Australian Field Ornithology 2024, **41**, 102–112
http://dx.doi.org/10.20938/afo41102112

Habitat diversity enriches waterbird community at Bolivar Wastewater Treatment Plant in South Australia

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Abstract. The wastewater treatment plant at Bolivar in South Australia contains three groups of ponds which provide different managed habitats. Ponds 1, 2 and 3 contain a constant level of water of >1 metre in depth throughout the year, whereas in Ponds 4, 5 and 6 the water level is reduced each year with the result that the ponds become largely dry for several weeks from late summer. The third group of eight ponds, the sludge lagoons, are anaerobic and each year two or three of these ponds gradually dry out. In this study, we compared the abundance of the various species of waterbirds on these three groups of ponds throughout the period from September 2021 until December 2023. We found major differences in abundance of birds between the three groups. Most of the waders, together with Black Swan *Cygnus atratus*, Hardhead *Aythya australis* and Eurasian Coot *Fulica atra*, were largely present on Ponds 4–6, whereas Blue-billed Duck *Oxyura australis,* dabbling ducks, and three species of cormorants (Phalacrocoracidae) tended to be more abundant on Ponds 1–3, with the sludge lagoons generally having mainly Grey Teal *Anas gracilis*.

Introduction

Historically, sewage farms and wastewater treatment plants have a reputation for attracting a diverse array of waterbirds because of their high abundance of soil invertebrates. However, in the United Kingdom and some other countries modernisation of the plants over the last *c*. 40 years has considerably reduced their size and hence potential attractiveness to waterbirds (Fuller & Glue 1980; Anika & Parasharya 2013). Nevertheless, in Australia various wastewater treatment plants still attract numerous waterbirds (Roberts 1981; Murray & Hamilton 2010) with, in some cases, a greater abundance at these sites than on other wetlands in the same area (Murray *et al.* 2012, 2014). This is likely to be at least partly because of high levels of nutrients in the water, which enhance the growth of algae and thus support high populations of invertebrates (Murray *et al.* 2012; Loyn *et al*. 2023), with the Western Treatment Plant near Melbourne, Victoria, attracting numerous waterbirds (Murray & Hamilton 2010; Loyn *et al*. 2014a,b, 2018, 2023; Murray *et al.* 2014; Papas *et al.* 2021). The wastewater treatment plant at Bolivar, located ~20 km north of the centre of Adelaide in South Australia, also sometimes attracts high numbers of waterbirds (Moise & Paton 2007; Breed *et al.* 2020, 2023), but how much the abundance of these species is dependent upon the variation in the habitat is not clear. The aim of the current study was thus to compare the abundance of the waterbirds in the three groups of ponds at Bolivar where varying water levels occur.

Materials and methods

Our project was conducted by three of the co-authors (JH, CR & WB) who visited Bolivar to determine the abundance of the birds and commenced in December 2018. Our visits took place between 0830 and 1200 h, with the visits planned to coincide with a high tide in the adjacent Gulf St Vincent. Until September 2021 we recorded only the total number of birds of each species. However, during our subsequent 34 surveys between September 2021 and December 2023, we recorded separately the abundance of the various species of waterbirds on the three groups of ponds (Ponds 1–3, Ponds 4–6, and the sludge lagoons). For this, counts were made from a stationary car using binoculars and, for a detailed study of the birds when necessary, with a telescope. When possible, counts of individuals of the various species were made, but when high abundance was evident the number was estimated individually, with our counts then compared to determine an agreed abundance of the number of the relevant species present at the time (see Breed *et al*. 2020).

Ponds 1–3 and 4–6 are operated as two parallel series of three flow-through ponds filled with effluent from the treatment plant. The influent water is typically high in nitrates and nitrites but low in ammonia. Ponds 1–3 have a total area of 217 ha and are hydraulically connected by a series of pipes. They are surrounded by concrete embankments, with the water level maintained at ~1.2 m throughout the year. The zooplankton in the water of these ponds includes rotifers (Rotifera), copepods (Crustaceae: Orders Calanoida, Cyclopoda and Harpacticoida), water fleas (Cladocera: Families Chydoridae, Daphniidae, Macrothricidae and Moinidae), and larvae of chironomid midges (Diptera: Family Chironomidae), as well as numerous fish (primarily European Carp *Cyprinus carpio*) and Freshwater Prawns *Macrobrachium australiense* (Family Palaemonidae) (SA Water unpubl. obs.). Increase in abundance of the zooplankton and algae in the ponds generally takes place during summer because of the elevated water temperature and sunlight at that time.

Ponds 4–6, which are ~130 ha, also have concrete walls and are taken offline in late summer of each year and allowed to largely drain. They then remain offline until winter. The macroinvertebrate composition of the water of these ponds is similar to that of Ponds 1–3 but there are

very few or no fish or prawns. Compared with Ponds 1–3, these ponds generally have lower levels of total nitrogen and algae. In Ponds 1–3, single-celled cyanobacteria (blue-green algae) are more common than filamentous green algae whereas in Ponds 4–6 the reverse occurs (SA Water Report).

Just north of Ponds 3 and 6, there is a stream which runs east to west, with the sludge lagoons occurring to the north of the stream. These sludge ponds are anaerobic and are used to treat digestor sludge, which contains high levels of nitrates and ammonia. They typically contain a thick layer of sediment, with some having shallow water of not less than 300 mm. On a rotation basis, a few of these ponds have the water drained in summer and the sediment removed whereas others temporarily contain water which gradually evaporates over 2–3 years.

Results

The various species of waterbirds observed occurred in seven functional groups, or guilds, as defined by Roshier *et al*. (2002). They are:

1. Dabbling ducks: Pink-eared Duck *Malacorhynchus membranaceus,* Freckled Duck *Stictonetta naevosa*, Australasian Shoveler *Spatula rhynchotis,* Pacific Black Duck *Anas superciliosa*, Grey *Teal A. gracilis* and Chestnut Teal *A. castanea*.
2. Deep-water-foraging birds: Blue-billed Duck *Oxyura australis*, Musk Duck *Biziura lobata,* Black Swan *Cygnus atratus,* Hardhead *Aythya australis* and Eurasian Coot *Fulica atra.*
3. Grazing waterbirds: Cape Barren Goose *Cereopsis novaehollandiae,* Australian Shelduck *Tadorna tadornoides* and Australian Wood Duck *Chenonetta jubata*.
4. Eaters of aquatic invertebrates and small fish: Hoary-headed Grebe *Poliocephalus poliocephalus,* Great Crested Grebe *Podiceps cristatus,* Australian Pelican *Pelecanus conspicillatus,* Little Pied Cormorant *Microcarbo melanoleucos,* Great Cormorant *Phalacrocorax carbo,* Little Black Cormorant *P. sulciroostris,* Caspian Tern *Hydroprogne caspia,* Whiskered Tern *Chlidonias hybrida* and White-winged Black Tern *C. leucopterus.*
5. Shoreline foragers: Black-tailed Native-hen *Tribonyx ventralis* and Masked Lapwing *Vanellus miles*.
6. Waders that breed in Australia: Banded Stilt *Cladorhynchus leucocephalus,* Red-necked Avocet *Recurvirostra novaehollandiae,* Pied Stilt *Himantopus leucocephalus,* Red-capped Plover *Charadrius ruficapillus,* Black-fronted Dotterel *Elseyornis melanops* and Red-kneed Dotterel *Erythrogonys cinctus.*
7. Waders that breed in the Northern Hemisphere and migrate to Australia during their nonbreeding season: Black-tailed Godwit *Limosa limosa*, Sharp-tailed Sandpiper *Calidris acuminata*, Curlew Sandpiper *C. ferruginea,* Red-necked Stint *C. ruficollis*, Pectoral Sandpiper *C. melanotos*, Common Sandpiper *Actitis hypoleucos*, Common Greenshank *Tringa nebularia*, Wood Sandpiper *T. glareola* and Marsh Sandpiper *T. stagnatilis*.

Figure 1 shows some aggregations of mainly swimming waterbirds on Ponds 1–3 (a, c), whereas in Ponds 4–6 (b, d, f) a much greater abundance of waterbirds is evident with a flock of mainly Banded Stilts (Figure 1f). The other figures show the abundance of the more common species in the various guilds and photographs of some of the species. Table 1 is a summary of the quantitative data. In the graphs from the data, the image at the top indicates the total number of individuals recorded for each species from December 2018, when our observations were initiated, until December 2023, with the separate counts for Ponds 1–3 and 4–6 and the sludge lagoons for the period September 2021 to December 2023 shown below.

Figure 2 shows that Pink-eared Duck (Figures 3a,b) and Grey Teal (Figure 3a) were both highly abundant in 2019, with the numbers of both species dropping markedly in early 2020 around which time the drought in the arid zone terminated. The numbers generally remained low throughout most of 2020, 2021 and 2022, except in the early months of 2021 when there were high numbers of Grey Teal and to a lesser extent Pink-eared Ducks. However, in early 2023, Grey Teal, and subsequently Pink-eared Duck, increased markedly in abundance, with Grey Teal initially occurring on both Ponds 1–3 and 4–6 and, subsequently, the sludge lagoons, whereas Pink-eared Duck also initially occurred largely on Ponds 1–3, but for the last few months of 2023 they largely moved to Ponds 4–6, with up to 1500–2000 occurring on these ponds towards the end of the year. Small numbers of Pacific Black Duck were present on both Ponds 1–3 and 4–6, whereas Australasian Shoveler was mainly on Ponds 5 or 6 but generally in very low numbers, with a maximum of 43 (Table 1). Chestnut Teal were also low in abundance, with a maximum of 160 individuals, whereas Freckled Duck (Figure 3a) was usually absent although a group of 60 was present on Pond 5 in December 2023.

Figure 4 shows that of the deep-water-foraging waterbirds (Group 2) the Black Swan peaked in early summer and was generally most abundant on Ponds 4–6, as was the Eurasian Coot, with highest numbers of the latter occurring in the last few months of 2023. Of the diving ducks, Blue-billed Duck (Figure 3c) was sometimes absent in 2022 although 100–200 occurred on Ponds 1–3 in early summer 2021 as well as in the winter of 2023. Up to several hundred Hardhead also occurred, mostly on Ponds 4–6, in spring/early summer 2021 and winter 2023, but generally the numbers were low in 2022. A few were, however, present on the sludge lagoons in the spring of 2021 and winter of 2023, and there was a peak of ~1000 on Ponds 1–3 in December 2023, when several hundred were also present on Ponds 4–6. Small numbers of Musk Duck (Figure 3d) were usually present on Ponds 4–6, with a maximum of 77 in December 2023 with display activity being observed on Pond 4 in October 2021.

Figure 5 shows that Australian Shelduck exhibited dramatic seasonal changes in abundance, with similar high numbers in summer generally being present on Ponds 1–3 and Ponds 4–6. Only small numbers of Australian Wood Duck were observed, and up to eight (but usually only three) Cape Barren Geese were present in 2022 and 2023 mainly on Ponds 4 or 6.

Figure 1. Bolivar Ponds 1, 2 and 3 (a, c, e), where the water level is maintained throughout the year, with swimming Black Swans (a, c) and a group of Hoary-headed Grebes (e). Ponds 4, 5 and 6 (b, d, f), where water levels decline from around midsummer which results in very shallow ponds with islands of sand and mud, with abundant waterbirds including a large flock of mainly Banded Stilts (f). Photos: William G. Breed

Figure 6 indicates that the Whiskered Tern which, when present, occurred over most of the ponds except the sludge lagoons, was generally present only in spring and/or early summer. Up to ~600 were seen in January 2022 and again in December 2023 although none occurred in summer 2022–2023. Hoary-headed Grebe (Figure 6) was the only grebe species that was periodically common (see Figure 1e). It was also largely seasonal in its occurrence, with up to 1500 on Ponds 1–3 in March 2023. Small numbers of Little Black, Little Pied and Great Cormorants were invariably present, mainly on Ponds 1 and 2, with no marked difference in distribution or abundance over time, although a flock of ~300 Little Black Cormorants was seen flying east high over the ponds in March 2023.

Figure 7 shows that, of the shoreline foragers, Masked Lapwing was fairly common on the tracks around all the ponds, especially Ponds 4–6, and occasionally elsewhere at Bolivar including around the sludge lagoons, whereas groups of up to 120 Black-tailed Native-hens (a species that was numerous in early 2022 and 2023) occurred mostly around both the groups of Ponds 4–6 but also elsewhere.

Several species of waders that breed in Australia occurred. They were usually present only in spring and/or summer, and generally occurred only on Ponds 4–6 (Figures 1f, 8, 9). These included up to 600 Pied Stilts, 370 Banded Stilts and 800 Red-necked Avocets (Figure 1f). Red-kneed Dotterels were also present each summer on Pond 6, with a maximum of ~50 in January 2022 and 82 in April 2023. Small numbers of Red-capped Plover and Black-fronted Dotterel also occurred, mainly on Pond 6 (Table 1).

Figure 10 shows that once the water levels of Ponds 4–6 became low, migrant waders from the Northern Hemisphere began roosting and feeding on them. These included ~800 Sharp-tailed Sandpipers and 70 Curlew Sandpipers in January 2022 and 300 Red-necked Stints in April 2022. The following year, in February and March 2023, there were ~300 Sharp-tailed Sandpipers and 150 Curlew Sandpipers, together with ~300 Red-necked Stints, 23 Black-tailed Godwits (see Figure 8a), 14 Marsh Sandpipers (Figure 8b), 33 Common Greenshanks, 6 Wood Sandpipers (Figure 8c), and a single Pectoral Sandpiper (Figure 8d), all of which were on Pond 6. No waders were seen on the sludge lagoons, but a few Common Sandpipers and Black-fronted Dotterels were sometimes present near or along the embankment of the stream that passed east to west adjacent to Ponds 3 and 6.

Table 1. Abundance of waterbirds at Bolivar Wastewater Treatment Plant, South Australia, between September 2021 and December 2023 (Surveys 41–76): numbers [maximum, mean and standard deviation (SD)] and usage of available habitat (mean number and percentage of observations). Percentages are shown in italics and are calculated as the mean number of observations for a habitat as a proportion of the mean abundance of the species.

Group	*Species*	*Abundance*			*Ponds 1–3*		*Ponds 4–6*		*Sludge lagoons*		*Other habitat*	
		Max.	*Mean*	*SD*	*Mean*	*%*	*Mean*	*%*	*Mean*	*%*	*Mean*	*%*
Birds predominantly using Ponds 1–3 (217 ha)												
1	Pink-eared Duck	3032	574	815	319	*56*	239	*42*	13	*2*	3	*1*
1	Pacific Black Duck	2040	431	360	240	*56*	148	*34*	28	*6*	15	*4*
2	Blue-billed Duck	250	51	73	40	*79*	11	*21*	0	*0*	0	*0*
4	Australian Pelican	120	35	28	20	*57*	13	*36*	0	*1*	2	*6*
4	Little Pied Cormorant	103	11	18	7	*63*	3	*31*	0	*0*	1	*5*
4	Great Cormorant	25	4	5	3	*70*	1	*14*	0	*8*	0	*8*
4	Little Black Cormorant	310	17	53	12	*73*	3	*18*	0	*0*	2	*9*
Birds predominantly using Ponds 4–6 (130 ha)												
1	Frecked Duck	60	2	10	0	*12*	2	*84*	0	*0*	0	*4*
1	Australasian Shoveler	43	7	11	2	*27*	5	*70*	0	*2*	0	*1*
2	Musk Duck	77	12	15	5	*37*	7	*56*	0	*0*	1	*6*
2	Black Swan	3700	747	798	123	*16*	620	*83*	1	*0*	3	*0*
2	Hardhead	1320	202	325	53	*26*	113	*56*	31	*1*	5	*2*
2	Eurasian Coot	3900	747	919	37	*5*	688	*92*	7	*1*	15	*2*
3	Australian Shelduck	5600	1097	1533	447	*41*	637	*58*	7	*1*	6	*1*
4	Caspian Tern	7	0	1	0	*18*	0	*76*	0	*0*	0	*6*
4	White-winged Black Tern	5	0	1	0	*10*	0	*60*	0	*0*	0	*30*
5	Masked Lapwing	140	49	42	9	*19*	33	*67*	2	*4*	5	*10*
6	Banded Stilt	370	28	80	11	*39*	17	*60*	0	*0*	0	*1*
6	Red-necked Avocet	800	71	149	7	*1*	62	*87*	0	*0*	2	*2*
6	Pied Stilt	600	132	172	11	*8*	114	*86*	1	*1*	7	*5*
6	Red-kneed Dotterel	82	8	17	0	*5*	6	*80*	0	*3*	1	*12*
7	Black-tailed Godwit	23	3	6	0	*2*	3	*98*	0	*0*	0	*0*
7	Sharp-tailed Sandpiper	800	68	160	2	*3*	60	*89*	0	*0*	6	*8*
7	Curlew Sandpiper	150	15	35	2	*1*	13	*81*	0	*0*	1	*3*
7	Red-necked Stint	300	23	65	0	*0*	19	*80*	0	*0*	5	*20*
7	Common Greenshank	33	7	9	1	*11*	6	*84*	0	*0*	0	*4*
7	Wood Sandpiper	6	1	1	0	*5*	0	*74*	0	*0*	0	*21*
7	Marsh Sandpiper	14	2	4	0	*3*	2	*96*	0	*0*	0	*1*
Birds using various habitats, including ponds												
1	Grey Teal	7300	1334	1606	513	*38*	502	*38*	255	*19*	63	*5*
1	Chestnut Teal	160	37	35	16	*44*	15	*41*	1	*2*	5	*13*
3	Cape Barren Goose	8	1	2	0	*0*	1	*47*	0	*4*	1	*49*
3	Australian Wood Duck	56	10	15	5	*49*	5	*46*	0	*1*	0	*4*
4	Hoary-headed Grebe	1540	143	256	68	*48*	62	*43*	2	*1*	11	*7*
4	Great Crested Grebe	20	2	5	0	*7*	0	*24*	0	*0*	1	*69*
4	Whiskered Tern	900	110	234	41	*37*	49	*45*	1	*1*	19	*17*
5	Black-tailed Native-hen	252	24	52	7	*28*	6	*25*	1	*2*	11	*45*
6	Red-capped Plover	42	5	9	0	*5*	1	*31*	0	*7*	3	*57*
6	Black-fronted Dotterel	26	6	7	2	*30*	1	*18*	0	*7*	3	*46*
7	Common Sandpiper	5	1	1	0	*47*	0	*0*	0	*3*	0	*50*
Total												
All	Total birds	13,409	6017	4040	2005	*33*	3466	*58*	352	*6*	195	*3*

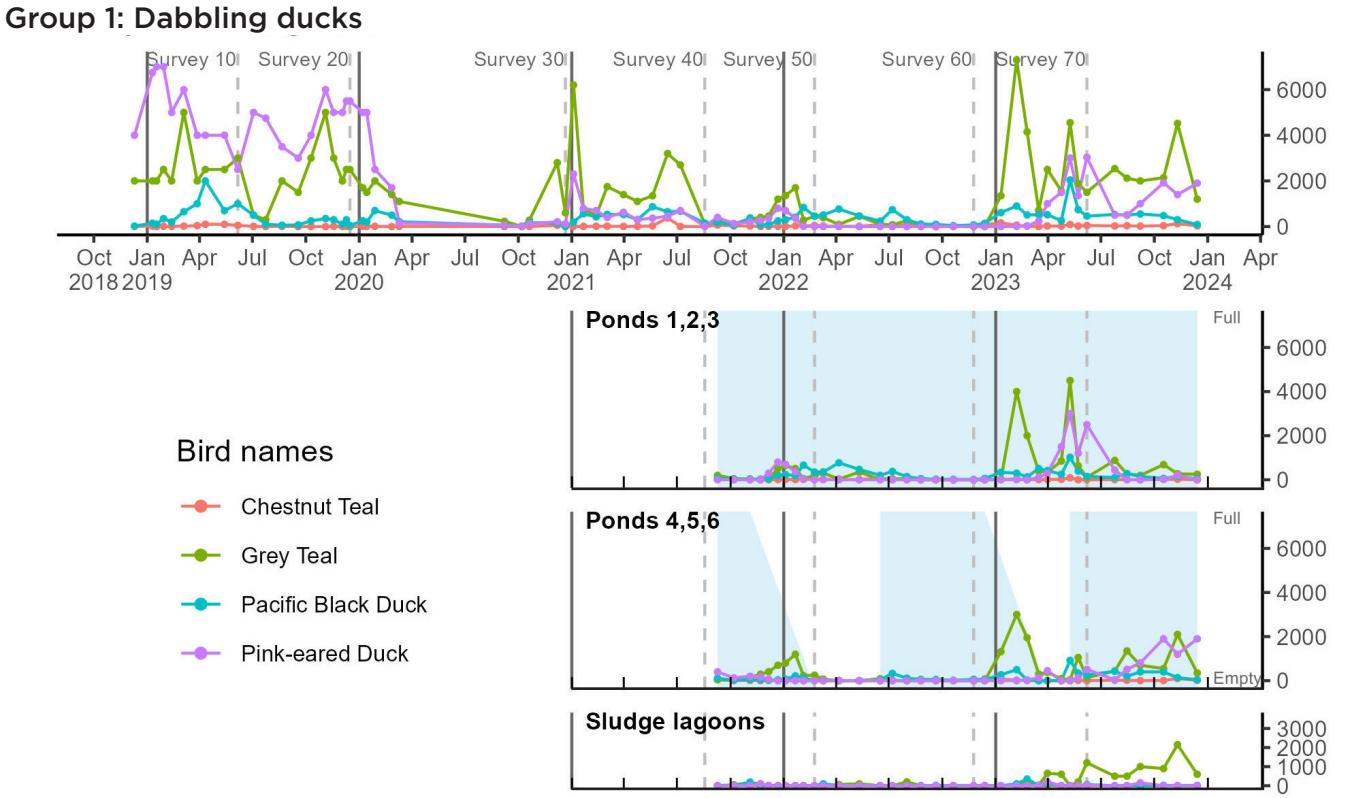

Figure 2. Abundance of dabbling ducks (Pink-eared Duck, Pacific Black Duck, Grey Teal and Chestnut Teal) (Group 1) at Bolivar, on the three groups of ponds (Ponds 1–3, Ponds 4–6 and sludge lagoons) from September 2021 to December 2023. Blue background denotes approximate level of pond water.

Figure 3. Ducks observed at Bolivar include (a) Pink-eared Ducks, two Freckled Ducks and a Grey Teal, (b) a group of ten Pink-eared Ducks, (c) a female Blue-billed Duck, and (d) a pair of Musk Ducks. Photos: Colin Rogers

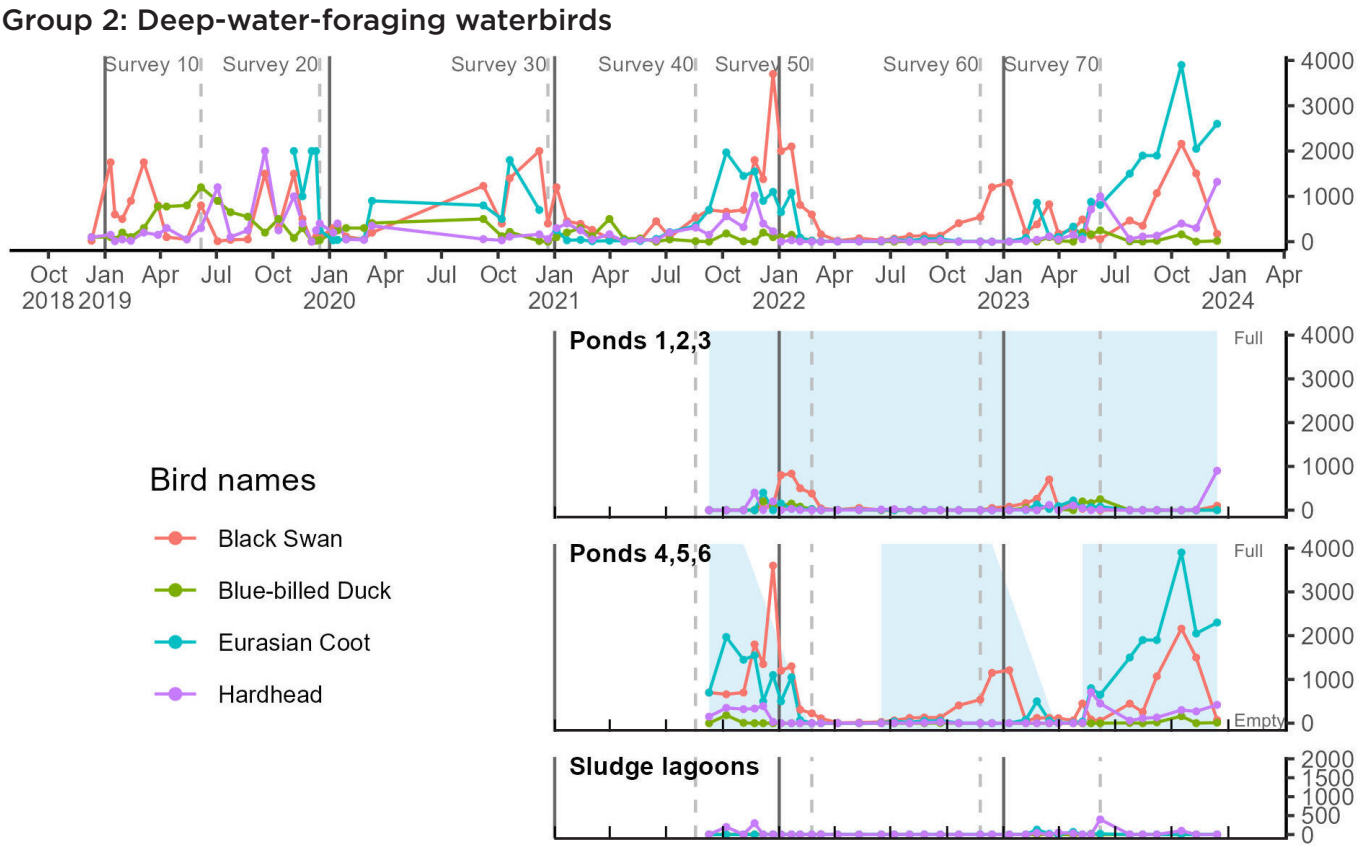

Figure 4. Abundance of deep-water-foraging waterbirds (Group 2) – Blue-billed Duck, Black Swan, Hardhead and Eurasian Coot – at Bolivar on the three groups of ponds. Note greater abundance of all four species on Ponds 4–6 than on Ponds 1–3. Blue background denotes approximate level of pond water.

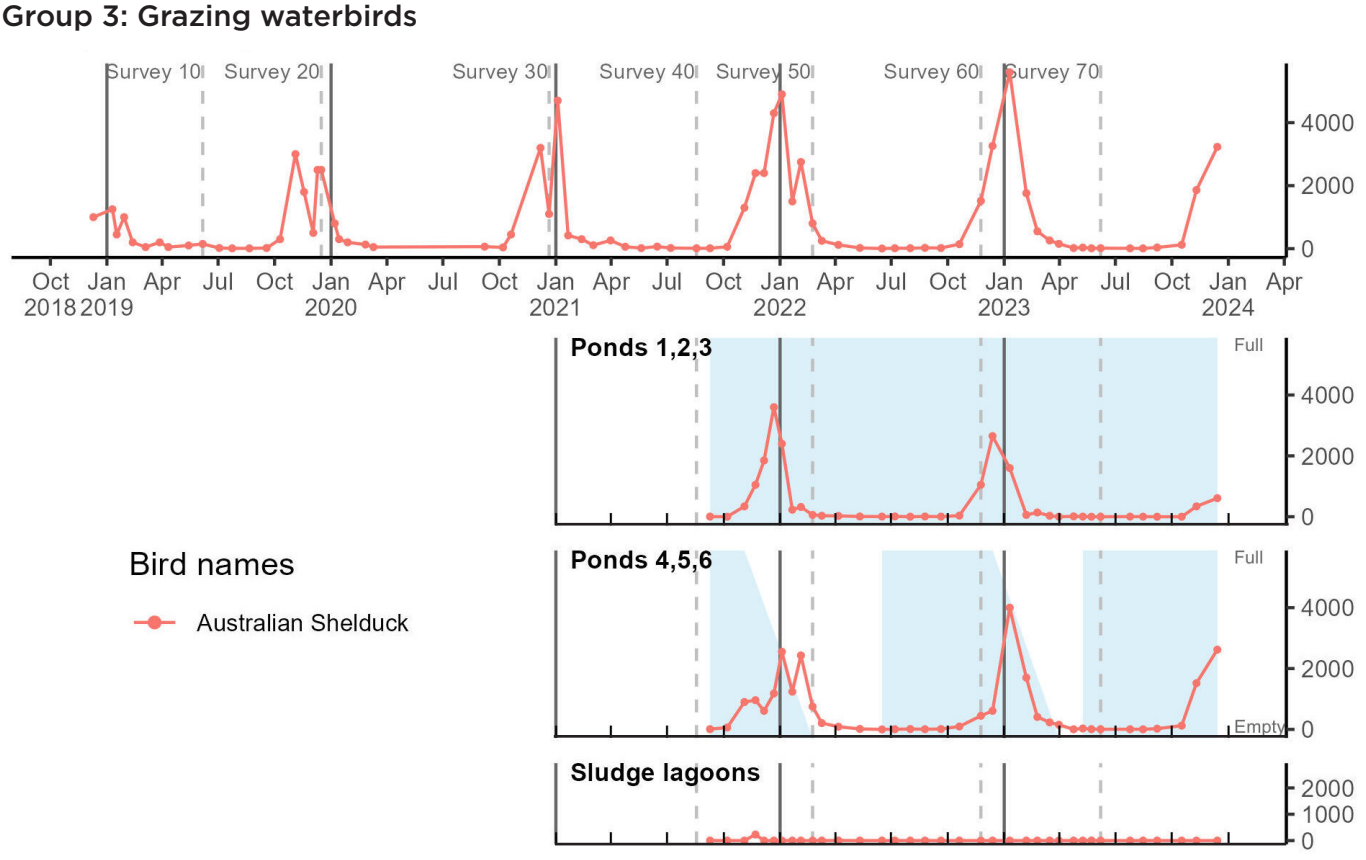

Figure 5. Abundance of Australian Shelduck (Group 3: grazing waterbirds) on the two groups of ponds at Bolivar, showing peak abundance in summer on both Ponds 1–3 and 4–6. Blue background denotes approximate level of pond water.

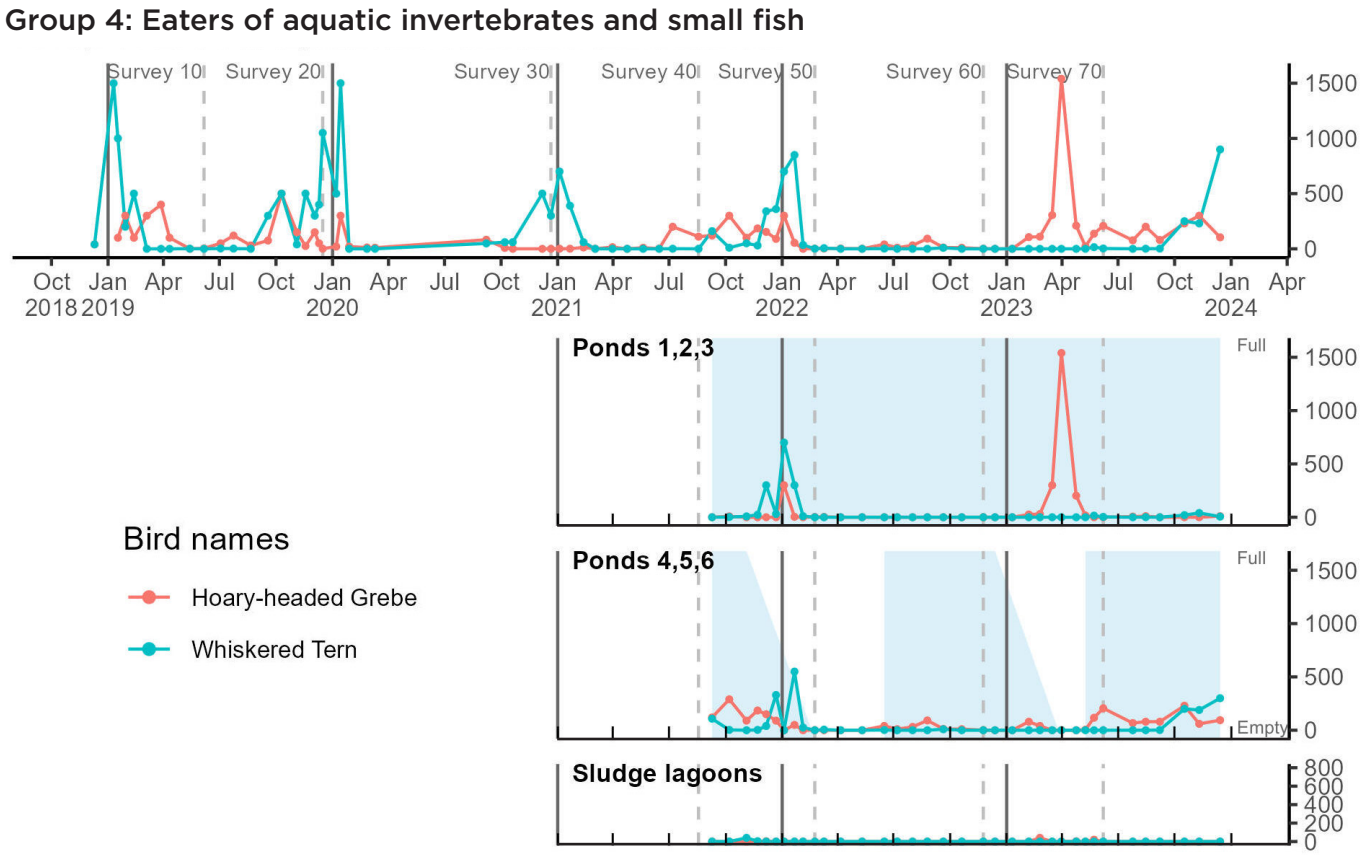

Figure 6. Abundance of Hoary-headed Grebe and Whiskered Tern (Group 4: eaters of aquatic invertebrates and small fish) on the three groups of ponds at Bolivar. Blue background denotes approximate level of pond water.

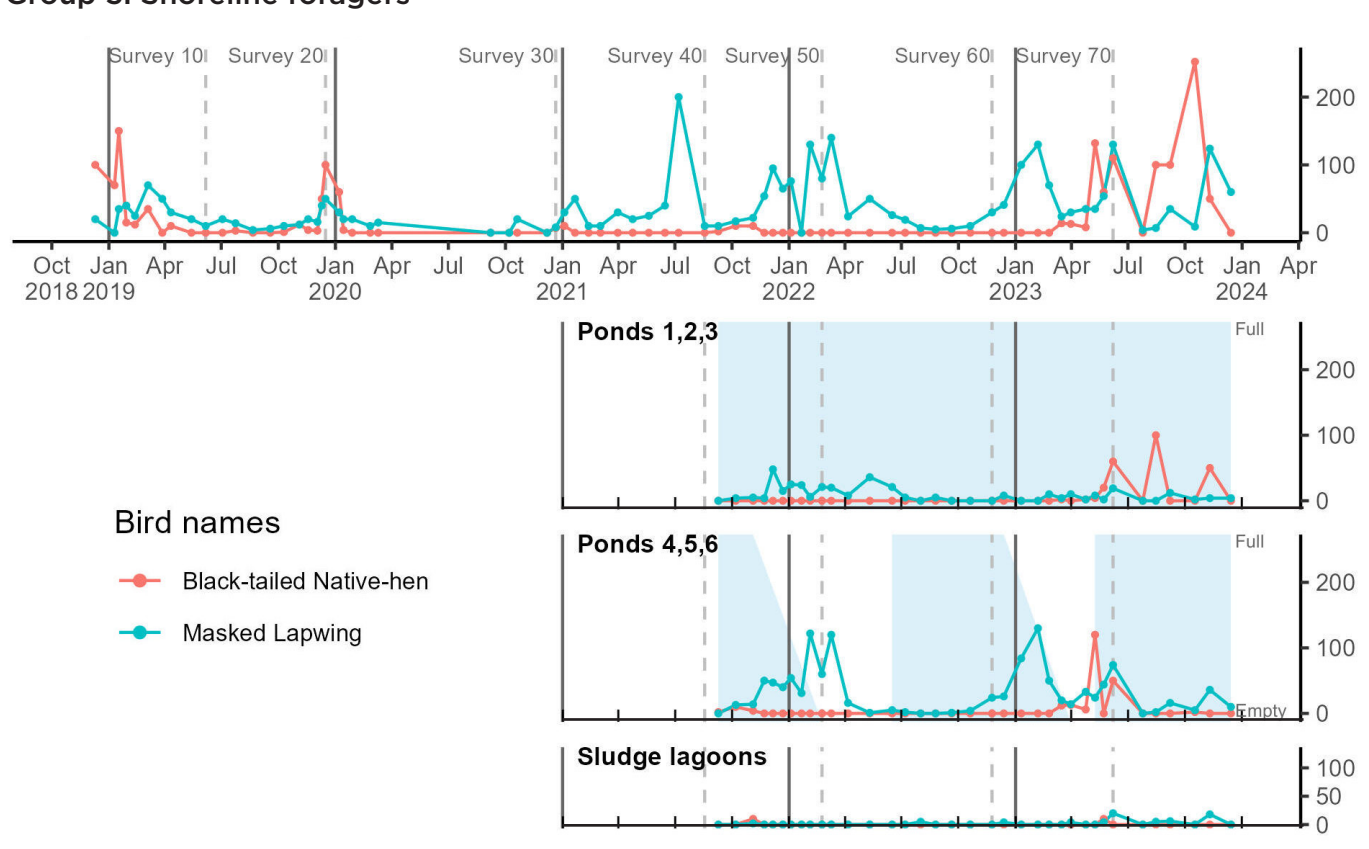

Figure 7. Abundance of Black-tailed Native-hen and Masked Lapwing (Group 5: shoreline foragers) on the three groups of ponds at Bolivar. Blue background denotes approximate level of pond water.

Figure 8. Waders observed at Bolivar include (a) a group of mainly Black-tailed Godwits together with a few Pied and Banded Stilts, Sharp-tailed Sandpipers and a Black Swan; (b) Marsh Sandpiper; (c) Wood Sandpiper; and (d) Pectoral Sandpiper. Photos: Colin Rogers

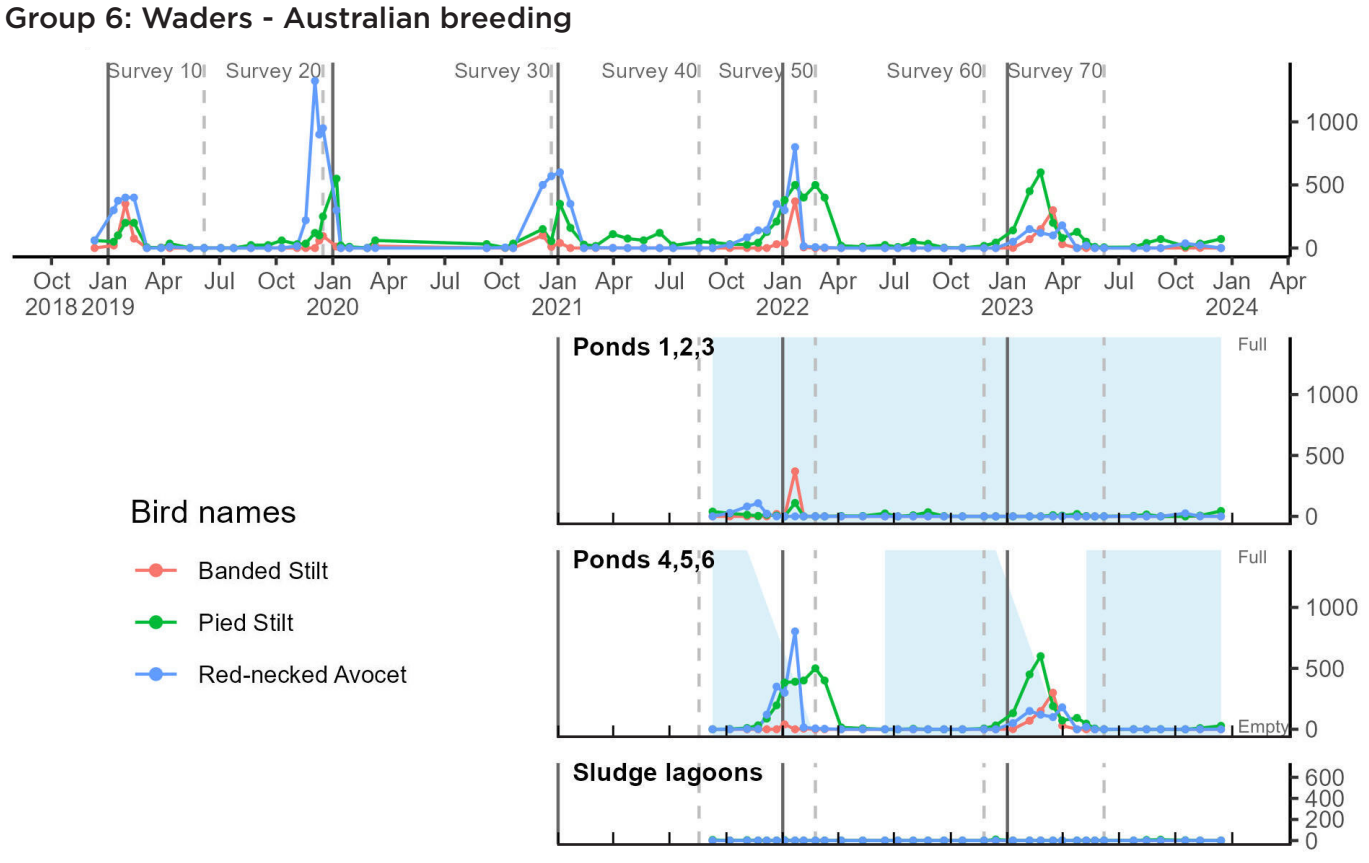

Figure 9. Abundance at Bolivar, mainly on Ponds 4–6, of waders that breed in Australia (Group 6). Blue background denotes approximate level of pond water.

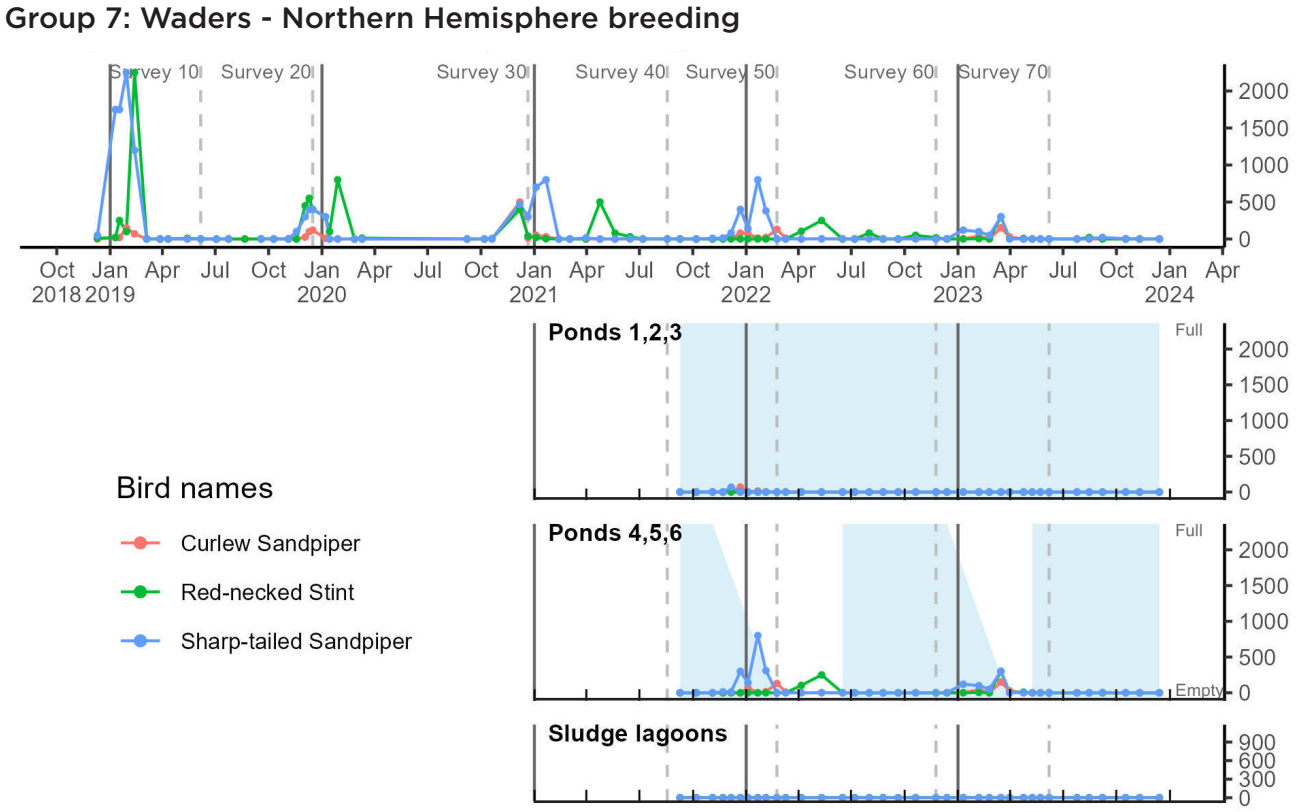

Figure 10. Abundance of waders that breed in the Northern Hemisphere (Group 7) on the ponds at Bolivar, almost entirely on Ponds 4–6. Blue background denotes approximate level of pond water.

Discussion

This study compares the abundance of waterbirds at the Bolivar wastewater treatment plant on the three groups of ponds from September 2021 until December 2023. During this time, the water in Ponds 1–3 was maintained at a constant high level, whereas in Ponds 4–6 the water level was decreased markedly each year from late summer, with Pond 6, then Ponds 4 and 5, becoming largely dry until May or early June when refilling occurred. All three common species of dabbling ducks (Pink-eared Duck, Pacific Black Duck and Grey Teal) occurred mainly on Ponds 1–3, with their greatest abundance usually occurring in late summer or autumn. By contrast, Australasian Shoveler was in far lower abundance than that previously observed by Moise & Paton in 2007, a finding that supports the view that this species is now of conservation concern.

Although most Pink-eared Duck and Grey Teal had probably migrated to the arid zone to breed in early 2020 (see Porter *et al.* 2022), both these species appeared again on the Bolivar ponds in late summer and autumn 2023. At this time, Grey Teal occurred on both groups of ponds, whereas the Pink-eared Duck was initially mainly on Ponds 1–3. Late in 2023, however, Grey Teal became more abundant on the sludge lagoons, whereas Pink-eared Ducks moved to Ponds 4–6. As this latter species is a specialised filter-feeder (Crome 1985), that might have been because of an abundance of invertebrates or plankton in these ponds at this time. Unlike during the dry time of 2019 in the arid zone, when Pink-eared Ducks were largely concentrated in late morning on the bank of Pond 3 (see Breed *et al.* 2020), during the time of our surveys in late 2023 the individuals on Ponds 4–6 were highly actively swimming for most of the time and often feeding in small groups by surface filtering.

Amongst the deep-water foragers, >1000 Black Swans occurred during spring and early summer. The reason for their abundance is not clear, but little feeding was generally evident; thus, as previously suggested (Breed *et al.* 2023), the ponds might have been acting as a refuge for individuals of this species during the high tide in the gulf where they feed on the seagrass (mainly *Posidonia* and *Amphibolis* spp.) at low tide.

The number of Australian Shelduck built up to several thousand in summer of all years and then dramatically dropped to only a few individuals in winter, with a similar annual cycle of abundance occurring at the Western Treatment Plant in Victoria (Loyn *et al.* 2014b, 2023; Papas *et al.* 2021). The very high numbers of Australian Shelducks and Black Swans at Bolivar may be descended from individuals that occurred in the very large flocks of these species recorded in this region in the 1920s (Tyler *et al.* 1976). However, their high abundance contrasts markedly with the observations of Moise & Paton (2007), who observed a maximum of only 356 Black Swans and 116 Australian Shelducks during their study in 2006–2007. The much greater abundance of Black Swans in the present study compared with the observations of Moise & Paton (2007) might have been because of the marked improvement in the conditions of the seagrass meadows in the adjacent area of Gulf St Vincent that have taken place over the last *c.* 15 years, where a net regrowth of seagrasses in the Adelaide region of the Gulf has increased by ~11,000 ha since 2000 (Fernandes *et al.* 2022).

The seasonality of the abundance of Whiskered Tern was similar to that at the Western Treatment Plant in Victoria,

where this species was largely absent when wet conditions prevailed in the arid zone (Loyn *et al*. 2014b; Papas *et al*. 2021). Similarly, we also did not see any individuals of this species at Bolivar in summer 2022–2023, which was a wet period in the southern arid zone. The very high numbers of Hoary-headed Grebe were present in autumn 2023 (see Figure 1e), when >1000 occurred on Pond 2. These birds might have been attracted to Bolivar, after a successful breeding period in the arid zone, with the abundance on Pond 2 probably due to the high nutrient level of the water resulting in abundance of aquatic invertebrates at that time.

In contrast to the observations of Moise & Paton (2007), who found that Ponds 4–6 were invariably largely dry during their study, in the current study these ponds were full of water for much of the year but were taken offline in summer, with the resultant water level falling to a very low level and, in some cases, becoming partly dry. At this time, the ponds became an excellent habitat for both waders that breed in Australia (e.g. Banded Stilt, Red-necked Avocet and Pied Stilt: see Breed *et al*. 2023) as well as those that migrate to Australia from the Northern Hemisphere (e.g. Sharp-tailed and Curlew Sandpipers and Red-necked Stint). Significant numbers of these species occurred on Ponds 4–6 in summer 2021–2022 in spite of wet conditions in the south-eastern region of the arid zone. This habitat at Bolivar clearly appears to be optimal for these species at this time.

This study has clearly shown that, by having Ponds 1–3 remaining full of water throughout the year, but Ponds 4–6 periodically becoming largely drained of water in late summer and autumn, this wastewater treatment plant is a highly attractive habitat to a diverse array of waterbirds. Some species of dabbling ducks that breed in the arid zone appeared to return to Bolivar even before the end of the wet period in the arid zone, whereas many individuals of several species of wader that breed in the Northern Hemisphere spent much of the winter at Bolivar. Although the numbers of waders during the summers of 2021–2022 and 2022–2023 were not as high as in 2019 when the arid zone was in drought (Breed *et al.* 2023), there were several hundred individuals of both Sharp-tailed Sandpiper and Red-necked Stint in both of these summers in spite of a marked drop in the populations of these species migrating to Australia from the Northern Hemisphere over the last 20–30 years (Clemens *et al.* 2016; Studds *et al.* 2017; Loyn *et al*. 2018).

In conclusion, our findings show that, unlike some other wastewater treatment plants, Bolivar is an important habitat for a diverse array of waterbirds, with the differences in treatment of water in Ponds 1–3 and 4–6 being highly beneficial, with Ponds 4–6 supporting many migrant and Australian-breeding waders (Purnell 2018; Lamanna *et al*. 2021; Lees 2023). Hopefully these differences in the treatment of water and the water levels in these two groups of ponds at Bolivar will be retained for the long term so that this diversity of waterbirds will continue to occur here.

Acknowledgements

We wish to thank SA Water for permission to carry out the bird surveys, and two referees as well as Richard Loyn for their most constructive comments on an earlier draft of this manuscript. We also thank SA Water for supplying us with a draft report of results of a study of the stabilisation lagoons.

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Received 19 February 2024, accepted 24 June 2024, published online 14 August 2024