Tanzania Journal of Science 50(3): 468-482, 2024
ISSN 0856-1761, e-ISSN 2507-7961
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Vegetation invasion influences waterbird assemblages and aquatic environmental parameters in urban areas of Dar es Salaam, Tanzania

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Received 11Apr 2024, Revised Aug 20 2024, Accepted Sept 6 2024, Published Sept 30 2024
https://dx.doi.org/10.4314/tjs.v50i3.5

Abstract

Waste Stabilisation Ponds (WSPs) serve as refuge habitats for waterbirds in response to the decline of natural wetlands especially in urban settings. Various sewage treatment stages within WSPs attract waterbirds differently based on the specific characteristics of each stage. This study examines the influence of treatment stages on both vegetated and non-vegetated WSPs over a period of one year in Dar es Salaam, Tanzania. Bird surveys were periodically conducted at each treatment stage along with different environmental variables; dissolved oxygen, electrical conductivity, water turbidity, water temperature, pH, and invertebrate biomass. In non-vegetated WSPs, waterbird densities and invertebrate biomass were significantly higher in facultative ponds than in maturation ponds ($p < 0.05$). The water pH was higher in maturation ponds than in facultative ponds ($p < 0.05$). However, in vegetated WSPs, no notable variations in waterbird density and environmental variables were observed across different treatment stages ($p > 0 .05$). The presence of vegetation in WSPs created similar environmental conditions across treatment stages, potentially reducing waterbird preferences for specific stages. These findings underscore the importance of understanding the characteristics of sewage treatment stages in order to enhance the management of WSPs as suitable habitats for waterbird populations in urban areas.

Keywords: Invertebrate biomass; Sewage treatment stages; Vegetated ponds; Waterbirds, Waste stabilising ponds

Introduction

Waste stabilisation ponds (WSPs) are man-made aquatic systems used for wastewater treatment from industrial and urban sources (Bansah and Suglo 2016, Alawa et al. 2022). They are shallow basins that leverage natural processes like biodegradation sunlight, temperature, and sedimentation to treat wastewater effectively (Mara 2008, Hayati et al. 2013). These ponds are known for their low maintenance and cost-effectiveness, making them a popular choice for treating wastewater through biological action. There are different types of WSPs each serving a specific purpose in the treatment process (Izdori et al. 2019). Some common types include; anaerobic ponds which lack oxygen and facilitate the breakdown of organic matter by anaerobic bacteria (Quiroga 2013), facultative ponds which have different zones with varying oxygen levels allowing for both aerobic and anaerobic processes to occur (Kalderén 2019), and lastly, the maturation ponds provide a final stage for further treatment where sunlight and algae help in the removal of remaining pollutants. The ponds can function independently or in sequence as anaerobic, facultative, and maturation ponds (Kalderén 2019).

Waste Stabilisation Ponds support wildlife by creating favourable habitats and food resources through their treatment processes especially due to the ongoing loss of natural wetlands (Selvaraj and Nagarajan 2023, Msaki et al. 2023). The treatment stages of WSPs can indeed influence animals, especially waterbirds, differently based on the environmental characteristics they possess such as water quality, nutrient levels, and habitat availability across different treatment stages (Hamilton and Taylor 2005). In WSPs, the different treatment stages create varying conditions that can attract or deter different types of wildlife. For example, the presence of algae and bacteria in facultative ponds can provide food sources for certain waterbird species, while the anaerobic ponds may have conditions less conducive to wildlife due to lower oxygen levels and different microbial activity (Murray and Hamilton 2010). Furthermore, the nutrient removal processes within WSPs, such as nitrogen and phosphorus uptake by algal biomass, can impact the availability of food sources for waterbirds and other aquatic organisms. The design parameters of WSPs, which focus primarily on Biological Oxygen Demand (BOD) and faecal coliform removal rather than nutrient removal, may inadvertently affect the ecological balance within and around the ponds, influencing the presence and behaviour of wildlife species like waterbirds (Andersen et al. 2003). The invasion of vegetation in WSPs has the potential to impact both biotic and abiotic components. Dense vegetation, for instance, may contribute to hypoxia, thereby affecting the utilisation of WSPs by wetland-dependent organisms such as invertebrates and birds (Augustin et al. 1999, Roberts et al. 2009). Additionally, floating vegetation can hinder sunlight penetration, promoting the growth of insect populations and potentially leading to odorous conditions (Kalderén 2019). The influence of vegetation is likely to impact the effectiveness of treatment stages, potentially affecting the presence of waterbirds and other aquatic organisms.

Few published literature exist on the utilisation of waterbirds at various treatment stages in temperate regions (Hamilton et al. 2005, Murray et al. 2014) yet the impact of these stages remains unclear in tropical regions at both vegetated WSPs and non-vegetated WSPs. The performance of these ponds in colder environments may differ from tropical regions (Liu et al. 2016), potentially requiring modifications in design and operation to optimise treatment efficiency based on the specific environmental conditions present (Kalderén 2019). This study investigates waterbird utilisation and environmental variables across different treatment stages within WSPs. It compares waterbird densities and environmental variables at vegetated and non-vegetated WSPs in Dar es Salaam, Tanzania. We hypothesized for the significant variations in different sewage treatment stages of vegetated and non-vegetated WSPs for both waterbird assemblages and aquatic environmental parameters.

Materials and Methods

Study area

The study was undertaken in Dar es Salaam located between 6°33' - 7°12' South and 38°59' - 7°12' East along the East African coast of Tanzania. Divided into five administrative districts, namely Ilala, Kinondoni, Temeke, Kigamboni, and Ubungo, the city spans 1350 km², with additional water bodies covering the remaining area, totalling 1800 km². Its equatorial location and proximity to the Indian Ocean bless it with a tropical climate characterised by hot and humid conditions throughout the year, with an average annual rainfall of about 1,100 mm and humidity ranging from 67% to 96%. The city experiences two rainy seasons annually, with long rains in April and May and short rains in November and December. Despite its urban landscape, Dar es Salaam harbours a rich biodiversity, hosting approximately 511 bird species (Harvey and Howell 1987, Wium-

Andersen and Reid 2000). Its coastal zone, featuring tidal mudflats, river inlets, and saltpans, serves as a vital habitat for migrating waders, including species from Palearctic regions; mostly eastern Europe. Constructed wetlands such as WSPs form an additional habitat for waterbirds in a city where freshwater habitats are scarce. Consequently, due to the high concentrations of waders including the Palearctic migrants at the coast mud flats, the Dar es Salaam region has been acknowledged as an Important Bird Area (Baker and Baker 2002).

A study focusing on WSPs was conducted at two sites: Lugalo WSPs and UDSM WSPs. Located at 06°45.060' latitude and 39°13.727' longitude, Lugalo WSPs, known as non-vegetated WSPs, lie within Kinondoni district. These ponds, adjacent to Lugalo Military Barracks and near Lugalo Primary School, feature four compartments. The ponds are periodically maintained including vegetation removal, and thus only about 5% of the ponds is invaded by vegetation dominated by *Cynodon dactylodon.* The ponds treat waste from Lugalo Military General Hospital (LMGH) and residential areas. Notably, the ponds support a diverse avian population, including storks, kingfishers, and cormorants. Contrastingly, UDSM WSPs, classified as vegetated WSPs, are situated in Ubungo district within the Mwalimu Julius K. Nyerere Mlimani Campus of the University of Dar es Salaam (UDSM), adjacent to the UDSM Estate Department. Covering an area of 19,132 m², these ponds are predominantly vegetated, with approximately 95% surface area adorned by vegetation, primarily *Pistia stratiotes* and *Typha capensis*. These WSPs play a crucial role in treating wastewater from UDSM's main campus, including a health centre, residential areas, and academic facilities. The surrounding environment attracts various waterbirds such as jacanas, crakes, and egrets, enhancing the ecological significance of the area.

The configuration of the WSPs differs between the two sites. Lugalo WSPs comprise four compartments, each housing a stage of the treatment process: first facultative pond (FP1), second facultative ponds (FP2), first maturation pond (MP1), and second maturation pond (MP2). In contrast, UDSM WSPs consist of seven compartments, featuring a primary facultative pond (PrFP) comprising one compartment, followed by first and second secondary facultative ponds (SFP1, SFP2), and a maturation pond (MP), with each stage comprising two compartments. Notably, both study sites, despite being in urbanized areas, are surrounded by green vegetation, including patches of forest and lawns, fostering a mosaic of habitats that support diverse flora and fauna. The juxtaposition of these artificial habitats with natural elements contributes to the ecological resilience of Dar es Salaam's urban landscape, emphasizing the importance of conservation efforts within rapidly developing urban centres.

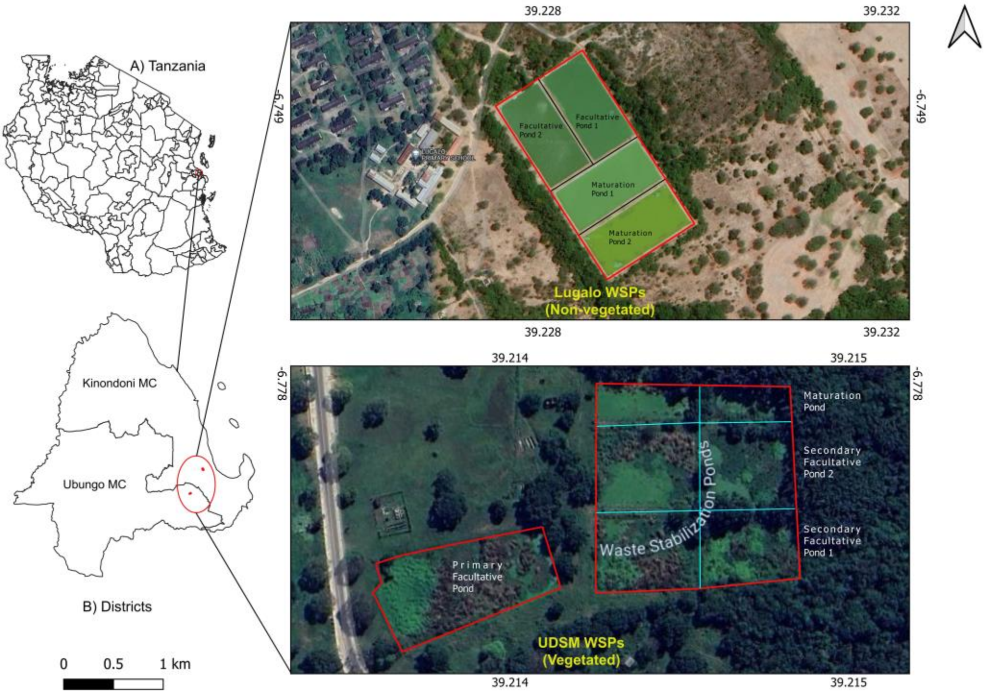

Figure 1: Location of the study sites; non-vegetated WSPs in Kinondoni District and vegetated WSPs in Ubungo District, Tanzania

Data collection

The study was carried out for one year starting from April 2022 to March 2023, to examine variation of waterbird assemblages and associated environmental parameters at the WSPs. To ensure that even passage migrants are covered, data for waterbirds and environmental parameters were collected every 10 to 15 days throughout the study period. The total count method, as described by Underhill and Prys-Jones (1994), was used for this study. Waterbird surveys were conducted from pre-defined observation points, which provided a broad field of view, allowing for observation of the entire surface of the WSPs using Bushnell binoculars (10 × 42). These observation points were strategically located within each compartment of the vegetated and non-vegetated WSPs. Surveys took place in the early morning between 0700 and 1100 hours when birds are typically most active.

Measurements of environmental variables

The environmental parameters examined are dissolved oxygen (DO), electrical conductivity (EC), water turbidity, water temperature, pH, and invertebrates` biomass. These were selected based on their influence on waterbird assemblages at the WSPs (Hamilton et al. 2005, Anika and Parasharya 2013). Water samples were collected using 500ml plastic bottles. The bottles were filled with water and tightened while submerged. Water samples were taken on the same day to the water laboratory for analysis at the Department of Water Resources Engineering (WRE), College of Engineering and Technology (CoET), UDSM. In the laboratories, samples were refrigerated at 6°C within 30 minutes after their collection. Multi 3430 SET was used to measure dissolved oxygen (DO), electrical conductivity (EC) and pH. Water turbidity was measured using the turbidity meter HI 93703. Water temperature was measured in situ using the HI9829 multiparameter as per Kayombo et al.

(2002). All the laboratory equipment were calibrated before measurements.

For the collection of aquatic macroinvertebrates, a D-frame kick net with a mesh size of 250µm was used (Gabriels et al. 2010, Ojija et al. 2015, Alavaisha et al. 2019). A duration of one minute was used to collect one sample in each compartment. The collected samples were emptied into the collecting dish to separate the macroinvertebrates from other contents. Samples were kept in 75% ethanol for 21 days to avoid the effect of weight loss, then biomass was measured using a weighing balance (Model: ATY224-SHIMADZU) in a controlled chamber after being dried up in the oven at 60°C for 24 hours (Poepperl 1998) in the Zoology laboratory at UDSM.

Data analyses

The data for waterbirds and environmental variables in this study are presented using descriptive and graphical approaches. Data analyses were done using PAST ver: 4.03 software program (Hammer et al. 2001). Following a normality check of all data with the Shapiro-Wilk test, the data for both waterbird density and environmental parameters were not normally distributed even after transformation. Therefore, a non-parametric Kruskal-Wallis test was used to test for the significant difference in waterbird density and environmental parameters among treatment stages of WSPs followed by Dunn's post hoc which assessed the difference between treatment stages. The waterbird density was determined by calculating the number of birds per unit total area covered by ponds at each site. The average number of birds was calculated by dividing the total number of individuals by the total number of observations. The naming and arrangement of bird species adhere to the guidelines provided by HBW and Birdlife International (2024).

Results

Waterbird assemblages among pond treatment stages

A total average of 168 ± 21 birds, from six orders, 14 families, and 29 species was recorded during the study. Non-vegetated WSPs had an average of 142 ± 20 birds from 6 orders, 13 families and 26 species, while vegetated WSPs had an average of 26 ± 2 birds from 5 orders, 5 families and 10 species recorded (Table 1 and 2). In the non-vegetated WSPs, the highest abundance was found at the facultative pond two (FP2), hosting an average of 58 ± 10 birds from 22 species. Following closely, was the facultative pond one (FP1) with an average of 58 ± 10 birds from 20 species, and maturation pond one (M1) with an average of 15 ± 2 birds across 12 species. The least abundant was maturation pond two (M2) with an average of 10 ± 2 birds from 16 species (Table 1).

On the other hand, amongst the vegetated WSPs, the highest abundance was observed at secondary facultative pond two (SFP2), accommodating an average of 11 ± 1 birds from seven species. Following this, the maturation pond, serving as the final stage, had an average of 6 ± 1 birds from six species, while the secondary facultative pond contained an average of 5 ± 1 birds from eight species. The least abundant stage was the second stage of the primary facultative pond (PrFP) (SFP1), which had an average of 4 ± 1 birds from 3 species (Table 2).

Table 1: The average number of individual waterbirds counted at different treatment stages of non-vegetated WSPs from April 2022 to March 2023

Family name	Common name	Scientific name	FP1*	FP2*	MP1*	MP2*
Anatidae	White-faced Whistling-duck	*Dendrocygna viduata*	40 ± 2	35 ± 7	11 ± 3	6 ± 4
Podicipedidae	Little Grebe	*Tachybaptus ruficollis*	17 ± 2	8 ± 1	8 ± 1	2
Ciconiidae	Yellow-billed Stork	*Mycteria ibis*	1	1		
Threskiornithidae	African Sacred Ibis	*Threskiornis aethiopicus*	5 ± 2	4 ± 1		4
Threskiornithidae	Hadada Ibis	*Bostrychia hagedash*	2	5	5 ± 4	3 ± 1
Threskiornithidae	Glossy Ibis	*Plegadis falcinellus*	15	17 ± 13		
Ardeidae	Black-crowned Night-heron	*Nycticorax nycticorax*		6		
Ardeidae	Green-backed Heron	*Butorides striata*				1
Ardeidae	Cattle Egret	*Bubulcus ibis*	4 ± 2	3		
Ardeidae	Grey Heron	*Ardea cinerea*		1	1	2
Ardeidae	Black-headed Heron	*Ardea melanocephala*	2	1		2
Ardeidae	Purple Heron	*Ardea purpurea*				1
Ardeidae	Yellow-billed Egret	*Ardea brachyrhyncha*		1		
Scopidae	Hamerkop	*Scopus umbretta*	1	1	1	1
Phalacrocoracidae	Long-tailed Cormorant	*Microcarbo africanus*	2	8 ± 1	3 ± 1	3
Burhinidae	Water Thick-knee	*Burhinus vermiculatus*	4 ± 1	11 ± 3	3 ± 1	3 ± 1
Recurvirostridae	Black-winged Stilt	*Himantopus himantopus*	17 ± 2	18 ± 3	2	

Family name	**Common name**	**Scientific name**	**FP1***	**FP2***	**MP1***	**MP2***
Charadriidae	Spur-winged Lapwing	*Vanellus spinosus*	1			1
Jacanidae	African Jacana	*Actophilornis africanus*	3 ± 1	2	2	1
Scolopacidae	Ruff	*Calidris pugnax*	2	2		
Scolopacidae	Red-necked Phalarope	*Phalaropus lobatus*		1		1
Scolopacidae	Common Sandpiper	*Actitis hypoleucos*	5 ± 1	5	4 ± 1	4 ± 1
Scolopacidae	Green Sandpiper	*Tringa ochropus*	3	3 ± 2	5 ± 3	5
Scolopacidae	Wood Sandpiper	*Tringa glareola*	7 ± 1	13 ± 4	3 ±1	5 ± 2
Scolopacidae	Marsh Sandpiper	*Tringa stagnatilis*	2	3		
Laridae	Common Tern	*Sterna hirundo*	1			

*FP1 = Facultative Pond 1, FP2 = Facultative Pond 2, MP1 = Maturation Pond 1and MP2 = Maturation Pond 2

Table 2: The average number of individual waterbirds counted at different treatment stages of vegetated WSPs from April 2022 to March 2023

Family name	**Common name**	**Scientific name**	**PrFP***	**SFP1***	**SFP2***	**MP***
Rallidae	Black Crake	*Zapornia flavirostra*	3	2	3	2
Threskiornithidae	Hadada Ibis	*Bostrychia hagedash*	5	4 ± 2	4 ± 2	3 ± 1
Ardeidae	Squacco Heron	*Ardeola ralloides*	1			
Ardeidae	Cattle Egret	*Bubulcus ibis*	1			
Ardeidae	Black-headed Heron	*Ardea melanocephala*	1		2	1
Ardeidae	Purple Heron	*Ardea purpurea*			1	1
Ardeidae	Great White Egret	*Ardea alba*				1
Ardeidae	Yellow-billed Egret	*Ardea brachyrhyncha*	1		1	
Scopidae	Hamerkop	*Scopus umbretta*	1		2	
Jacanidae	African Jacana	*Actophilornis africanus*	3	4 ± 1	9 ± 1	6 ± 1

*PrFP = Primary Facultative Pond, SFP1= Secondary Facultative Pond 1, SFP2 = Secondary Facultative Pond 2 and MP = Maturation Pond

Density of waterbirds in different treatment stages of the non-vegetated and vegetated WSPs

The variation in waterbird density among the treatment stages within the non-vegetated WSPs was found to be statistically significant (H = 9.441, p = 0.020). Subsequent analysis using Dunn's post hoc test revealed specific differences in waterbird density between the treatment stages (Table 3). Notably, no significant differences were recorded within the facultative ponds, nor were there significant variations within the maturation ponds. However, a noteworthy difference emerged when comparing the facultative pond stages to the maturation pond stages (Table 3). Furthermore, the density of waterbirds was notably higher at the initial treatment stages, FP1 and FP2, compared to the final treatment stages, MP1 and MP2 (Figure 2).

Table 3: Pairwise comparison for the significant difference in the density of waterbirds (birds/m²) between different treatment stages at non-vegetated WSPs using Dunn's post hoc test

	Facultative Pond 1	**Facultative Pond 2**	**Maturation Pond 1**	**Maturation Pond 2**
Facultative Pond 1		0.515	0.043*	0.107
Facultative Pond 2	0.515		0.007*	0.024*
Maturation Pond 1	0.043*	0.007*		0.677
Maturation Pond 2	0.107*	0.024*	0.677	

* = Significant

In the vegetated WSPs, there was no notable variation in waterbird density across various treatment stages (H = 1.863, p = 0.574). Despite higher density recorded at the third stage (SFP2), and subsequently at the final stage (MP), waterbird density was comparatively lower at the first two stages, PrFP and SFP (Figure 2).

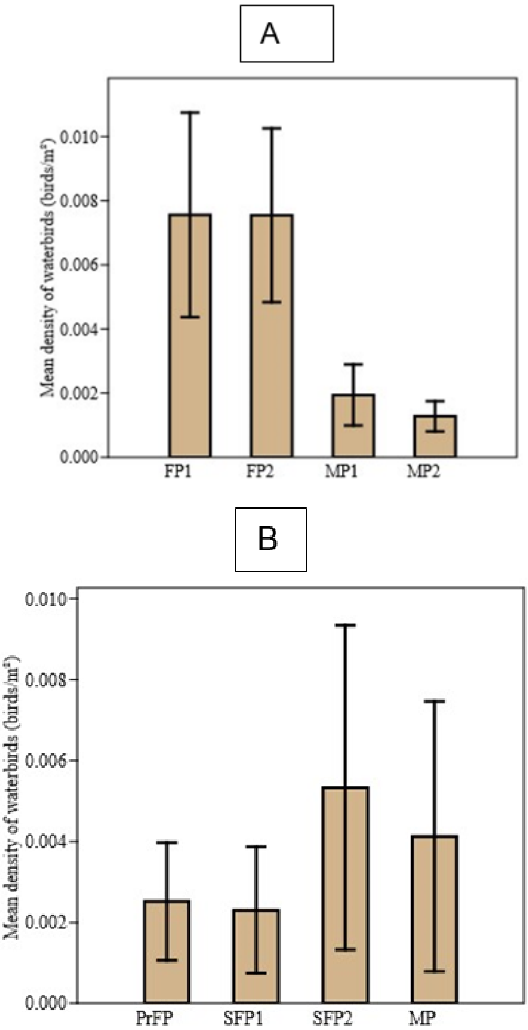

Figure 2: A) Mean density of waterbirds (birds/m²) at non-vegetated WSPs in both Facultative (FP1 and FP2) and Maturation (MP1 and MP2) treatment stages.
B) Mean density of waterbirds (birds/m²) at vegetated WSPs in both Facultative (PrFP, SFP1 and SFP2) and Maturation treatment stages. Error bars represent the standard errors

Environmental variables at the treatment stages of non-vegetated and vegetated WSPs

In non-vegetated WSPs, the pH levels were observed to be higher in maturation ponds compared to facultative ponds ($H = 21.25$, $p < 0.05$) (Table 4). Dissolved oxygen (DO) levels increased progressively across the treatment stages, while turbidity decreased across the treatment stages, although the variations were not significant. Additionally, invertebrate biomass was found to be higher in facultative ponds than in maturation ponds ($H = 40.5$, $p < 0.05$) (Table 4). No trends were observed in the variation of environmental variables across the treatment stages in vegetated WSPs (Table 5).

Table 4: The mean value of the environmental variables at non-vegetated WSPs along the treatment stages

Environmental variable	**FP1**	**FP2**	**MP1**	**MP2**	**P - Value**
pH	7.397 ± 0.128	7.605 ± 0.122	8.235 ± 0.162	8.145 ± 0.162	< 0.05
Water temperature (°C)	28.773 ± 0.593	28.387 ± 0.0.429	29.221 ± 0.451	29.777± 0.454	0.138
Dissolved oxygen (mg/L)	1.640 ± 0.164	1.565 ± 0.121	1.854± 0.201	2.000 ± 0.235	0.538
Water turbidity (NTU)	58.395 ± 11.505	52.615 ± 10.618	39.843± 5.803	41.889 ± 9.897	0.607
Electrical conductivity (µs/cm)	700.138 ± 30.101	675.983 ± 25.205	679.759 ± 18.072	712.172 ± 16.529	0.381
Invertebrate biomass (g)	1.366 ± 0.492	1.897 ± 0.927	0.157 ± 0.025	0.041 ± 0.011	< 0.05

FP1 = Facultative Pond 1, FP2 = Facultative Pond 2, MP1 = Maturation Pond 1and MP2 = Maturation Pond 2

Table 5: The mean values of the environmental variables at vegetated WSPs along the treatment stages

Environmental variable	**PrFP**	**SFP1**	**SFP2**	**MP**	**p-value**
pH	7.098 ± 0.103	7.159 ± 0.087	7.087 ± 0.080	7.076 ± 0.070	0.981
Water temperature (°C)	26.112 ± 0.298	26.088 ± 0.462	26.055 ± 0.238	26.498 ± 0.264	0.531
Dissolved oxygen (mg/L)	1.332 ± 0.133	1.215 ± 0.106	1.289 ± 0.100	1.343 ± 0.105	0.848
Water turbidity (NTU)	61.928 ± 11.166	34.484 ± 4.754	38.452 ± 5.263	35.423 ± 6.120	0.426
Electrical conductivity(µs/cm)	854.862 ± 18.772	833.569 ± 17.397	861.255 ± 16.699	883.564 ± 20.522	0.241
Invertebrate biomass (g)	0.127 ± 0.026	0.137 ± 0.042	0.092 ± 0.013	0.157 ± 0.031	0.292

PrFP = Primary Facultative Pond, SFP1= Secondary Facultative Pond 1, SFP2 = Secondary Facultative Pond 2 and MP = Maturation Pond

Discussion

Waterbird assemblages among pond treatment stages

In this study, there were differences in the assemblages and the ecology of waterbirds between the vegetated and non-vegetated WSPs at different treatment stages. Waterbird response to different treatment stages of WSPs differed between the vegetated and non-vegetated WSPs. At the non-vegetated WSPs, there was a significant difference in the density of waterbirds at different treatment stages (Figure 2). In contrast, no significant difference in waterbird density at different treatment stages in vegetated WSPs (Figure 2). Apart from many other factors that attract waterbirds in WSPs, these findings at the vegetated WSPs can be attributed to the influence of vegetation, which helps to maintain the equilibrium of the aquatic ecosystem (Liu et al. 2016 and Kalderén 2019). This probably results in similar habitats at different treatment stages of vegetated WSPs (Liu et al. 2016), making it less likely for waterbirds to exhibit preferences for specific stages, unlike the non-vegetated WSPs where waterbirds exhibited preference at different stages (Figure 2).

Based on the existing published data, this study probably represents the first study in Tanzania to investigate the density of waterbirds at different treatment stages of the vegetated and non-vegetated WSPs. Previous studies in Australia have reported that maturation ponds with less vegetation cover on their surface support higher densities, abundance, and richness of waterbirds, providing favourable feeding habitats compared to other ponds (Hamilton et al. 2005, Murray et al. 2014). Murray et al. (2014) in Australia also reported a positive correlation of waterbirds with invertebrate biomass. Likewise, in this study at the non-vegetated WSPs, the highest density of waterbirds was recorded at the stages with high invertebrate biomass (Table 4). However, high density was found at the facultative ponds at the initial stages, unlike the findings from Hamilton et al. (2005), which reported that ponds at the end of the treatment system often had the highest density and diversity of waterbirds.

The facultative and maturation ponds at non-vegetated WSPs exhibit different waterbird densities. The two facultative ponds, FP1 and FP2, showed no significant difference in waterbird densities, similarly, the two maturation ponds, which are designed for the final stage of treatment, also showed no significant difference in waterbird density. This suggests that ponds performing the same function in the treatment process are likely to affect waterbirds equally, as they have similar environmental characteristics (Table 4 and Table 5). However, a significant difference in waterbird density was recorded between the facultative and maturation ponds (Table 3). The difference in waterbird densities among different treatment stages of WSPs was found to be significant at non-vegetated WSPs (Table 3). The current study found that the facultative ponds, which had a high density of waterbirds, also had a high invertebrate biomass (Table 4). These findings are similar to the findings of Murray et al. (2014), who reported that the food (invertebrates) was the major factor influencing waterbird distribution within the treatment stages. These findings suggest that the availability of food resources is an important environmental variable in attracting waterbirds at different treatment stages of WSPs.

In the non-vegetated WSPs, facultative ponds had over 95% of all recorded waterbird species (Table 1) this is probably due to favourable habitat and food availability in the facultative ponds. This highlights the crucial role of facultative ponds in bird conservation at WSPs in tropical regions. The vegetated WSPs had African Jacana and Black Crake recorded in all treatment stages. This is because of the presence of vegetation in all the treatment stages which is the favourable habitat for these species (Froneman et al. 2001). Throughout the study period, immature African Jacana and Black Crake were recorded, showing that the vegetated ponds provide a habitat that supports the breeding of the two species.

Environmental variables in different treatment stages of the non-vegetated and vegetated WSPs

The non-vegetated WSPs representing the well-maintained WSPs in this study had some environmental variables with significant variation in different treatment stages (Table 4). Similar to the findings reported by Hamilton et al. (2005) and Murray et al. (2014) the dissolved oxygen was recorded to increase along the treatment stages and the turbidity decreased along the treatment stages. The pH was significantly higher at the maturation stages than the facultative stages (Table 4) presumably due to the removal of contaminants and organic matter by the algae and microbial communities in the maturation ponds that can contribute to a rise in pH as the water quality improves (Dos Santos and van Haandel 2021). This shift towards higher pH levels at the maturation stages indicates a more advanced treatment process and a cleaner effluent ready for discharge (Dos Santos and van Haandel 2021). The invertebrate biomass was significantly higher at the facultative stages compared to the maturation stages this is probably because these stages have higher levels of organic material as stipulated in Kalderén (2019) creating a more suitable habitat for invertebrates to thrive. In contrast, the maturation stage focuses more on the final treatment processes and the removal of contaminants (Kalderén 2019), resulting in lower organic matter levels and potentially less favourable conditions for invertebrate growth.

The environmental factors within the vegetated WSPs showed no significant variation across the treatment stages, likely due to the impact of vegetation. Vegetation plays a crucial role in maintaining the overall equilibrium of the ecosystem within the ponds by influencing variables such as temperature, light availability, and nutrient cycling (Liu et al. 2016). This interaction between vegetation and environmental variables fosters a harmonised environment across different treatment stages and probably affects the treatment performance throughout the pond system as hypothesised by Liu et al. (2016).

Conclusion

Waterbird assemblages varied significantly across different treatment stages in non-vegetated WSPs, with facultative ponds supporting higher densities of waterbirds than maturation ponds. In vegetated WSPs, however, no significant differences were observed. Vegetation invasion in WSPs alters the environmental conditions at the WSPs resulting in similar habitats at different treatment stages reducing the likelihood of waterbirds preferring specific treatment stages. Furthermore, ponds serving the same function in the treatment process affect waterbirds similarly due to their comparable environmental characteristics. In vegetated WSPs, environmental variables showed no significant differences across treatment stages, unlike in non-vegetated WSPs, where dissolved oxygen (DO) decreased along the treatment stages, and invertebrate biomass was higher in facultative ponds than in maturation ponds. The pH was significantly higher in maturation ponds than in facultative ponds.

The study demonstrated that the facultative stage of the non-vegetated WSPs is most preferred for waterbird conservation in WSPs. However, we recommend conducting additional research to include more WSPs in tropical regions, where information on waterbird use of different WSP treatment stages is limited. We also recommend managing of vegetation in the treatment stages of WSPs, as this will ensure the efficient functioning of their primary function in treating wastewater (Mairi et al. 2012), while simultaneously supporting waterbird conservation. This study provides baseline information and highlights the importance of considering the specific characteristics of each treatment stage in designing and managing WSPs to support waterbird populations.

Acknowledgements

We thank the Wildlife Conservation Society of Tanzania for initiating the research and providing initial financial support. Appreciation goes to the University of Dar es Salaam's Department of Zoology and Wildlife Conservation and the Department of Water Resource Engineering for granting laboratory access. The University Estate Department and Dar es Salaam Water and Sewage Authority permitted the study at the WSPs. Special thanks to Manyama Mkama, Akshita Rabdiya, Beatrice Mambo, Edigar Apolinary, Brown Mchani, Elwyn Malipesa, Samweli Slaa, and Jimminus Kakoko for their contributions.

Conflict of interest statement

None.

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