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Waterbird use of different treatment stages in waste-stabilisation pond systems

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Abstract. The significance of waste-stabilisation ponds (WSPs) to waterbirds has been well documented, but WSP differ depending on their place and purpose in the sewage-treatment system, and there is little information on how birds use these different types of pond. In mid-winter (July) 2012, waterbirds were counted on WSP at 18 sewage-treatment plants in the Goulburn Valley, Victoria. Winter-storage and maturation ponds supported greater abundance, density (birds ha^{-1}) and richness of waterbirds than aerated and anaerobic ponds. There were no significance differences in the number of species per hectare among types of pond. The abundance and density of diving waterfowl on maturation and winter-storage ponds was greater than on anaerobic and aerated ponds. A multivariate analysis revealed that waterbird community composition (based on both abundance and density) differed significantly between maturation ponds and anaerobic ponds ($P < 0.001$) and also between winter-storage and anaerobic ponds ($P < 0.01$). Comparing among types of WSPs, the waterbird communities of anaerobic ponds were the most distinct and winter-storage and maturation ponds the least different. Although the primary objective of a treatment plant is to treat sewage there is some design flexibility and, where possible, increasing the size or number of maturation and winter-storage ponds, or both, would generally benefit waterfowl.

Additional keywords: biodiversity, conservation, ecology, sewage, wildlife management.

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Introduction

The global importance of waste-stabilisation ponds (WSPs) for waterbirds has been well documented (Murray and Hamilton 2010 and references therein), including in Victoria, Australia (Hamilton and Taylor 2004; Hamilton *et al*. 2004; Steele *et al*. 2006), and in the United Kingdom (Fuller and Glue 1980, 1981), Africa (Blaker and Winterbottom 1968) and North America (Piest and Sowls 1985). The importance of artificial and recreated wetlands to waterbirds has increased as a result of the loss of natural wetlands. The use of such wetlands, including WSPs, by waterbirds is typically opportunistic, and little consideration has been given by managers of WSPs to the potential implications for either wastewater treatment or waterbird conservation. Further, there seems to have been little examination of how differences in avian species richness, abundance and density through the sewage treatment system might affect these objectives. This study seeks to redress this paucity of information.

In a recent study of the use of different types of wetlands by waterfowl over 22 years in south-eastern Australia, WSPs were found to support significantly greater species richness, abundance and density of many waterfowl species and also a different waterfowl community to other wetland types examined (deep marsh, open water, permanently saline and semi-permanent saline wetlands) (Murray *et al*. 2012). Although the Western Treatment Plant (WTP) at Werribee, west of Melbourne, is clearly the most well known sewage treatment plant (STP) to birdwatchers – a ‘Disneyland for birdwatchers’ (Dooley 2007) – we confirmed that the finding of the importance of WSPs in Victoria was not an artefact arising from this single STP (Murray *et al*. 2012).

Despite the importance of WSPs, only one published study (Hamilton *et al*. 2005) has investigated whether waterbirds exhibit a general preference for WSPs at a particular stage of waste-water treatment and that study was restricted to the WTP alone. Hamilton *et al*. (2005) found that the highest density and diversity of waterbirds, and of zooplankton, were usually found in the ponds towards the end of the treatment system, although no conclusions could be drawn regarding the importance of the oxygenation or limnological status of the ponds.

In a typical waste-treatment system, the first one or two ponds are classified as anaerobic because there is no free oxygen owing to the high organic loading (>250 kg biochemical oxygen demand (BOD) ha^{-1} day^{-1}) within the ponds (Smith and Scott 2005). The first ponds are usually followed by facultative ponds, which have an anaerobic lower layer of water and an aerobic upper layer. The last ponds in the series, the maturation ponds, are oxygenated throughout their depth profile and are sometimes called aerobic or oxidation ponds. There are many variants on this basic typology, but the two noteworthy additions in Victoria are aerated ponds, which are ponds that would otherwise be anaerobic but are oxygenated artificially, and winter-storage ponds. The latter are common in STPs in the grazing country of the Goulburn Valley, Victoria, where treated effluent is used to irrigate pastures from late spring to early autumn. In winter, when irrigation demand is low or non-existent, winter-storage ponds are a useful means of avoiding discharge to inland waters, which typically requires further (and costly) treatment. Winter-storage ponds have the same oxygenation status as maturation ponds but are typically larger ponds.

A review of waste-water treatment wetlands found little scientific evidence to guide the construction of such wetlands, especially WSPs, with waterbird conservation in mind (Murray and Hamilton 2010). For waterbird conservation, it is important to know which ponds are preferred as habitat for waterbirds.

Conversely, it is recognised that waterbirds that inhabit waste-water treatment wetlands are potential sources of pathogens (Murray and Hamilton 2010). For example, Pour (2012), studying the risks of using treated waste water from the Shepparton STP for the irrigation of lettuce, found that in winter (June–August) the concentrations of *Escherichia coli* were low relative to summer (December–February), even though summer waste-water flows were larger owing to the increased activity of fruit canneries that did not contribute to the concentration of *E. coli*. It was expected that the concentrations of *E. coli* would be diluted in summer and Pour (2012) hypothesised that the large population of waterbirds on the WSPs in summer contributed to the increased concentrations of *E. coli*. For this reason, there may be instances where managers of STPs may need to discourage birds, and understanding which ponds they use most frequently would help direct such decisions. An alternative hypothesis to that proposed by Pour (2012), however, is that the concentrations of *E. coli* are temperature dependent and that lower concentrations of *E. coli* in winter are common with or without the presence of birds.

The aim of this study is to determine which WSPs in the sewage-treatment system are preferred by which species or foraging guilds of waterbirds. This knowledge should assist managers of STPs to manipulate the ponds or construct systems with the dual purposes of the efficient operation of STPs and the conservation of waterbirds. To this end, we surveyed 18 STPs in the southern Murray–Darling Basin to determine differences in abundance, density and species richness of waterbirds and waterbird community composition between the different types of WSPs.

Methods

Study area

The study area was the Goulburn Valley, a regional area of rural Victoria, 178 km north of Melbourne (Fig. 1) and within the Murray–Darling Basin, the food bowl of Australia (Burge 2011). The Murray–Darling Basin is a critical region for Australia's waterbirds (Frith 1982) and an area where water resources have been under threat from the effects of agricultural irrigation (Kingsford 2000; Leslie 2001). We surveyed birds at 18 STPs throughout the Goulburn Valley in late July (mid-winter) 2012, a non-breeding period for waterbirds in south-eastern Australian.

The region was selected because the STPs within it are all managed by Goulburn Valley Water (GVW), whose management allowed us to visit their facilities. Access to the sites is restricted and admission is only possible with GVW staff in attendance. The security of the sites and limited human activity means that waterbirds present are rarely disturbed, providing a unique habitat for waterbirds.

In total, we surveyed 127 WSPs in the 18 STPs (Fig. 1, Table 1). Owing to low BOD or low flow-rate from the sewer, or both, the systems servicing many small towns omit anaerobic ponds and start treatment with a facultative WSP. Conversely, the three largest treatment plants (Shepparton, Mooroopna and Tatura), begin treatment with high-rate anaerobic lagoons (Wall *et al.* 2000). Such WSPs are covered and provide no habitat for waterbirds, and were thus excluded from the survey. The area and depth of each of the 127 WSPs were provided by Goulburn Valley Water (unpubl. data) are summarised for each of the five types of WSP in Table 2.

Waterbird surveys

The 18 STPs were grouped into three geographical strata (northern, central and southern; Fig. 1) to assist with sampling, so that each surveys of all the STPs within each stratum could be surveyed within 1 day. The three strata were surveyed in random order over 3 consecutive days, with each STP surveyed only once.

Waterbirds were counted at all WSPs at each STP surveyed. Waterbirds were identified to species, except for Australasian Grebes (*Tachybaptus novaehollandiae*) and Hoary-headed Grebes (*Poliocephalus poliocephalus*), which were combined (as 'grebes') because it was too difficult to identify them definitively owing to the large numbers present, often combined with large observation distances. The two grebes are combined in the diving foraging guild (Table 3) (Ropert-Coudert and Kato 2009). Surveys were conducted throughout the day, with all counts conducted either on foot or by car by the senior author, with the other authors tracking any movements of individuals or flocks and confirming identifications when required. Each WSP was surveyed only once at different times of the day. On each day, sampling started at *c.* 0900 hours (1.5 h after sunrise) and finished at *c.* 1700 hours (0.5 h before sunset). At each pond, we observed the entire shoreline and water surface with the aid of binoculars (Swarovski 8.5 × 40; Wattens, Austria). Birds on embankments between WSPs were considered to be on the pond closest to them. We have assumed that there was minimal diel variation in abundance (Hamilton 2004). We acknowledge that there may be diel movement of waterbirds between ponds (e.g. Mizutani

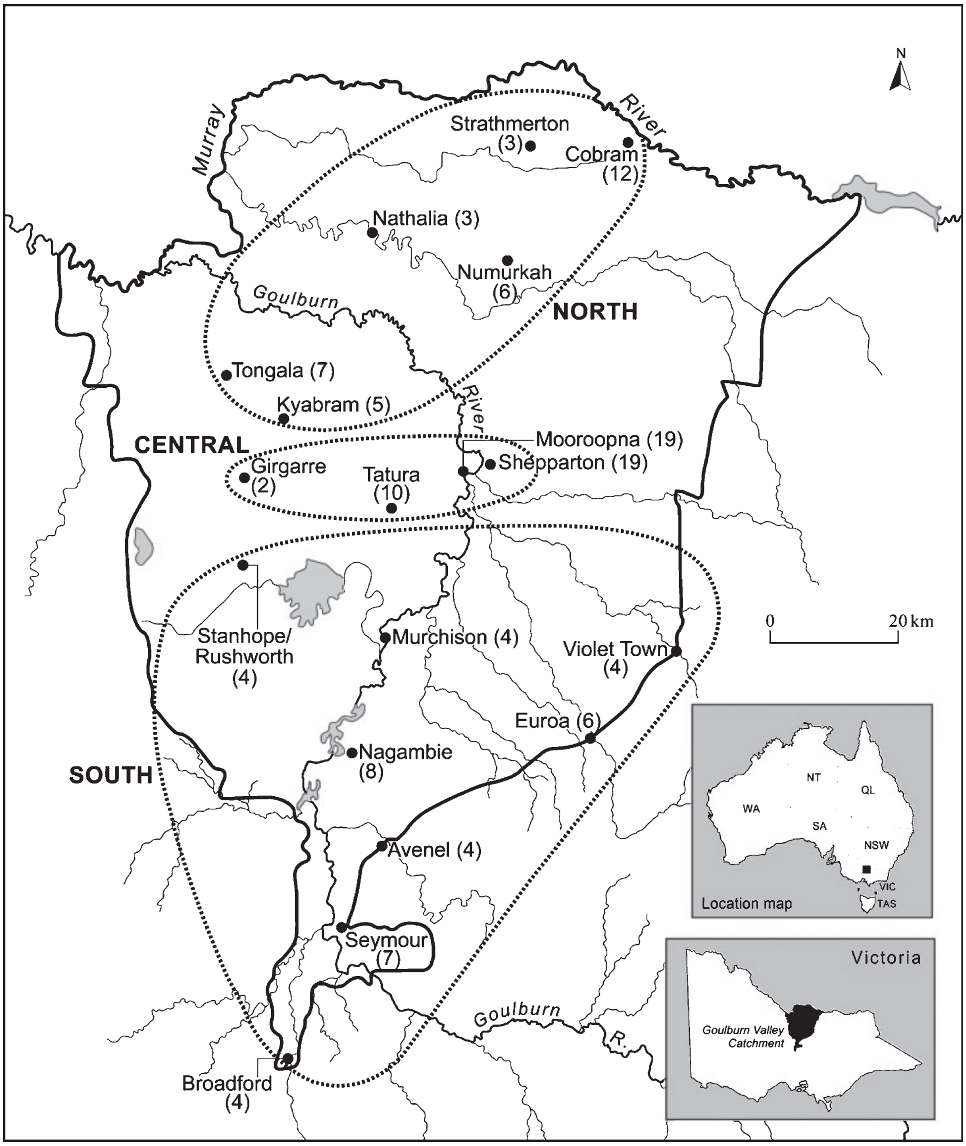


Fig. 1. Location of 18 sewage-treatment plants (STP) in the Goulburn Valley, located within three sampling strata (northern, central and southern). Numbers in parentheses indicate the number of waste-stabilisation ponds surveyed within each STP.

et al. 1990) but consider our single observation at each pond a 'snapshot' in time that is adequate for the comparative purposes of this study.

Analysis of data

Individual ponds of each type of WSP at each treatment plant are grouped together spatially. For this reason the statistical sampling unit for all analyses was WSP type within a specific treatment plant and not the individual ponds at a treatment plant. The individual ponds are effectively subsamples for each type of WSP at each STP. Thus, we had 53 sampling units across the five types of WSP (Table 1).

For both individual species and foraging guilds (Table 3), the effect of type of WSP on waterbird abundance and density (birds ha^{-1}) was analysed using linear mixed models, which employed restricted maximum likelihood (Patterson and Thompson 1971). Mixed models provide a more general procedure than analysis of variance (ANOVA) and reduce to ANOVA in simple balanced cases. In this case, the design was unbalanced because the number of WSPs surveyed varied between type of WSP and across strata. The fixed effect (equivalent to a treatment in ANOVA) of WSP type was tested using a Wald statistic (Buse 1982), which is analogous to the F statistic used to assess treatment effects in ANOVA. For the random effects model, which equates to a blocking model in ANOVA, STP was nested within stratum. The response variables, abundance and density, were $\log_{10}(x{+}1)$ transformed to improve normality and stabilise the variances; overall there was a significant effect of area on wetland type (Restricted Estimated Maximum Likelihood (REML), P

Table 1. Sewage treatment plants (STP) surveyed in the Goulburn Valley and the numbers of each type of waste-stabilisation pond at each
Values are the total number of interlinked ponds of each type of WSP. For the overall total under STP, values in brackets are the number of STPs each type of pond was recorded

STP	Anaerobic	Aerated	Facultative	Maturation	Winter-storage	Total number of ponds
Avenel			1	2	1	4
Broadford		2	2			4
Cobram	4		4	2	2	12
Euroa				5	1	6
Girgarre			2			2
Kyabram		1		2	2	5
Mooroopna		1	4	3	11	19
Murchison			2	2		4
Nagambie	2		1	4	1	8
Nathalia			2		1	3
Numurkah	2		2		2	6
Seymour			2	4	1	7
Shepparton		1	3	15		19
Rushworth			2	1	1	4
Strathmerton			1	1	1	3
Tatura		3	2	2	3	10
Tongala	2		1	2	2	7
Violet Town			1	2	1	4
Total number of ponds (number of STPs)	10 (4)	8 (5)	32 (16)	47 (14)	30 (14)	127 (53)

Table 2. Mean surface area and depth (±s.d.) of each type of waste-stabilisation ponds in STPs in the Goulburn Valley

Category	Surface area (ha)		Depth (m)	
	Mean (s.d.)	Range	Mean (s.d.)	Range
Anaerobic	1.06 (0.71)	0.45–2.49	1.27 (0.46)	0.8–1.96
Aerated	2.43 (3.18)	0.33–9.99	1.82 (0.75)	0.59–2.88
Facultative	2.74 (2.70)	0.38–11.14	1.89 (0.86)	0.8–3.61
Maturation	3.39 (3.07)	0.11–12.23	1.86 (0.87)	0.71–3.7
Winter storage	6.37 (4.66)	1.29–22.48	2.04 (1.82)	0.5–4.34

0.001), so area was not included in the design as a covariant. Fisher's least significance difference (l.s.d.) test (at $P = 0.05$) was used to make *post hoc* pairwise comparisons between means of fixed-effect levels (i.e. wetland types) for abundance and density analyses. All mixed model analyses were fitted using the statistical package Genstat V 11 (Lawes Agricultural Trust, Institute of Arable Crops Research (IACR)-Rothamsted).

The model was simplified in order to obtain convergence for several species in the abundance data. Block was removed from the abundance data for Grey Teal (*Anas gracilis*) and Pacific Black Duck (*Anas superciliosa*) and for the density data for grebes, Hardhead (*Aythya australis*) and the number of waterbirds per hectare. Negative variances were found, or convergence of the model did not occur, in those waterbird species or foraging guilds in which $\leq$10 birds were counted or where the waterbird was found on only one pond, and these species were eliminated from analyses of both abundance and density. Species excluded were Australian Pelican (*Pelecanus conspicillatus*; 14 birds, on only one pond), Australian White Ibis (*Threskiornis molucca*; 5 birds), Little Black Cormorant (*Phalacrocorax sulcirostris*; 4 birds), Australasian Darter (*Anhinga novaehollandiae*; 2 birds), Great Cormorant (*Phalacrocorax carbo*; 1 bird), Red-necked Avocet (*Recurvirostra novaehollandiae*; 1 bird) and White-faced Heron (*Egretta novaehollandiae*; 1 bird). The foraging guild of long-legged wading birds (6 individuals) was also eliminated.

Permutational multivariate analysis of variance (PERMANOVA) (Anderson 2001; Anderson *et al*. 2008) was used to test the effect of type of WSP on the composition of waterfowl communities, on the basis of abundance and density. The full model followed that used in the univariate analysis and included WSP type (fixed factor), stratum (random factor) and STP (random factor). Significance testing of the Bray–Curtis similarity measures ($\log_{10}(x+1)$ transformed) and *post hoc* comparisons (at $P = 0.05$) were made using 9999 permutations. Permuted residuals were calculated under a reduced model, and Type III sums of squares were used because the design was unbalanced (Anderson *et al*. 2008). Where differences were significant, a SIMPER test (Clarke 1993) was used to determine the waterbird species that contributed most to dissimilarity in the composition of waterbird communities among WSPs types. Principal coordinates ordination (PCO; Gower 1966) of distances between centroids was used to visualise the output of the PERMANOVA model (Anderson *et al*. 2008). All multivariate analyses were performed with PRIMER (V6.1.15) and PERMANOVA+ (V1.0.5) (PRIMER-E, Plymouth, UK).

Results

Abundance, density and species richness

Overall, across all 18 STPs, the mean abundance of waterbirds at each STP was 566 individuals and mean density at each STP 23.6 birds ha^{-1}, with a overall mean species richness at each STP of 7.6 species and a species density of 0.8 species ha^{-1} (Table 4).

The total abundance, density and species richness of waterbirds varied significantly between types of WSP (Table 5). Waterbird abundance and species richness generally increased progressively through the treatment system, with

Table 3. Foraging groupings of 14 species of waterbirds detected on the 18 STPs in the Goulburn Valley based on their foraging behaviour

'Grebes' are Hoary-headed and Australasian Grebes combined; species eliminated from the species-level analyses owing to low numbers are in parentheses; scientific names of other species are listed in Table 5

Functional grouping	Shorebirds (Charadriiformes)	Long-legged wading birds	Swamphens and coot (Rallidae)	Pursuit predators	Waterfowl and grebes			
					Diving	Dabbling	Filtering	Herbivorous
General behaviour	Wade in shallow water	Can wade in deeper water and often forage in moist grasslands. Stalk–wait–attack predators	Spend most of their time on land among tall grasses and sedges	Active vertebrate predators (may also feed on invertebrates, but not exclusively)	Usually spend much of their time on or in the water (especially when feeding) or grazing on adjacent vegetation			
Species	Masked Lapwing	White-faced Heron	Eurasian Coot	Silver Gull	Hardhead	Pacific Black Duck	Pink-eared Duck	Australian Wood Duck
				(Australian Pelican (*Pelecanus conspicillatus*))				
	(Red-necked Avocet (*Recurvirostra novaehollandiae*))	(Australian White Ibis (*Threskiornis molucca*))		(Australasian Darter (*Anhinga novaehollandiae*))	Musk Duck	Grey Teal	Australasian Shoveler	Australian Shelduck
				(Little Black Cormorant (*Phalacrocorax sulcirostris*))	Grebes	Chestnut Teal		Black Swan
				(Great Cormorant (*Phalacrocorax carbo*))				

Table 4. Abundance, density and species richness of waterbirds at 18 sewage-treatment plants (STP) in the Goulburn Valley

STP	Total abundance (number of birds)	Density (birds ha^{-1})	Number of species	Density of species (species ha^{-1})	Wetland area (ha)
Avenel	98	38.1	5	2.0	2.6
Broadford	408	39.2	6	0.6	10.4
Cobram	703	19.7	12	0.3	35.8
Euroa	211	21.8	9	0.9	9.7
Girgarre	6	4.9	1	0.8	1.2
Kyabram	570	19.7	10	0.4	28.8
Mooroopna	2531	50.6	14	0.3	50.0
Murchison	65	44.8	4	2.8	1.4
Nagambie	276	33.0	9	1.1	8.3
Nathalia	113	20.7	6	0.3	5.5
Numurkah	556	23.7	9	0.4	23.4
Seymour	343	13.4	8	0.3	25.6
Shepparton	1814	13.0	14	0.1	139.4
Rushworth	354	58.1	4	0.5	7.4
Strathmerton	73	31.6	4	1.7	2.3
Tatura	1740	28.2	10	0.2	61.8
Tongala	113	7.5	6	0.4	15.1
Violet Town	210	61.0	7	2.0	3.4
Overall mean (s.d.)	566 (716)	23.6 (16.6)	7.6 (4)	0.8 (0.8)	24.0 (33.7)

values in winter-storage and maturation ponds significantly greater than in anaerobic and aerated ponds, and with similar trends for waterbird density (Table 5). Facultative ponds also supported a greater abundance and density of waterbirds than anaerobic ponds (Table 5). There were no significant differences in density of species (species ha^{-1}) among WSP types (Table 5).

Significant differences in abundance and density of individual waterbird species and foraging guilds among types of types was limited to grebes, Hardhead and diving waterfowl (Table 5). With the exception of abundance in winter-storage ponds, maturation ponds supported a greater abundance and density of grebes than all other types of WSP (Table 5). Abundance and density of Hardhead in winter-storage and maturation ponds were significantly greater than in anaerobic and aerated ponds, with also significantly greater abundance and density in winter-storage ponds relative to facultative ponds (Table 5). The abundance and density of diving waterfowl on winter-storage ponds and maturation ponds was significantly greater than in anaerobic and aerated ponds (Table 5).

Community structure

PERMANOVA indicated that the composition of waterbird communities differed significantly among types of WSP, both in terms of waterbird abundance ($P = 0.0134$) and density ($P = 0.0097$). Pairwise comparisons revealed that the abundance and density of waterbird communities differed significantly between maturation ponds and anaerobic ponds ($P < 0.001$) and also between winter-storage and anaerobic ponds ($P < 0.01$). These differences were clearly evident in the distribution of samples across the first two axes of the PCO that respectively explained 93 and 94% of the total variance for waterbird abundance (Fig. 2*a*) and density (Fig. 2*b*). The PCO also demonstrated that the composition of waterbird communities within anaerobic ponds differed most from all other WSPs, and those of the winter storage and maturation ponds the most similar(Fig. 2*a*, *b*).

SIMPER analysis indicated that for both abundance and density data, Grey Teal, grebes and Hardhead made the greatest contributions to dissimilarity between maturation ponds and anaerobic ponds (combined dissimilarity 66–72%) and winter-storage and anaerobic ponds (58–63%).

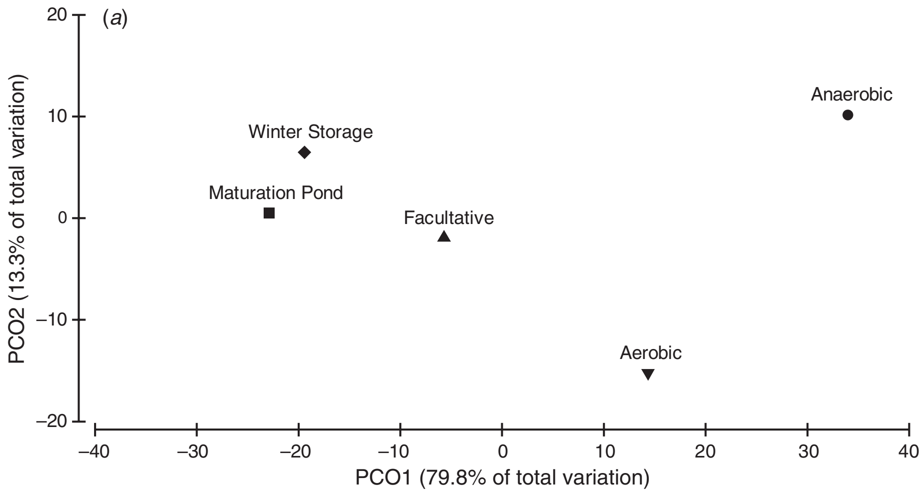
Discussion

A recent analysis of the use of five different wetland types by waterfowl (Anatidae plus grebes (Podicipedidae) and the Eurasian Coot *Fulica atra* (Rallidae)) over a 22-year period across the state of Victoria found that WSPs supported greater numbers of individuals and greater density of species than all other types of wetland (deep marsh, open water, permanent saline, semi-permanent saline) (Murray *et al*. 2012). In this study of the Goulburn Valley STPs, waterbird abundance, density and species richness tended to be greatest in those ponds further through the treatment system, a finding consistent with the results of a previous study of a single STP, which found a positive correlation between the waterbird and invertebrate communities, with the greatest density and richness of invertebrates towards the end of the treatment system (Hamilton *et al*. 2005). Hamilton *et al*. (2005) suggested that this correlation implied that a diverse and abundant planktonic invertebrate community generally represents the type of pond ecosystem likely to support a high abundance and diversity of waterbirds. Hamilton *et al*. (2005) also found that the abundance of Hoary-headed Grebes tended to increase along a continuum of sewage-treatment stage. In this present study, we found that the abundance of grebes, Hardhead and diving waterfowl, tended to increase along a continuum of stage of treatment. These waterbirds also clearly preferred WSPs further through the treatment system where the preferred foods of Australasian Grebes (fish, snails and arthropods; Marchant and Higgins 1990) and

Table 5. Mean abundance (number of birds) and, in parentheses, mean density (birds ha^{-1}) of 14 species of waterbirds and six foraging guilds in different types of waste-stabilisation ponds (WSPs) at sewage-treatment plants in the Goulburn Valley

Means are back transformations of means generated from the REML analyses on $\log_{10}(x+1)$ data (see Methods); within rows (separately for abundance and density), values followed by different letters are significantly different; *P* value is test of the null hypothesis of equal means. 'Grebes' are Hoary-headed and Australasian Grebes combined

Waterbird species	Scientific name	Type of WSP					*P*
		Anaerobic	Aerated	Facultative	Maturation	Winter-storage	
Grebes	–	0^{A} (0^{A})	0.26^{A} (0.17^{A})	4.06^{AB} (1.69^{A})	17.62^{C} (5.52^{B})	8.75^{BC} (2.61^{A})	0.007 (<0.001)
Black Swan	*Cygnus atratus*	0.11 (0)	0 (0)	0.1 (0.01)	0.32 (0.04)	0.49 (0.03)	0.226 (0.696)
Australian Shelduck	*Tadorna tadornoides*	0.49 (0.34)	0 (0)	0.66 (0.14)	0.55 (0.13)	0.49 (0.1)	0.596 (0.573)
Pacific Black Duck	*Anas superciliosa*	0 (0)	0 (0)	0 (0.1)	0.17 (0.11)	0.35 (0.04)	0.253 (0.470)
Grey Teal	*Anas gracilis*	0.73 (0.99)	3.55 (1.6)	16.5 (5)	22.44 (7.38)	17.84 (3.72)	0.099 (0.284)
Chestnut Teal	*Anas castanea*	0.24 (0.02)	0.24 (0.25)	0.32 (0.09)	0.8 (0.12)	0.81 (0.15)	0.621 (0.797)
Australasian Shoveler	*Anas rhynchotis*	0.1 (0)	0.11 (0)	0.14 (0.03)	0.42 (0.04)	0.79 (0.11)	0.239 (0.331)
Pink-eared Duck	*Malacorhynchus membranaceus*	0.05 (0)	0 (0)	0.9 (0.34)	1.12 (0.31)	2.52 (1.49)	0.382 (0.769)
Hardhead	*Aythya australis*	0^{A} (0^{A})	0.07^{A} (0.1^{A})	5.28^{AB} (1.87^{AB})	9.09^{BC} (2.83^{BC})	32.5^{C} (5.67^{C})	<0.001 (0.002)
Australian Wood Duck	*Chenonetta jubata*	0.84 (0.6)	0 (0)	0.31 (1)	0.33 (1.57)	1.34 (0.25)	0.062 (0.274)
Masked Lapwing	*Vanellus miles*	0.02 (0.15)	0.11 (0)	0.12 (0.02)	0.12 (0.13)	0.29 (0.07)	0.124 (0.518)
Silver Gull	*Chroicocephalus novaehollandiae*	0.17 (0.2)	0.32 (0.14)	0.22 (0.02)	0 (0)	0.08 (0)	0.575 (0.068)
Musk Duck	*Biziura lobata*	0.02 (0.01)	0.1 (0.02)	0.09 (0.01)	0.45 (0.042)	0.45 (0.088)	0.660 (0.472)
Eurasian Coot	*Fulica atra*	0.25 (0.14)	1.06 (0.62)	1.44 (0.66)	1.00 (0.43)	1.45 (0.21)	0.902 (0.741)
Foraging guild							
Shorebirds		0.41 (0.15)	0 (0)	0.12 (0.02)	0.7 (0.12)	0 (0.07)	0.23 (0.49)
Pursuit predators		0.2 (0.2)	0.3 (0.15)2	0.29 (0.07)	0.05 (0.07)	0.58 (0.02)	0.48 (0.71)
Diving waterfowl		0^{A} (0^{A})	1.11^{AB} (0.30^{A})	9.92^{BC} (3.91^{B})	28.99^{CD} (9.44^{C})	49.36^{D} (8.54^{BC})	<0.001 (<0.001)
Dabbling waterfowl		0.73 (0.77)	3.96 (1.46)	16.75 (6.04)	23.60 (7.84)	18.30 (3.81)	0.104 (0.223)
Filtering waterfowl		0.1 (0)	0 (0)	0.91 (0.35)	1.45 (0.35)	3.27 (0.62)	0.24 (0.64)
Herbivorous waterfowl		1.14 (0.58)	0 (0)	0.91 (1.2)	1.04 (0.23)	2.24 (0.38)	0.11 (0.41)
Total waterbird abundance		2.69^{A}	7.00^{B}	36.07^{BC}	87.51^{C}	90.62^{C}	0.008
Waterbird density (birds ha^{-1})		1.77^{A}	2.77^{AB}	12.96^{BC}	28.79^{C}	15.18^{C}	0.006
Number of species		0.97^{A}	1.73^{A}	2.76^{AB}	4.51^{B}	4.58^{B}	0.017
Species density (species ha^{-1})		0.64	0.8	0.96	1.82	0.82	0.127
Total number of birds		24	80	2251	3210	4619	10184



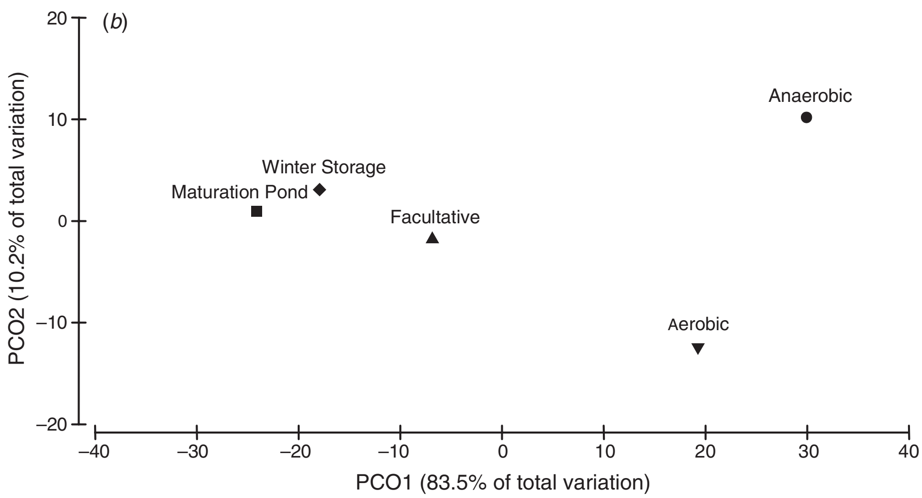


Fig. 2. Principal coordinates ordination (PCO) of distances among centroids showing differences in waterbird communities in Victoria with type of waste-stabilisation pond (WSP): (*a*) abundance (number of birds per WSP regardless of its size) and (*b*) density (number of birds ha^{-1}).

Hoary-headed Grebes (predominantly invertebrates; Ropert-Coudert and Kato 2009) are more likely to occur. It should also be noted that because of the large number of ponds and treatment facilities surveyed in our study, we did not have time to quantify how the birds were using the ponds, but our informal observations of the birds seen on the anaerobic ponds suggested that they were using them as resting rather than feeding habitat, whereas much feeding was observed on all the other pond types.

In the earlier study of Murray *et al*. (2012), analysing a 22-year database derived from the Victorian Summer Waterfowl Count (for details, see Murray *et al*. 2012), WSPs supported a mean density of 22 birds ha^{-1} and species density of 0.5 species ha^{-1}, compared with 3–5 birds ha^{-1}and 0.06–0.10 species ha^{-1}for other wetland types. In the present study, we found the 127 WSPs at 18 STPs supported a mean density of 23.6 birds ha^{-1} and a species density of 0.8 species ha^{-1}, strikingly similar to the values obtained by Murray *et al*. (2012) from fewer STPs ($n = 8$) but over a much longer period (Murray *et al*. 2012). Interestingly, stormwater-treatment ponds surveyed in an urban environment (Murray *et al*. 2013) supported high densities similar to those of the WSPs (23.4 birds ha^{-1} and 3.8 species ha^{-1}). Likewise, the densities on urban lakes (14.3 birds ha^{-1} and 3.0 species ha^{-1} (Murray *et al*. 2013) were also high and more similar to those on WSPs than the other, generally more natural, wetlands in the long-term study across Victoria (Murray *et al*. 2012). It is also of interest that for the Tatura STP, the total number of waterbirds counted (1740 birds) found on the single survey date in this study, approximates the waterfowl abundance for that site derived from the 22-year study (mean abundance 1101 ± s.d. 935), but of course this could merely be a coincidence. These findings confirm the consistency and importance of WSPs as non-breeding habitat for waterbirds.

There is a movement in Europe and elsewhere in the developed world towards the replacement of WSPs with activated sludge plants and other more intensive treatment systems, and it is unfortunate, from a conservation perspective, that government regulation may reduce the valuable waterbird habitat that WSPs constitute. In Europe, a law regulating urban waste-water treatment (*COUNCIL DIRECTIVE* of 21 May 1991 concerning urban waste water treatment (91/271/EEC) (OJ L 135, 30.5.1991, p. 40; see http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1991L0271:20081211:EN:PDF, accessed 2 August 2013) has been established 'to protect the environment from the adverse effects of urban waste water discharges and discharges from certain industrial sectors (see Annex 3 of the Directive).' This law prevents the use of open sewage fields for towns with a population exceeding 15 000 people after 2015 for new accession countries, and 15 years earlier, i.e. 2000, for other members of the European Community. However, the Urban Waste Water Treatment Directive does not explicitly prohibit the use of WSPs, because member states are required to ensure that waste-water treatment facilities are provided, particularly in sensitive areas such as freshwater bodies and coastal areas. In Australia there is no legal, or impending legal, impediment to WSPs but a disincentive to their use is that they require large areas of land and land is expensive. If the land was cheap and available this would be the preferred treatment method. However, within urban growth regions, demand for land is high and so STPs with a smaller footprint, such as activated sludge plants or other biological reactors, are preferred (Tsagarakis *et al*. 2003).

Within the Murray–Darling Basin, WSPs provide a permanent waterbird habitat that has been particularly important as a refuge in times of drought (Murray *et al*. 2012). However, after the Commonwealth *Water Act* 2007 was enacted, which created the Murray–Darling Basin Authority (http://www.mdba.gov.au/, accessed 2 August 2013), environmental flows have taken precedence over agricultural water requirements so that WSPs may become less critical for waterbirds. Conservation considerations must be part of any regulatory process, and water management practices at STPs that mitigate the effects of STP modernisation should be mandated to maintain the established role of WSPs for waterbirds. STP design engineers enjoy a measure of flexibility such that they can provide more maturation ponds, but environmental needs must be measured against the water demands for irrigated agriculture.

There are, however, management costs associated with releasing treated waste water to grazing paddocks or for the irrigation of crops. The gradual accumulation of salts in the soil, as well as degradation of soil structure related to sodicity, are of particular concern in many waste-water irrigation schemes (Hamilton *et al*. 2007), particularly on the heavy soils found in much of south-eastern Australia (Bond 1998; Muyen *et al*. 2011). Indeed, such problems have required management at STPs considered here, such as at Shepparton (Surapaneni and Olsson 2002). For this reason it may be more cost effective to retain some of the water in winter-storage ponds over summer so that they become in effect summer-storage ponds or ponds for conservation purposes. It is also expensive to treat waste water to a stage where it can be released into inland rivers (Pour 2012) and, if the economic argument can be made, it may be more cost effective to construct several conservation ponds and that will have benefits for the environment and consequently for waterbird conservation.

In the past, many of the STPs in the Goulburn Valley disposed of excess water through the use of evaporation basins, and anecdotal evidence from STP managers suggests that these basins were well used by waterbirds. With the environmental and regulatory push to increase water recycling (mostly pasture irrigation; Boland *et al*. 2006), such evaporation basins are no longer used at most STPs. However, at Murchison STP, the only plant surveyed where evaporation basins are still used, we observed several species that were not recorded at other STPs Brolga (*Grus rubicundus*; 2 birds), Purple Swamphen (*Porphyrio porphyrio*; 88) and Little Pied Cormorant (*Phalacrocorax melanoleucos*; 1). This supports the potential of evaporation basins for waterbird conservation, which is not surprising as the more gently sloping edges of evaporation ponds, compared with WSPs, would be more likely to be used by wading species. For example, White-faced Herons prefer to forage in open areas over soft to firm substrates and shallow water (Lowe 1983) and WSPs would be too deep for foraging whereas evaporation basins provide a more favourable foraging habitat (Powell 1987; White and Main 2005). Of course, salts would gradually concentrate in such evaporation ponds over time, which would lead to changes in pond ecology, to the advantage of some species but not others. This could be managed to a degree by periodic flushing or harvesting of salt.

Little waterbird breeding occurs on WSPs but evaporation basins might provide a useful substitute for the breeding habitat of ephemeral wetlands (Taylor 2008; Harrison *et al*. 2010). In Victoria, approximately one-third of the natural wetlands of the state have been lost through drainage since 1835 (Corrick and Norman 1980; Corrick 1981, 1982; State of the Environment Advisory Council 1996). Floods have also diminished as a result of water regulation and, as they are a requirement for breeding for the many species of Australian waterfowl that are known to breed on receding waters (Frith 1982), water regulation has also adversely affected waterbird populations (Briggs *et al*. 1994; Kingsford and Johnson 1998; Kingsford 2000; Leslie 2001). The ability to regulate water flows to evaporation basins to simulate floods may provide a significant benefit for breeding populations of some species of waterbirds and warrants further investigation.

Large congregations of waterbirds have the potential to affect the nutrient budgets of WSPs. However, whereas there is a wealth of literature demonstrating nutrient contribution of birds to lakes (Portnoy 1990; Manny *et al*. 1994; Marion *et al*. 1994; McKinnon and Mitchell 1994; Scherer *et al*. 1995; Post *et al*. 1998), no such studies have been conducted on WSP systems. WSPs are clearly different to lakes, not only in terms of typical nutrient concentrations and size, but with respect to the typically much higher densities of birds they support (Murray *et al*. 2012). The role of waterbirds in nutrient import and export warrants investigation, particularly because the potential exists for negative or positive effects on the sewage-treatment process. To date, the only study relating to municipal sewage treatment was of a constructed wetland, where birds were found to make a negligible contribution to levels of nitrogen and phosphorus, and certainly not enough to compromise the treatment objectives (Andersen *et al*. 2003).

Conclusions

Natural wetlands are being lost as a result of the increase in human population and, if waterbirds are to maintain their place in the ecosystem, alternative wetlands must be found. WSPs provide a viable alternative and this paper suggests possible pathways for optimising this valuable habitat resource. Providing environmental water to maximise the size of WSPs at the end of the treatment chain (maturation and winter-storage ponds), within the constraints of appropriate STP engineering, will provide further benefits for waterbirds, particularly for diving waterbirds. This paper provides a basis for the conservation argument for the use of environmental water for STPs.

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