = 0.80$, $p = 0.37$). The interaction between treatment and season was not significant ($\chi^2_3 = 0.28$, $p = 0.96$).

Species richness likewise was significantly influenced by WTP type ($\chi^2_3 = 13.92$, $p = 0.003$, Fig. 4b) and also by season with more species

present in winter than in summer ($\chi^2_3 = 10.57$, $p = 0.001$). Size of the WTP area tended to have an effect ($\chi^2_1 = 3.54$, $p = 0.060$). The interaction between treatment and season was not significant ($\chi^2_3 = 2.04$, $p = 0.57$). Notably, treatment D showed a significantly lower species richness compared to treatments A and B (A-D estimate 10.48, $p = 0.025$; B-D estimate 11.52, $p = 0.012$; all other comparisons, $p > 0.15$).

Also the Shannon-Wiener diversity (H') index was significantly affected by WTP type ($\chi^2_3 = 20.62$, $p = 0.0001$, Fig. 4c), with treatment C showing significantly higher species diversity compared to the treatments B and D (B-C estimate -1.17 , $p = 0.025$; C-D estimate 1.61, $p = 0.001$) and a tendency of higher diversity compared to treatment A (A-C estimate = -0.95 , $p = 0.068$). In both summer and winter, avian diversity (H') on average was consistently lowest in WTP type D compared to type A, B, and C (Fig. 4c). Neither season ($\chi^2_1 = 0.11$, $p = 0.74$) nor area ($\chi^2_1 = 1.46$, $p = 0.23$) had a significant effect on the species diversity (H') but latitude did have a positive effect with higher species diversity in the South ($\chi^2_1 = 4.63$, $p = 0.03$). The interaction between treatment and season was not significant ($\chi^2_3 = 1.4$, $p = 0.71$).

3.1. Community composition

The community composition analysis showed that WTPs types have distinct species assemblage in each season (Fig. 5). In the winter counts, WTPs of type A and C were characterized by species from many guilds (raptors, insectivores, waders, aquatic omnivores, vertebrate foragers)

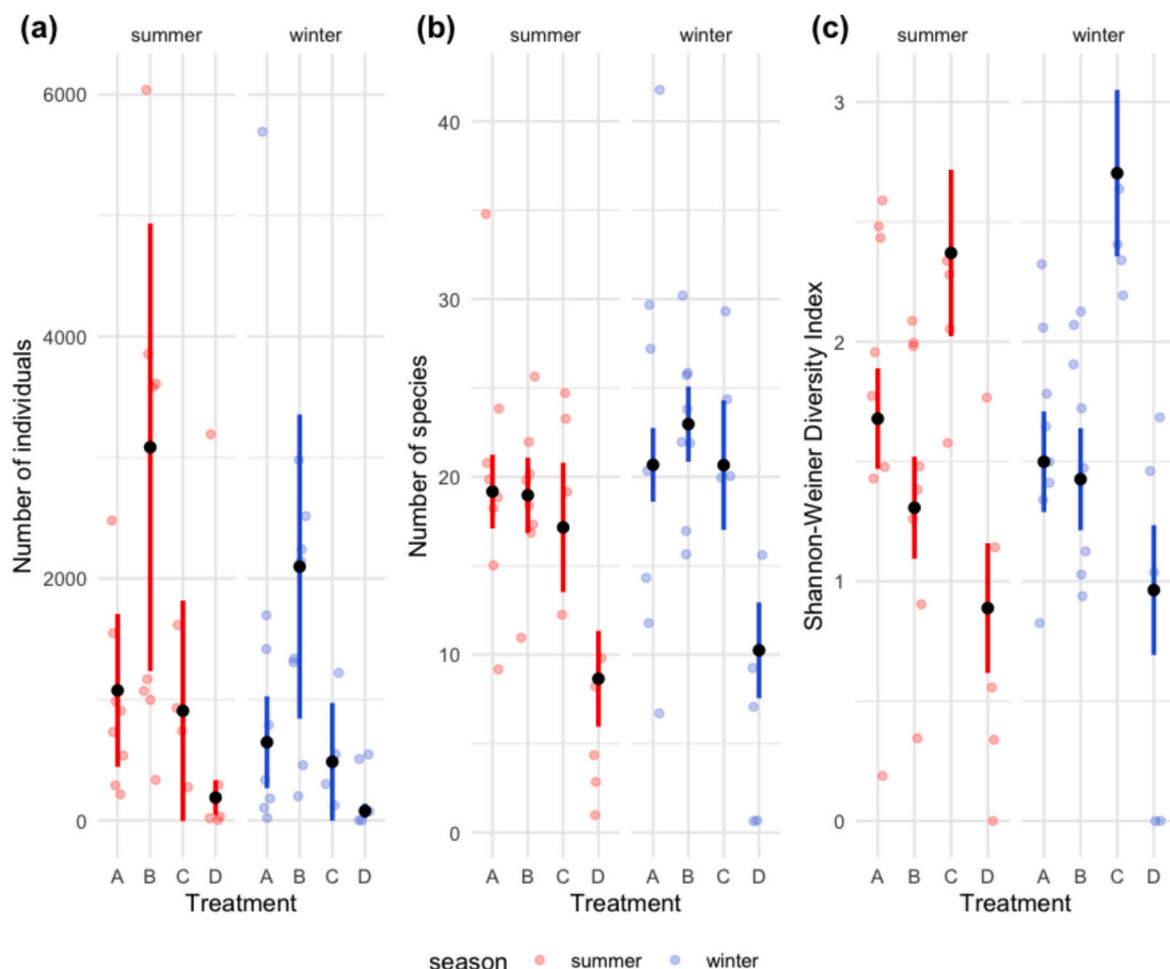


Fig. 4. WTP types effect on (a) bird abundance, (b) species richness and (c) the Shannon Wiener Index of species diversity (means, standard errors and original values from the WTP sites). Different WTP types indicated by capital letters (Fig. 2). A, primary WTP with an associated unmanaged water pond; B, primary WTP without an associated unmanaged water pond (just concrete ponds); C, secondary WTP with a stirring mechanical facility and an associated unmanaged water pond; D, secondary WTP with a stirring mechanical facility and without water pond, but with open sludge pools. Shown are original sites values, mean and SE.

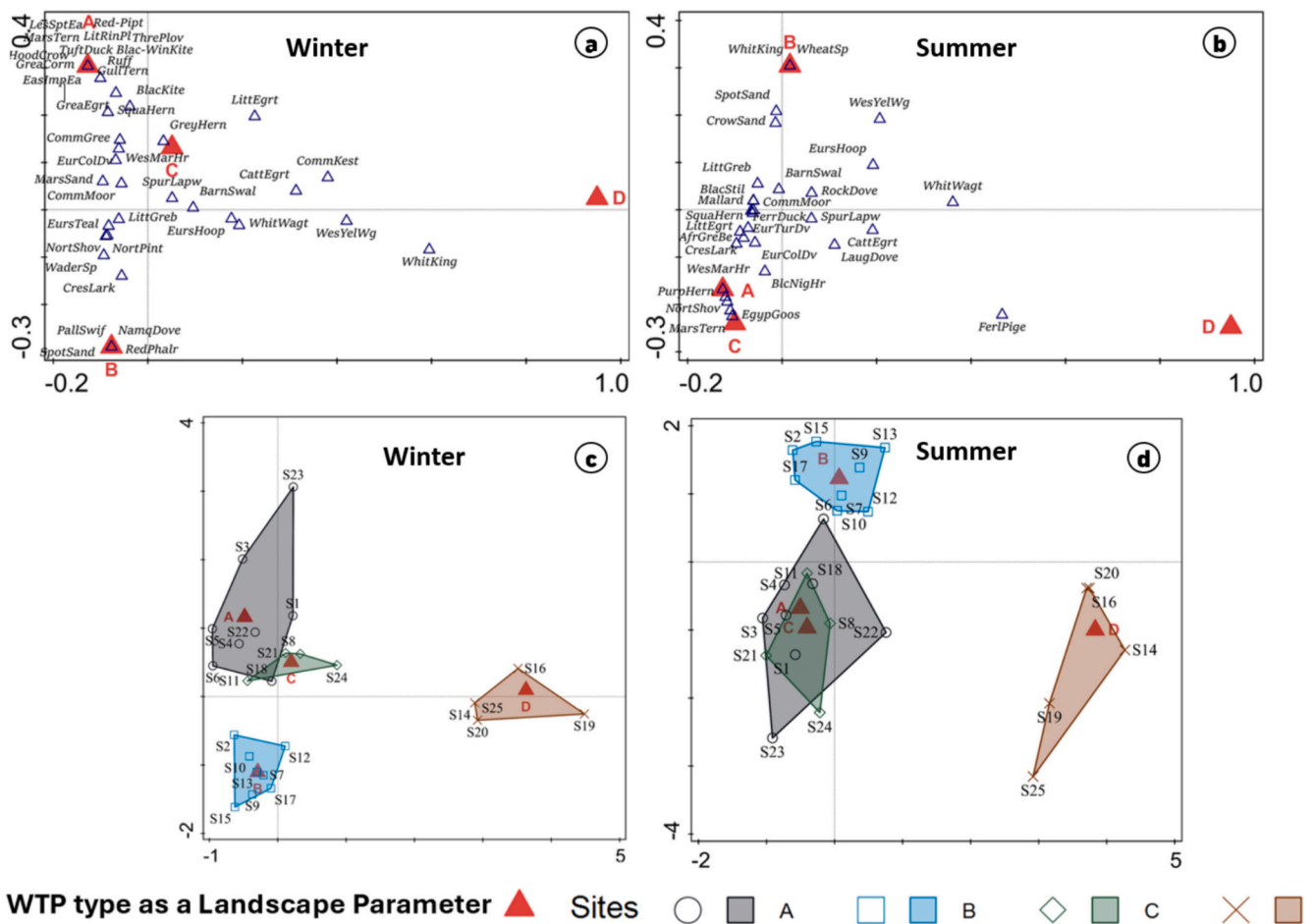


Fig. 5. Canonical correspondence analysis (CCA) depicting species communities across seasons and treatment types. (a) and (b) illustrate bird community ordination around treatment types in winter and summer. (c) and (d) display positioning of treatment types relative to each other based on bird community ordination distribution in winter and summer. Overlapping polygons denote shared bird communities within treatment types. A, primary WTP with an associated unmanaged water pond; B, primary WTP without water ponds (just concrete ponds); C, secondary WTP with an associated unmanaged water pond; secondary WTP without water pond (mechanical steering facilities).

and with a range of habitat requirements, forming a complex community composition. These species included the lesser-spotted eagle (*Clanga pomarina*), red-throated pipit (*Anthus cervinus*), little-ringed plover (*Charadrius dubius*), tufted duck (*Aythya fuligula*), hooded crow (*Corvus cornix*), and gull-billed tern (*Gelochelidon nilotica*). The WTPs of type B likewise was distinguished by a complex community consisting of species from different guilds and foraging requirements, yet different ones compared to WTP A and C. These included granivores like the spotted sandgrouse (*Pterocles senegallus*) and namaqua dove (*Oena capensis*) as well as insectivores and zooplankton feeders like pallid swift (*Apus pallidus*), and the rare red phalarope (*Phalaropus fulicarius*). In summer, in contrast, WTPs of type A and C were characterized by yet another community of species like the purple heron (*Ardea purpurea*), Northern shoveler (*Spatula clypeata*), marsh tern (*Sternula albifrons*), Egyptian goose (*Alopochen aegyptiaca*), and Western marsh harrier (*Circus aeruginosus*). WTPs of type B accommodate species like sandgrouse (*Pterocles sp.*), white-breasted kingfisher (*Ceryle rudis*), and wheatears (*Oenanthe sp.*). In contrast to the other types of WTPs, type D did not attract diverse species communities. Most species were species typically found in urban environments and most individuals were house sparrows or wagtails (Figs. 3 and 5).

The community composition analysis reveals that the difference in WTP management explains about 21 % of the total variance of community compositions in both summer and winter (permutation test| winter; pseudo F = 1.9, p = 0.002 and summer; pseudo F = 1.8, p =

0.002; Fig. 5). The constrained ordination plots for both seasons reveal a distinctive triangular shape for the sites' treatment types. WTP of A and C cluster toward one end of the triangle, specifically so in summer, while WTP of type B and D each is located at one of the other two ends, respectively (Fig. 5).

4. Discussion

Here we show that wastewater treatment plant (WTP) sites in arid zones host high numbers of birds, as we counted 26,736 individuals from 82 bird species in winter and 32,446 individuals from 63 species in summer. Thus, in situations as studied here, WTP ponds provide important habitats for resident and migratory birds. Considered as a combined network of habitats, the WTPs studied here already meet the criteria of Important Bird Areas (IBA), as they together hold >20,000 waterbirds (BirdLife International, 2004), but they lack IBA designation. It is notable that the total area of WTPs studied here (combined ca. 38 km²) is relatively small compared with designated IBAs in Egypt (e.g., Upper Nile IBA > 150 km²) (Baha el Din, 1999). These findings highlight the potential significance of WTPs as conservation sites, particularly given the presence of >440 operational WTPs across Egypt (Holding Company for Water and Wastewater, 2021).

Our findings further identify an important relationship between different types of WTPs and avian diversity parameters, such as abundance, species richness, species diversity, and community composition,

across winter and summer seasons. The usage of WTP types by large avian numbers and a high species diversity, suggests that two habitat features are of key relevance: (1) the availability of surface water and (2) the presence of unmanaged water ponds (Hamza et al., 2024). These factors provide key resources for many species, as also highlighted in earlier studies (Hamilton et al. (2005), Lewis-Phillips et al. (2019)). WTPs with an extensive availability of concrete water ponds (type B) supported the highest avian abundance, dominated by barn swallows, indicating that the surface size matters for the number of individuals, but this was not reflected in the number of species or species diversity. WTPs with unmanaged water ponds (types A and C), resembling natural wetlands, exhibited similar or higher species richness values than type B. Type C, with its unmanaged water pond of cleaned water even had the highest species diversity, despite its relatively lower values for abundance of individuals. Conversely, WTPs without open water bodies (type D) supported the lowest avian diversity and abundance, as these systems resemble typical urban environments and primarily attract birds adapted to disturbed urban settings (Vincze et al., 2016). These findings indicate that any WTP type, except D with no water, provides sufficient habitat characteristics to host similarly large numbers of species while the ponds with unmanaged ponds and thus also more complex surrounding vegetation provide a higher species diversity.

Moreover, the community composition analysis reveals the distribution of avian species varied along distinct landscape characteristics provided by the different WTP types. WTPs of types A and C supported very complex and similar avian communities with species from different guilds and foraging requirements, including threatened eagles. The reason for this most likely is that these WTPs provide more niches for a variety of species from different guilds with different ecological requirements and foraging strategies and needs. For instance they provide habitats also for raptors, presumably due to the presence of high trees, providing suitable perching and roosting habitats for species such as greater-spotted eagles (*Clanga clanga*), imperial eagles (*Aquila heliaca*), and other raptors. Perching on higher objects is well documented for eagle species, as in Dwyer et al. (2020) and Nadjafzadeh et al. (2016).

Building on this analysis, the canonical correspondence analysis (CCA) further illustrates how treatment types influence bird community composition as the advanced WTP type D diverged significantly from other types, revealing its limited ecological suitability due to its lack of water surface and complex vegetation. Most species recorded here were species typically seen also elsewhere in urban environments, like house sparrows and wagtails. The consistent pattern of avian diversity values across all WTPs types and seasons reflects the availability of treated stabilization surface water in types B and C, which are relatively cleaner compared to type A and the absence of exposed water in type D.

WTPs type C was the most diverse overall but its avian community composition was most similar to types A, which likewise had an unmanaged water pond. The larger open concrete water ponds in type B create excellent habitats for zooplankton feeders, such as northern shovelers (*Spatula clypeata*), and insectivorous birds like barn swallows (*Hirundo rustica*), so these species were highly abundant. Other species though, including raptors, were less represented, in line with Guillemain et al. (2000). The low representation of raptors in these areas is likely due to the lack of suitable perching or roosting habitats, such as tall trees, which are critical for raptors. Notably, type B hosted a rare record of the red phalarope (*Phalaropus fulicarius*), observed for the first time in Egypt, likely benefiting from the relatively deeper concrete ponds and zooplankton abundance. These findings are in line with those of Hamilton et al. (2005), who reported a positive correlation between invertebrate abundance and water bird presence in the later stages of treatment within stabilization ponds.

Taken together, unmanaged water ponds, often resulting from water exceeding the carrying capacity of the WTP, thus play a pivotal role in the suitability of WTPs for bird species diversity. These ponds provide varying microhabitats that cater to different ecological requirements, supporting a broad range of niches for many species from different

guilds. In contrast, type D, despite being technologically efficient and advanced, lacks the habitat diversity necessary to sustain diverse bird populations. These findings suggest that wastewater management strategies should balance technological efficiency with ecological considerations, particularly in areas with limited alternative water sources.

In arid zones where natural wetlands are scarce or degraded, such as in Egypt, these ponds act as crucial stopover and wintering sites for migratory birds. However, the ecological benefits they provide come with potential risks, including pollution. WTPs may contain toxic substances that can lead to negative health effects or even be lethal to birds (Stoewsand et al., 1984). These effects can be harmful also to humans when poisoned birds are being consumed (Stoewsand et al., 1984; Custer et al., 1996). Regular monitoring of water quality is essential to indicate when these sites accumulate health threats, and if so, such findings lead to compensatory management actions. Otherwise, such WTP may become ecological traps that negatively affect biodiversity (Merken et al., 2015). Such instances like a mass mortality of White Storks (*Ciconia ciconia*) near Sharm El-Sheikh highlight the critical importance of such measures (Schimkat, 2013).

Also, the seasonal observations of bird abundance and community composition highlight the importance of WTPs in supporting migratory and resident species along the Nile flyway. As migratory birds depend on consistent water and food availability during their journeys, WTPs fill a critical ecological niche in arid landscapes. This aligns with findings from (Prigent et al., 2012) and (Murray et al., 2014), which emphasize the role of artificial water bodies in sustaining avian populations. The structural and technological differences among WTP types determine their suitability for different bird communities, further underlining the need for tailored conservation strategies.

Our findings further identify a conflict between different sustainable development goals, an aspect important to consider in conservation policies. They specifically identify an ecological trade-off between SDG 6 (clean water) and SDG 15 (life on land), emphasizing the importance of balancing resource efficiency with biodiversity conservation. The advanced WTPs prioritize water reuse, supporting the sustainable development goal (SDG) 6 to increase water-use efficiency by 2030 (UN, 2015). However, the absence of additional water ponds in these facilities significantly reduces their habitat value for birds, acting against SDG 15 (life on land). This trade-off between water conservation and biodiversity conservation is particularly pronounced in regions along major migration flyways, where the loss of suitable habitats can have serious implications. These findings highlight concerns raised by (Gleick, 2000) and (Gude, 2017) about the unintended ecological consequences of water-saving technologies. Such advanced treatment technologies, while beneficial for water conservation, thus can inadvertently reduce habitat availability for migratory and resident birds. Strict water reuse policies thus should incorporate measures to mitigate their impact on avian populations, especially in arid and ecologically sensitive regions.

Based on our findings, we recommend implementing wastewater treatment measures that effectively balance water recycling and biodiversity conservation. Specifically, treated water bodies should feature large surface areas and slow water flow to promote the growth of zooplankton and other invertebrates, which serve as vital food sources for water birds (Hamilton et al., 2005). Additionally, encouraging the growth of wild vegetation and native trees around these water ponds would provide birds with essential foraging habitats, shelter, and perching opportunities, further enhancing the ecological value of these sites.

In conclusion, this study demonstrates the critical role of WTPs in supporting bird populations, particularly in regions where natural wetlands are scarce, absent, or highly disturbed. The ecological value of WTPs extends beyond their primary function, serving as key habitats for resident and migratory species. Policymakers and facility managers should integrate biodiversity conservation into WTP design and operation, ensuring these artificial wetlands remain functional and healthy ecosystems. Future research should focus on long-term monitoring,

toxicity assessments, and innovative wastewater treatment solutions that balance ecological and other development priorities, as well as WTP being part of a functional migration network (Xu et al., 2019, 2022). By doing so, WTPs can play a pivotal role in conserving biodiversity along major migration flyways, supporting both local and global ecological connectivity and safe migration.

CRedit authorship contribution statement

Khaled Noby: Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Ignas M.A. Heitkönig:** Writing – review & editing. **Erwin Bulte:** Writing – review & editing. **Marc Naguib:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Conceptualization.

Impact statement

Advanced wastewater treatment technology significantly affects avian biodiversity thus, this results in SDGs targets conflict.

Advanced wastewater tech impacts avian diversity, causing conflicts in SDG targets.

Declaration of competing interest

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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