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Effects of rainfall in the arid zone on waterbird abundance at a wastewater treatment plant in coastal South Australia

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Abstract. We investigated which species of waterbirds at Bolivar, a wastewater treatment plant in Metropolitan Adelaide, South Australia, are likely to have been immigrants from the ephemeral wetlands in the arid zone. To do this, we compared the abundance of waterbird species observed at Bolivar during the dry period in the eastern arid zone of late 2018 and 2019 with that during the subsequent wet period 2020–2022. Pink-eared Duck *Malacorhynchus membranaceus*, Grey Teal *Anas gracilis*, Australasian Shoveler *Spatula rhynchotis*, Hardhead *Aythya australis* and Blue-billed Duck *Oxyura australis* were all more abundant during the arid-zone dry period. By contrast, Australian Shelduck *Tadorna tadornoides*, Eurasian Coot *Fulica atra* and Black Swan *Cygnus atratus* showed increased abundance in spring and early summer in all years, with no marked differences between the dry and wet periods in the arid zone. Wader species that breed in the Northern Hemisphere – Sharp-tailed Sandpiper *Calidris acuminata* and Red-necked Stint *C. ruficollis* – also tended to be more abundant during the arid-zone dry year, as did Red-necked Avocet *Recurvirostra novaehollandiae*, whereas Pied Stilt *Himantopus leucocephalus* tended to be more abundant in the arid-zone wet years, with breeding by this species taking place in spring. These data suggest that Bolivar is a critically important conservation site for waterbirds and that various species use this location as a refuge during dry times in the arid zone of eastern Australia.

Introduction

Wastewater treatment plants often contain a diverse array of waterbirds. Within Australia, the Western Treatment Plant near Melbourne in Victoria is a Ramsar-listed site at which abundant ducks and migratory waders occur (Hamilton *et al*. 2002; Steele 2008; Murray & Hamilton 2010; Loyn *et al*. 2014a,b, 2018; Murray *et al.* 2012, 2014), and Papas *et al.* (2021) have shown that wastewater treatment plants across the Murray–Darling Basin of rural Victoria may also support waterbirds, as does the sewage farm near Alice Springs in central Australia (Roberts 1981). Following high rainfall in the arid zone, temporary inland lakes develop and can also become important feeding and breeding sites for various species of waterbirds as well as refuge sites for migratory waders (Lane 1987; Kingsford *et al*. 1999a,b, 2010; Roshier *et al*. 2002; Geering *et al.* 2007; Pedler & Kovac 2013; Bino *et al*. 2020).

Over the last 20 years or so, there has been a considerable reduction in abundance of both endemic and migratory waders in Australia (Gosbell & Clemens 2006; Nebel *et al*. 2008; Hansen *et al.* 2015; Clemens *et al*. 2016; Studds *et al*. 2017; Loyn *et al.* 2018), which includes the population that occurs in Gulf St Vincent, South Australia (Close 2008; Purnell *et al*. 2017; Purnell 2018; Lamanna *et al*. 2021) and in this region the migratory waders using the Dry Creek saltfields have also been negatively impacted by the cessation of salt production (Rogers & Cox 2018). However, waterbird abundance at the adjacent wastewater treatment plant at Bolivar appears to have been little investigated although high numbers of several species of ducks and waders were observed at this location during the arid-zone dry period of late 2018 and 2019 (Breed *et al*. 2020). Whether this abundance was because Bolivar acted as a refuge for species from the arid zone is not known. The current study thus builds on our previous investigation and compares the abundance of waterbirds at Bolivar during the wet years of 2020–2022 in the arid zone of eastern Australia (Bureau of Meteorology 2020) with those of the dry period of late 2018 and 2019.

Methods

The Bolivar Wastewater Treatment Plant (35°S, 138°E), ~20 km north of the centre of Adelaide and just south of the Adelaide International Bird Sanctuary, lies to the east of the mangroves of Barker Inlet–St Kilda Aquatic Reserve east of Torrens Island. The site contains 340 ha of flow-through effluent-stabilisation ponds that occur as two parallel series of three ponds: a western series comprising Ponds 1–3 just inland from the intertidal mangroves, whereas Ponds 4–6 lie just to the east of these ponds (see Figure 1 in Breed *et al*. 2020), with a semi-permanent watercourse flowing through a 60-m vegetation strip that passes east to west between the ponds. All the ponds have concrete banks and clay floors.

In the western Ponds 1–3, water is maintained at a depth of ~1.2 m throughout the year. In spring, green algae are common, with cyanobacteria becoming more abundant in summer. The zooplankton in these ponds include rotifers (Rotifera), copepods (Crustaceae: Orders Calanoida, Cyclopoida and Harpacticoida), and water fleas (Cladocera: Families Chydoridae, Daphniidae, Macrothricidae and Moinidae) that, together with the larvae of chironomid midges (Diptera: Family Chironomidae), rapidly increase in abundance in spring because of the increase in temperature of the water at that time. European Carp *Cyprinus carpio* and Freshwater Shrimps *Macrobrachium australiense* (Family Palaemonidae) are also abundant.

In the eastern Ponds 4–6, filamentous green algae are also common. However, these ponds are taken offline in spring and allowed to drain. This results in a gradual decrease of the water level to ~300 mm, after which time water evaporation occurs over a period of *c*. 2 months. This reduction of water produces an excellent habitat for various species of waders because of the gradual increase in exposed mud and high density of chironomid midge larvae occurring in the sediment. The ponds remain dry over summer and are refilled in late autumn.

Just to the north of Pond 6 is a shallow recycled-water storage pond, which runs more or less east to west, and just to the north is another group of small ponds, the sludge lagoons, of 120 ha, which are sequentially dried out over a 3-year cycle.

For the regular counts of the various waterbird species we surveyed each of the ponds. To do this, we first drove along the track around Ponds 4, 5 and 6, after which we continued to the sludge ponds where we visited two observation sites overlooking the lagoons. We then returned to the ponds and drove around Ponds 1, 2 and 3.

We recorded the numbers of the various species of waterbirds on, or around, each pond, together with any signs of breeding, including the number of pairs of birds, or females, with chicks. All surveys were carried out between 0800 and 1200 h on days when there was an early-morning high tide in the adjacent aquatic reserve.

In order to investigate the potential effect on the populations of waterbirds at Bolivar of the environmental conditions in the eastern region of the arid zone, we compared the abundance of species at Bolivar during the arid-zone dry period of late 2018 and 2019 with their abundance during 2020, 2021 and early 2022, which were wet periods in this part of the arid zone (Bureau of Meteorology 2020). Changes in abundance were calculated for key species, with significant differences being determined using two-sample *t*-tests (unequal variance) for null hypothesis of equal means of abundance. The graphs showing the numbers of individuals recorded for each trip were produced using the *R* package ggplot2 (Wickham 2016).

For most species, our first count was in either December 2018 or January 2019 but for the Eurasian Coot *Fulica atra* counts were not started until early November 2019 as it was not evident until then that their numbers were also changing markedly over time.

For comparison of the abundance of the individual species, we used the six functional groups as defined by Roshier *et al.* (2002), except that we separated their 'small wader' group into two groups: species that breed in Australia, and those that migrate from breeding areas in the Northern Hemisphere to spend the austral summer in Australia.

Results

Table 1 compares the abundance of waterbird species at Bolivar Wastewater Treatment Plant that had a mean count of >20 individuals for the 20 surveys in late 2018–2019 during the dry period in the arid zone with the data obtained for the same species for the wet years 2020 to early 2022. Figures 1–5 show some of the ponds at Bolivar together with waterbirds: Black Swans, Eurasian Coots and ducks in Figure 1, waders that breed in the Northern Hemisphere in Figure 2, Pink-eared Ducks in Figure 3, and Pied Stilts in Figures 4–5. Figures 6–12 show graphs of the counts for groups of the various species.

Group 1 – Dabbling (= surface-feeding) ducks

The Pink-eared Duck *Malacorhynchus membranaceus* (Figure 3) is a classic nomadic species that breeds in the arid zone. During late 2018 and 2019, it was the most abundant species of duck present (Figure 6) and had a population of between 2500 and 7000 individuals, with a mean of almost 5000. Significantly smaller numbers occurred in 2020–2022 (P <0.001, Table 1), although a high number was present in January and February 2020 just before the drought broke. The other common nomadic arid-zone duck species in this group, the Grey Teal *Anas gracilis*, was also abundant on most occasions during late 2018 and in 2019, with >2000 usually being present except in mid winter (Figure 6). The numbers during 2020, 2021 and early 2022 were significantly fewer (P = 0.002, Table 1), with peaks occurring in early January and June 2021, and very low numbers in spring.

The Pacific Black Duck *A. superciliosa* was at times quite common during early 2019, with an average of ~410 birds (Figure 6). However, late in 2019 and subsequently there were generally low numbers present although broods of ducklings of this species were observed in December 2020, January and December 2021, and January 2022. The Chestnut Teal *A. castanea* was also usually present, in both wet and dry periods, albeit in very low abundance and, like the Pacific Black Duck, pairs of Chestnut Teal were sometimes accompanied by broods of ducklings during January 2019, October 2020 to January 2021, and October 2021 to January 2022.

The only other duck species in this group that occurred with any regularity was the Australasian Shoveler *Spatula rhynchotis*. During 2019, there were up to 100 present but, after the end of the drought, significantly fewer occurred (P <0.001, Table 1) with no more than ~15 on any one occasion. Up to 22 Freckled Ducks *Stictonetta naevosa* were also present in the dry year of 2019, but subsequently only a single individual was observed on just two occasions, in January and November 2021.

Group 2 – Deep-water foragers

Numbers of Black Swans *Cygnus atratus* (Figure 1) varied markedly across the visits regardless of conditions in the arid zone. Up to ~2000 usually occurred in spring and/or summer of each year, with a maximum of ~3700 in December 2021 (Figure 7), whereas in winter the numbers were usually very low. One nest was found in March 2021 and cygnets were present from March to August of that year.

Of the deep-water duck species, Hardheads *Aythya australis* showed considerable variability in abundance (Figure 7), with the highest numbers occurring in winter and spring 2019, with peaks of ~1200 in July and 2000 in September of that year. During 2020, 2021 and early

Table 1. Mean abundance (± standard deviation) of waterbird species at Bolivar Wastewater Treatment Plant: during the drought period in the arid zone (2018–2019), *n* = 20; and after the cessation of the arid-zone drought (2020–2022), *n* = 30. For details of the individual data see **Supplementary material**. Group: 1 – Dabbling ducks, 2 – Deep-water-foraging waterfowl, 3 – Grazing waterfowl, 4 – Fish- and invertebrate-eaters, 5 – Waders that breed in Australia, 6 – Waders that breed in the Northern Hemisphere, and 7 – Shoreline foragers. Species listed here are those with a mean abundance of >20 individuals per survey in 2018–2019, excluding Masked Lapwing, Australian White Ibis and Eurasian Coot (see text for further details).

Group	*Species*	*Mean abundance (± standard deviation)*			*Change*	*Significance*
		2018–2019	*2020–2022*			
		No. birds	*No. birds*	*% of 2018–2019 abundance*	*%*	*P value*
1	Pink-eared Duck *Malacorhynchus membranaceus*	4875 ± 1241	827 ± 1269	17	–83	<0.001
1	Grey Teal *Anas gracilis*	2390 ± 1109	1242 ± 1242	52	–48	0.002
1	Pacific Black Duck *Anas superciliosa*	413 ± 466	339 ± 241	82	–18	0.533
1	Australasian Shoveler *Spatula rhynchotis*	44 ± 39	4 ± 4	10	–90	<0.001
1	Chestnut Teal *Anas castanea*	21 ± 29	28 ± 67	136	36	0.599
2	Black Swan *Cygnus atratus*	569 ± 602	813 ± 822	143	43	0.241
2	Blue-billed Duck *Oxyura australis*	382 ± 350	152 ± 142	40	–60	0.012
2	Hardhead *Aythya australis*	359 ± 483	198 ± 214	55	–45	0.184
3	Australian Shelduck *Tadorna tadornoides*	756 ± 937	1091 ± 1476	144	44	0.341
4	Whiskered Tern *Chlidonias hybrida*	317 ± 417	222 ± 342	70	–30	0.414
4	Hoary-headed Grebe *Poliocephalus poliocephalus*	125 ± 139	70 ± 96	56	–44	0.112
4	Australian Pelican *Pelecanus conspicillatus*	53 ± 41	35 ± 34	65	–35	0.113
5	Red-necked Avocet *Recurvirostra novaehollandiae*	248 ± 377	140 ± 221	56	–44	0.269
5	Pied Stilt *Himantopus leucocephalus*	65 ± 73	139 ± 165	215	115	0.039
5	Banded Stilt *Cladorhynchus leucocephalus*	35 ± 79	21 ± 68	59	–41	0.518
6	Sharp-tailed Sandpiper *Calidris acuminata*	410 ± 707	147 ± 248	36	–64	0.115
6	Red-necked Stint *Calidris ruficollis*	202 ± 499	76 ± 181	38	–62	0.304
6	Curlew Sandpiper *Calidris ferruginea*	25 ± 45	31 ± 92	121	21	0.787
7	Black-tailed Native-hen *Tribonyx ventralis*	28 ± 42	3 ± 11	12	–88	0.021

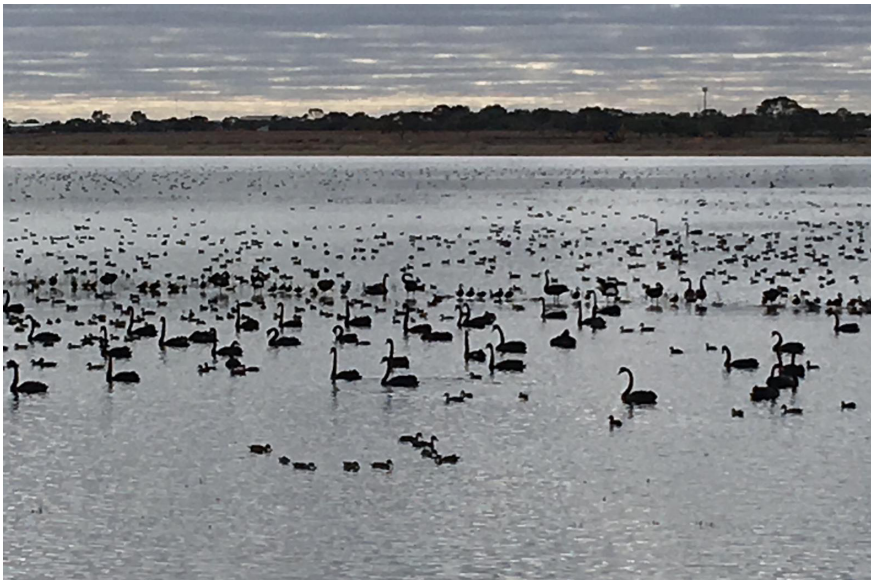

Figure 1. Pond 4 at Bolivar Wastewater Treatment Plant early in the morning showing an abundance of Black Swans, Eurasian Coots and a variety of ducks. Photo: William G. Breed

Figure 2. Pond 6 at Bolivar Wastewater Treatment Plant, showing a flock of waders from the Northern Hemisphere, mainly Sharp-tailed Sandpipers. Photo: William G. Breed

Figure 3. Pond 3 at Bolivar Wastewater Treatment Plant with a flock of Pink-eared Ducks. Photo: William G. Breed

Figure 4. Pond 5 at Bolivar Wastewater Treatment Plant, showing numerous adult Pied Stilts. Photo: William G. Breed

Figure 5. Pond 5 at Bolivar Wastewater Treatment Plant, showing young Pied Stilts, including a swimming chick. Photo: William G. Breed

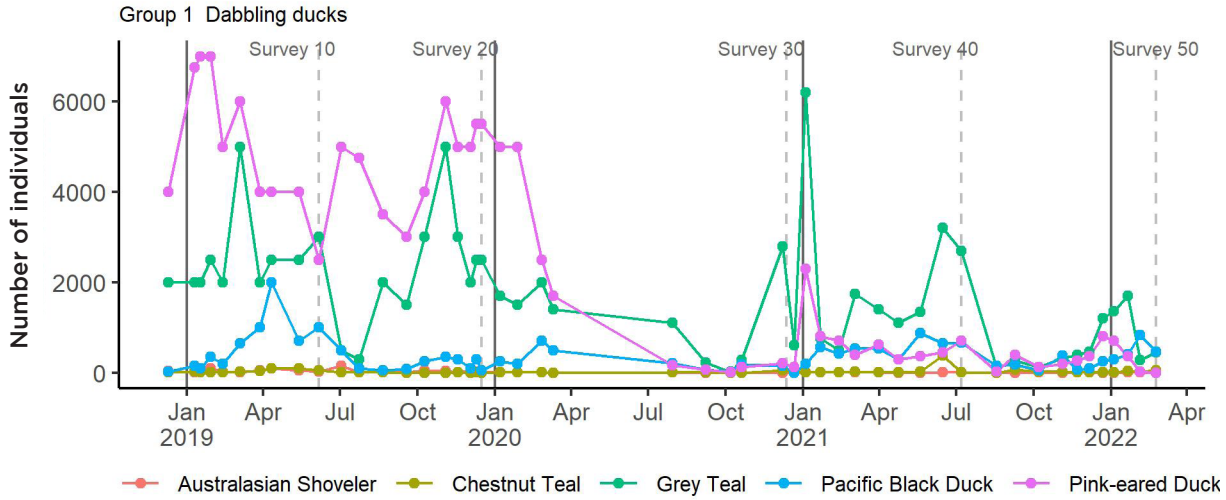

Figure 6. Abundance of dabbling ducks – Australasian Shoveler, Chestnut Teal, Grey Teal, Pacific Black Duck and Pink-eared Duck – at Bolivar Wastewater Treatment Plant from December 2018 to February 2022.

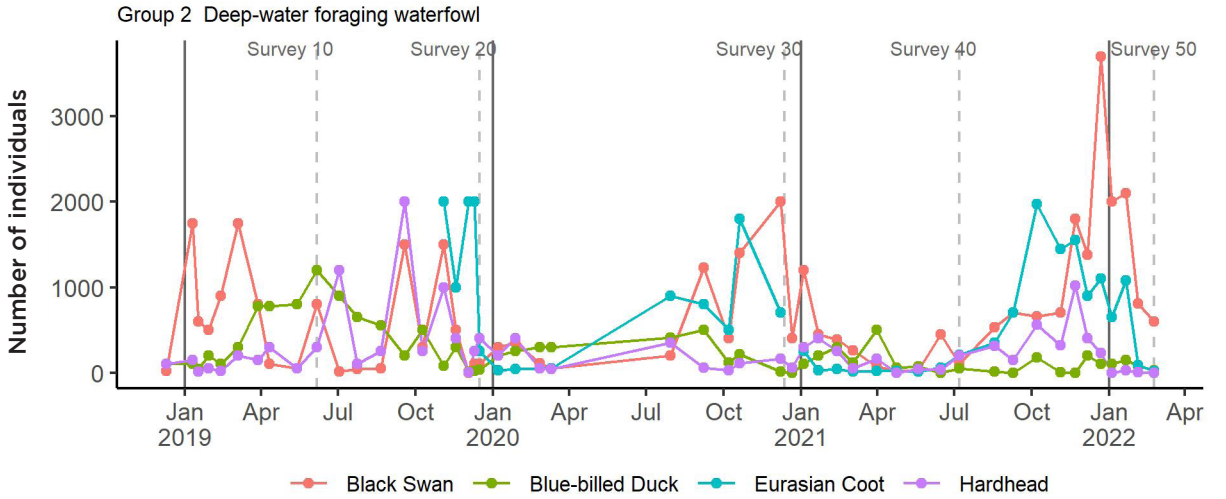

Figure 7. Abundance of deep-water-foraging waterfowl – Black Swan, Blue-billed Duck and Hardhead – at Bolivar Wastewater Treatment Plant from December 2018 to February 2022, and of Eurasian Coot from November 2019.

2022, there was some variability in abundance but the average number was <200. Blue-billed Ducks *Oxyura australis* were also abundant during 2019, with an average of ~380 and peak abundance of ~1200 in June (Figure 7). Subsequently, during 2020, 2021 and early 2022, significantly fewer occurred (P = 0.012), with the average number being ~150 (Table 1).

Musk Ducks *Biziura lobata* were always relatively scarce, with usually <20 being present. The highest numbers tended to occur in spring or early summer regardless of conditions in the arid zone, with low numbers in mid and late summer (Figure 12). A maximum of 80 individuals was recorded in early November 2019 and 95 in October 2020, with both of these observations being followed by very low numbers on the subsequent visit.

Eurasian Coots *Fulica atra* (Figure 1) were not counted during the first few surveys, but there were 1000–2000 when counts were initiated in November 2019. There were peaks of similar magnitude in late spring or early summer in the following 2 years but numbers were generally low in winter (Figure 7).

Group 3 – Grazing waterfowl

Australian Wood Ducks *Chenonetta jubata* were very few, with <10 present on most occasions, and a maximum of 36 in March 2021. By contrast, the Australian Shelduck *Tadorna tadornoides* was periodically very abundant in late spring and early summer of all years, regardless of conditions in the arid zone (Figure 8). These peaks of abundance typically lasted 2–3 months, with numbers being low at other times of year. Four pairs of Australian Shelducks with 4, 7, 9 and 13 ducklings, respectively, were present in early October 2019, and another brood of four ducklings was observed in October 2020.

Cape Barren Geese *Cereopsis novaehollandiae* were not present until December 2019, when a single individual

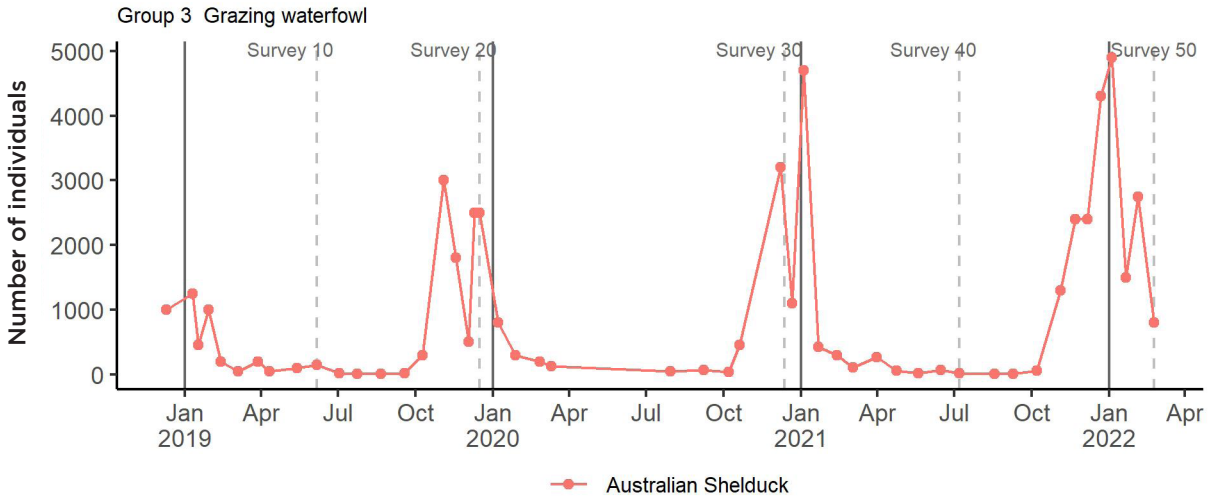

Figure 8. Abundance of Australian Shelduck at Bolivar Wastewater Treatment Plant from December 2018 to February 2022.

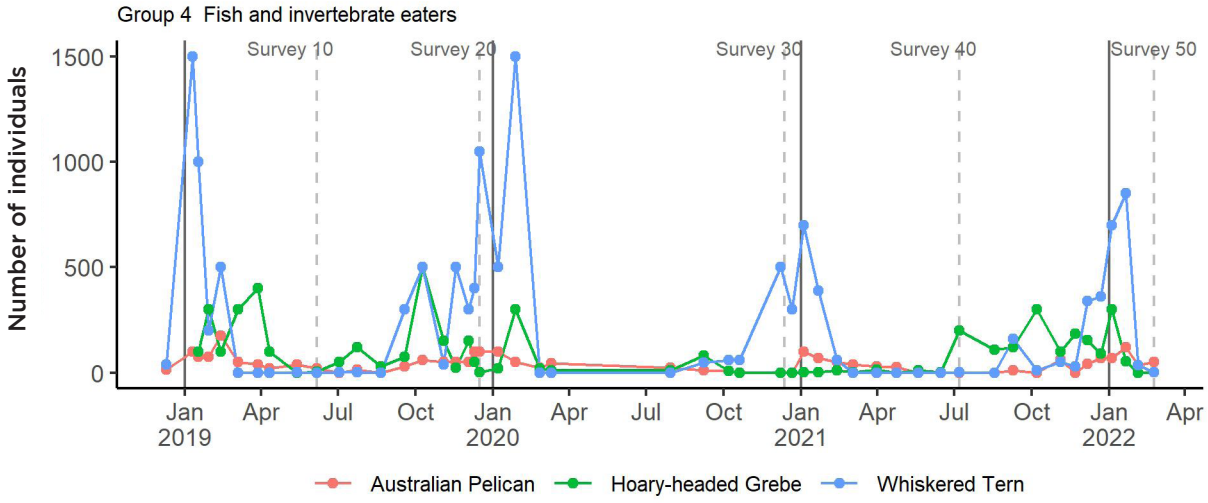

Figure 9. Abundance of fish- and invertebrate-eaters – Australian Pelican, Hoary-headed Grebe and Whiskered Tern – at Bolivar Wastewater Treatment Plant from December 2018 to February 2022.

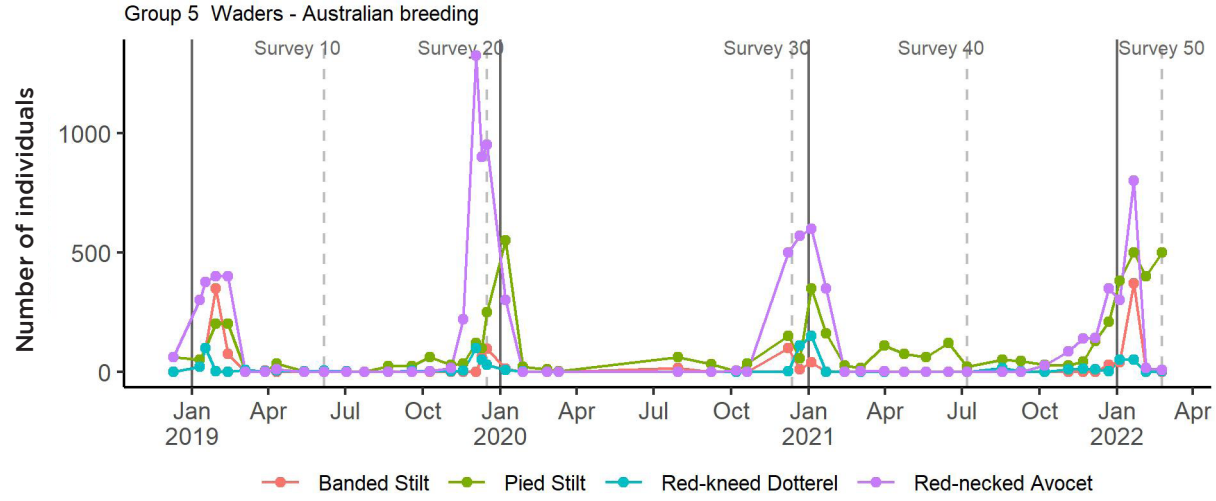

Figure 10. Abundance of waders that breed in Australia – Banded Stilt, Pied Stilt, Red-kneed Dotterel and Red-necked Avocet – at Bolivar Wastewater Treatment Plant from December 2018 to February 2022.

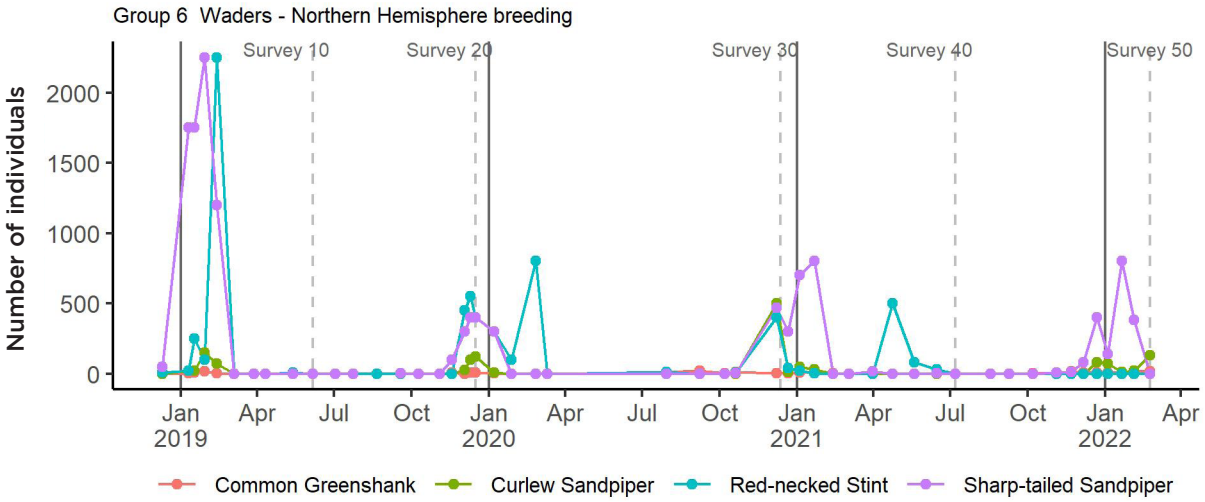

Figure 11. Abundance of waders that breed in the Northern Hemisphere – Common Greenshank, Curlew Sandpiper, Red-necked Stint and Sharp-tailed Sandpiper – at Bolivar Wastewater Treatment Plant from December 2018 to February 2022.

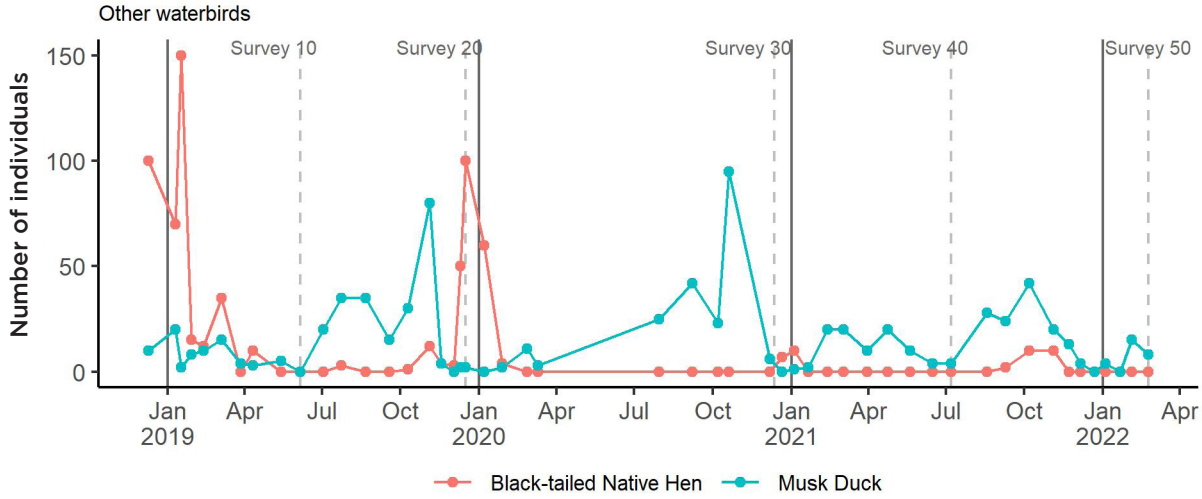

Figure 12. Abundance of Black-tailed Native-hen (a shoreline-forager) and Musk Duck (which forages in deep water) at Bolivar Wastewater Treatment Plant from December 2018 to February 2022.

appeared. They were then absent until February 2021, after which a few were present during most of 2021, with a maximum of four in May 2021, and eight in February 2022.

Group 4 – Fish- and invertebrate-eaters

Two species of fish-, or invertebrate-, eating waterbirds were at times very abundant – Hoary-headed Grebe *Poliocephalus poliocephalus* and Whiskered Tern *Chlidonias hybrida* – with occasional Great Egrets *Ardea alba*, Little Egrets *Egretta garzetta,* Australasian Grebes *Tachybaptus novaehollandiae*, Great Crested Grebes *Podiceps cristatus*, Caspian Terns *Hydroprogne caspia* and White-winged Black Terns *Chlidonias leucopterus* being present. Hoary-headed Grebe numbers varied and more were present in the dry year of 2019, with peak numbers occurring in April and October 2019 and February 2020 (Figure 9).

Whiskered Terns clearly showed seasonal abundance regardless of the conditions in the arid zone (Figure 9). In all years, numbers built up from October and peaked in January before declining abruptly so that almost none were present from February to July.

Australian Pelicans *Pelecanus conspicillatus* were usually present in small numbers, with ~100 individuals occasionally occurring in summer (Figure 9). Three species of cormorants – Little Pied *Microcarbo melanoleucos*, Great *Phalacrocorax carbo* and Little Black *P. sulcirostris* – were all usually present in very small numbers and showed no obvious seasonal or yearly changes in abundance.

Group 5 – Waders that breed in Australia

The Red-necked Avocet *Recurvirostra novaehollandiae* was a summer visitor, and was generally abundant from November to February regardless of the conditions in the arid zone, with very few, or none, present in autumn or winter (Figure 10). Banded Stilts *Cladorhynchus leucocephalus* occurred in small numbers and also generally were present only in summer, with up to ~370 occasionally being

present (Figure 10). By contrast, the Pied Stilt *Himantopus leucocephalus* (Figures 4–5) was usually present throughout the year, albeit only in small numbers in winter, with significantly more Pied Stilts occurring in the wet years of 2020–2022 (P = 0.04, Figure 10, Table 1). Pied Stilt chicks, accompanied by adults, were present in late spring of most years especially in 2020 and 2021. Occasionally, Glossy Ibises *Plegadis falcinellus* (maximum of 14 on 21 December 2020), Straw-necked Ibises *Threskiornis spinicollis* and Royal Spoonbills *Platalea regia* (maximum of five on 10 December 2019) also occurred. There were also occasionally small numbers of Red-capped Plovers *Charadrius ruficapillus*, Red-kneed Dotterels *Erythrogonys cinctus* and Black-fronted Dotterels *Elseyornis melanops*, with up to ~150 Australian White Ibises *Threskiornis moluccus* present on most occasions, and 100–150 Red-kneed Dotterels in summer (Figure 10).

Group 6 – Waders that breed in the Northern Hemisphere

The Northern Hemisphere waders were generally present only in summer, with no statistically significant differences between the arid-zone dry year of 2018–2019 and the subsequent wet years, although >2000 Sharp-tailed Sandpipers *Calidris acuminata* (Figure 11) and a similar number of Red-necked Stints *C. ruficollis* occurred early in 2019, with the largest number of the former species being present in January and of Red-necked Stints in February of that year (Figure 11). Smaller peaks of 300–500 of both these species were observed in summer 2019–2020 and 2020–2021, with similar numbers of Sharp-tailed Sandpipers also occurring in summer 2021–2022. The largest flock of Curlew Sandpipers *C. ferruginea* (~500) was present in early December 2020 (Figure 11), with numbers of <100 generally occurring in summer 2020–2021 and 2021–2022. In addition, occasionally there were also Pectoral Sandpipers *C. melanotos* and Long-toed Stints *C. subminuta* as well as small numbers of Common Sandpipers *Actitis hypoleucos*, Common Greenshanks *Tringa nebularia*, Marsh Sandpipers *T. stagnatilis* and Wood Sandpipers *T. glareola,* with a few individuals of these species being present in both dry and wet years in the arid zone. Up to 11 Black-tailed Godwits *Limosa limosa* were present in the wet summer of 2021–2022, with only 1–6 individuals present on a few other occasions. Up to 21 Common Greenshanks were also recorded in the austral winter of 2020, suggesting a few overwintering individuals of this species. That a few Red-necked Stints also sometimes spent the winter in the area is suggested by the occurrence of 10 individuals in May 2019, 12 in July 2020, 80 in May 2021, and 30 in June 2021, whereas a record of 500 in late April 2021 might have been of birds that were about to migrate.

Group 7 – Shoreline foragers

The Black-tailed Native-hen *Tribonyx ventralis* is a typical arid-zone species that disperses to the south of the country during dry times. At Bolivar, there were up to 150 individuals during the dry 2018–2019 summer in the arid zone whereas, after termination of the drought, significantly fewer occurred, with no more than 10 individuals (P = 0.02) on any one occasion, but usually none being present (Figure 12). Small numbers of Masked Lapwings *Vanellus miles*, as well as an occasional Banded Lapwing *V. tricolor*, were usually present, regardless of the conditions in the arid zone.

Discussion

In this study, we compared the abundance of waterbirds at Bolivar Wastewater Treatment Plant in South Australia during the wet years in the arid zone of eastern Australia of 2020, 2021 and early 2022 with the abundance recorded during the dry period of late 2018 and 2019 (Breed *et al*. 2020) to gain some insight into the potential effect(s) in a change of the environmental conditions of the arid zone on abundance of waterbird species at Bolivar.

Pink-eared Ducks were invariably abundant during the dry time in the arid zone whereas after the drought broke significantly fewer occurred and almost none were present by late February 2022. Grey Teal showed a similar trend but there was much greater variability in abundance of this species during the dry year, with few occurring in mid winter in the wet years 2020 and 2021. There were, however, significantly fewer individuals of both this species, and Australasian Shoveler, after the termination of the arid-zone drought. By contrast, the Australian Shelduck had very different patterns of abundance and showed little variation between dry and wet years in the arid zone but marked seasonal changes in population density. It was invariably abundant from early November to early January, with foraging in spring often taking place in the adjacent paddocks. By autumn, however, the numbers had dropped markedly, with only a very few individuals being present in winter. These annual changes in Shelduck abundance and periodic spring abundance indicate that Bolivar is a very important annual post-breeding (and presumably moulting) refuge for this species.

Black Swans did not show significant differences of abundance between arid-zone wet and dry years. There was usually high abundance of nonbreeding birds in spring and/or early summer, perhaps at least partly because the adjacent Gulf intertidal seagrass meadows (which included *Zostera* spp.: Bryars *et al.* 2008) were an attractive food resource for this species, as in Western Port, Victoria (Loyn *et al*. 2018). Although the outflow of wastewater could have a negative effect on the abundance of seagrass in this area in South Australia (e.g. Bryars *et al.* 2008), numerous Swans were often observed feeding on the intertidal mudflats off St Kilda at low tide (WGB unpubl. obs.); thus, the Bolivar ponds appear to act as a location for the Swans to reside during high tide, when most of the current observations were made.

The other species that showed relatively little change between the arid-zone dry and wet times but clear seasonal differences in abundance were Eurasian Coot and Whiskered Tern, and also, to some extent, Hoary-headed Grebe. The observations on the seasonal abundance of these species were similar to the findings at the Western Treatment Plant in Victoria (Loyn *et al*. 2014b). The numbers of Whiskered Terns in spring and early summer of the arid-zone dry year of 2018–2019 and early 2020 were somewhat greater than those in the subsequent wet years. This suggests the possibility that some Whiskered

Terns might have remained in the ephemeral wetlands of the arid zone, perhaps to reproduce, in late 2020 and the summer of 2021–2022. Numbers of Hoary-headed Grebes remained low for the first summer of the wet period but were back to high numbers in the subsequent summer, similar to the number present during the dry year of 2019.

The two duck species that forage in deep water, Hardhead and Blue-billed Duck, both tended to be more abundant at Bolivar during the dry year of 2019. Bolivar thus appears to act as a refuge for these two species of diving ducks as well as for the dabbling duck species (Pink-eared Duck and Grey Teal) during dry times in the inland region. In contrast with these species, this was not apparent for three other duck species – Chestnut Teal, Pacific Black Duck and Australian Shelduck – although adults of these species were seen accompanied by ducklings, suggesting a typical spring and early summer breeding period for these three species. The periodic occurrence of Australian Pelicans, which did not differ markedly between the dry and wet years, was probably because individuals of this species dispersed from the large breeding colony on Bird Island in Barker Inlet (Johnston & Wiebkin 2008).

Wet conditions in the arid zone can at times support large numbers of waders of species that breed in Australia as well as migrants from the Northern Hemisphere (Frith 1977; Roshier *et al.* 2002, 2008; Bino *et al.* 2020; Papas *et al.* 2021). The abundance in Australia of the latter has been reported to have markedly declined in recent years (Gosbell & Clemens 2006; Nebel *et al.* 2008; Hansen *et al.* 2015; Clemens *et al*. 2016; Studds *et al*. 2017; Loyn *et al*. 2018), with this decline being reflected by lower numbers of migrants from the Northern Hemisphere in Gulf St Vincent, South Australia. Nevertheless, at Bolivar ~2000 individuals of both Sharp-tailed Sandpipers and Red-necked Stints were present early in the summer of 2018–2019, which suggests that, like the Western Treatment Plant in Victoria (Loyn *et al*. 2014a,b; Papas *et al.* 2021), Bolivar is at times a significant refuge for these species.

Of the waders that breed in Australia, the Red-necked Avocet was at times the most abundant species. It was always present in summer even in the arid-zone wet years of 2020–2021 and 2021–2022 although there was no evidence of breeding. The Pied Stilt was also abundant in summer, with significantly more individuals occurring during the arid-zone wet years (Table 1), with several pairs breeding at this location in 2020–2021 and 2021–2022.

Our records of waterbird data from numerous surveys over the last 3 years are summarised in Figures 6–12. They indicate a complexity of inland aridity and seasonality on the abundance of the birds at Bolivar and suggest that this site is an important refuge for several species of ducks when dry conditions prevail inland. However, seasonality is indicated for waders regardless of the conditions in the arid zone, as well as for Australian Shelduck, Black Swan, Hoary-headed Grebe and Whiskered Tern. Several other factors, such as food availability, are also likely to influence the abundance of waterbirds at Bolivar but these factors have not been considered in this current investigation.

Conclusion

The present observations extend our earlier study on the waterbirds at Bolivar and suggest that this South Australian wastewater treatment plant is an important refuge for five species of ducks – Pink-eared Duck, Grey Teal, Australasian Shoveler, Hardhead and Blue-billed Duck – during dry times in the arid zone of eastern Australia. In addition, these ponds form an important seasonal refuge during summer for Australian Shelduck, Black Swan, Eurasian Coot and Whiskered Tern as well as for several species of both Australian and migrant Northern Hemisphere waders. These findings thus confirm that this wastewater treatment plant is a very important habitat, and at times refuge, for various species of waterbirds in South Australia, especially as no duck hunting is permitted at this site. Appropriate management of these ponds is thus important for the conservation of these native duck species as well as for the waders that breed in Australia and those that migrate to southern Australia from their Northern Hemisphere breeding sites.

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