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Waterbird use of artificial wetlands in an Australian urban landscape

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Running Head: Artificial wetland use by waterbirds

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Abstract

With the loss of natural wetlands, artificial wetlands are becoming increasingly important as habitat for waterbirds. We investigated the relationships between waterbirds and various biophysical parameters on artificial wetlands in an Australian urban valley. The densities (birds per hectare) of several species were correlated (mostly positively) with wetland area, and correlations were observed between certain species and other physical and water chemistry variables. Waterbird community structure, based on both abundance (birds per wetland) and density data, was most consistently positively correlated with the relative amount of wetland perimeter that was vegetated, surface area, distance to nearest wetland, public accessibility, and shoreline irregularity. We also compared the relative use of the two types of urban wetlands, namely urban lakes and stormwater treatment wetlands, and found for both abundance and density that the number of individuals and species did not vary significantly between wetland types but that significant differences were observed for particular species and feeding guilds, with no species or guild being more abundant or found in greater density on an urban lake than a stormwater treatment wetland. Designing wetlands to provide a diversity of habitat will benefit most species.

Introduction

It has been widely acknowledged that there has been a decrease in the area of wetlands as a direct result of the increase in the human population, with this decrease largely being driven by dry land requirements for agriculture but also urbanisation, such that roughly half the world's natural wetlands have disappeared (Russi et al. 2013). In south-eastern Australia there has been a significant loss of wetlands since European settlement, with about one third of natural wetlands being lost through drainage since 1835 in the state of Victoria (Corrick and Norman 1980). Many species of Australian waterfowl use permanent coastal wetlands as non-breeding refuges during summer, when inland wetlands dry out (Loyn et al. 1994; Kingsford and Norman 2002).

The construction of artificial wetlands in the urban environment, usually for either stormwater treatment or public amenity, can be expected to become increasingly important for waterbirds as natural wetlands decline (Zedler 2000). Stormwater treatment systems (SWTSs) are used as a means of decreasing nutrient transport through denitrification and sedimentation of phosphorous-rich particles (Craft 1997), and urban amenity lakes (henceforth urban lakes) are primarily installed for aesthetics and public recreation. However, both have also been well documented to provide significant waterbird habitat and this consideration is increasingly being used in the design process (Zedler 2000).

The factors making an artificial wetland suitable for waterbirds are varied (Halse et al. 1993). Wetland size, connectivity, susceptibility to disturbance, accessibility to food within the wetland, and the presence of both emergent and adjacent vegetation are all known to affect wetland use by waterbirds. Waterbird richness and abundance are influenced by wetland size (Froneman et al. 2001; Sanchez-Zapata et al. 2005). Connectivity of complementary wetlands within a mosaic can provide the means to reduce disturbance and provide the resources required by diverse waterbird assemblages (Kelly et al. 2008), and the amount and composition of food can affect the use of foraging habits by waterbirds (Taft and Haig 2005; Hartke et al. 2009). Vegetation is important as a food source for waterbirds and provides food for their invertebrate prey. Vegetation also provides roosting and nesting habitat for many species and may decrease human disturbance by reducing accessibility to the wetlands and by buffering noise (Hattori and Mae 2001; Sanchez-Zapata et al. 2005). Sediment and water quality can also affect the use of wetlands by waterbirds. For example, organic matter content in water affects plant growth, which in turn influences invertebrate abundance (Rehfisch 1994), and dissolved oxygen concentration can indirectly affect the foraging of waterbirds by influencing the vertical distribution of prey (Kersten et al. 1991).

Communities and governments face many challenges reconciling the need for urban development with the need to conserve wetland biodiversity. Artificial wetlands are useful for waterbird conservation (Froneman et al. 2001; Ma et al. 2010; Navedo et al. 2012), although it is recognised that they are generally not the functional equivalents of natural wetlands (Campbell et al. 2002). One positive feature of artificial wetlands is that they may be amenable to explicit management to benefit waterbirds or other elements that are valued by the human community. To date there has been little evaluation of environmental variables that may need to be managed to enhance the value of artificial wetlands for waterbirds in south-eastern Australia.

Using an urban valley in south-eastern Australia as a case study, this paper aims to assess for waterbird species, guilds, and communities, (i) the relationships with physical, chemical, and biological characteristics of urban wetlands, and (ii) the relative importance of two wetland types, namely, urban lakes and SWTSs.

Methods

Study area

The study area was the Lower Dandenong Valley (Fig. 1), an area of approximately 20 × 30 km in the outer south-eastern suburbs of Melbourne (population 4 million), in the state of Victoria. This area was selected as it offers the largest number and variety of potential wetlands in the vicinity of Melbourne, including urban lakes and SWTSs. Waterbird abundance was determined at 53 separate waterbodies in 31 wetland systems in October 2009, March 2010, October 2010 and March 2011. All samples for water chemistry and phytoplankton analysis and measurements of physical characteristics were obtained from these wetland systems in March 2010.

Study design

Six SWTSs, comprising a total of 28 individual ponds and 25 urban lakes, were surveyed (Table 1). The mean area of urban lakes was 3.3 ha and SWTS ponds 0.5 ha; Appendix A. To aid sampling, the 31 wetlands were grouped into three geographic blocks (E, N, W), each comprising two contiguous strata (A,

B) with similar numbers and types of wetlands, as far as possible (Fig. 1; Table 1). The rationale for this grouping was to ensure that each block could be surveyed within a day. During each survey period all sites within one block were visited in a day. Within each block, the survey order of strata was randomised by toss of a coin.

The survey times were selected to coincide with periods of contrasting waterbird distribution. March coincides with late summer when breeding by waterbirds is at its annual minimum (Loyn 1989; Murray et al. 2012) and waterbirds are most in need of refuges. October is the breeding season for many species. During each survey counts were taken at all wetland sites over the two-week sampling period.

All of the SWTSs were surface-flow constructed wetlands, which are intended to mimic natural marshes by passing water through macrophytes over a short distance (< 25 m) between the individual ponds (Scholz and Lee 2005).

Waterbird surveys

All surveys were conducted on foot by the senior author. The time of day chosen for survey of a particular wetland varied between the four sampling periods. The assumption was made that birds seen on the wetland were using the resource and that there was minimal diel variation (Hamilton et al. 2002; Hamilton et al. 2004). The overarching approach was to observe the entire perimeter of the wetland and the entire water surface with observations conducted with the aid of binoculars (8.5 × 40°). Counts were made from one or several points (depending on visibility and wetland size and shape) with each field of view being maintained for 3 minutes to allow ample time for diving birds to surface, and no attempt was made to flush birds from vegetation.

Water sampling (phytoplankton and chemical properties)

Five random sub-samples were collected from each pond using a 2-L bucket fixed to a 3-m stick and combined into one composite sample representing the pond. Phytoplankton genera were enumerated under light microscopy, with sample storage and concentration techniques in accordance with APHA et al. (2005). Likewise, the following chemical parameters were determined using standard methods approved by APHA et al. (2005): NO_3^--N, NH_4^+-N, oxidised nitrogen-N, Kjeldahl N and PO_4^{3-}, total P (TP), chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD), sulphide, pH, electrical conductivity

(EC), dissolved organic carbon (DOC), turbidity, Hg, Zn, Cd, Pb, B, Cd Cu, and chlorophyll *a* (CHLA). Also, the following suite of 20 organochlorine compounds was analysed using either gas or mass spectrophotometry: BHC (Beta isomer), BHC (delta isomer), chlordane, *cis*-chlordane, trans chlordane, 44-DDD, 44-DDE, 44-DDT, dieldren, endosulphan I, endosulphan sulphate, endrin aldehyde, endrin, endrin ketone, endosulphan II, hexachlorobenzine, heptachlor epoxide, heptachlor, lindane, and methoxychlor.

Physical characteristics

Eight habitat variables were determined for each waterbody: perimeter and surface area (using GIS), shoreline irregularity (ratio of the perimeter of the wetland to the perimeter of a circle of the same area), littoral angle (Powell 1987), and the extent of buffer zone, vegetated perimeter, emergent vegetation, and mown grass. The last four habitat variables were measured using a six-step Likert scale (0–5), with values being the means of the estimates made by three observers. A buffer zone was considered to be present when there was at least 50 m of vegetation from the wetland edge and the presence of the buffer zone was calculated so that 0 = no buffer zone of substantial shrubs and trees and 5 = wetland completely surrounded by such a buffer zone. A vegetated perimeter was considered to be present when shrubs or trees lined the wetland perimeter (to a thickness greater than 1 m) and was calculated where 0 = no woody vegetation around the perimeter of the waterbody and 5 = wetland completely surrounded by woody vegetation. Emergent vegetation on the wetland was calculated where 0 = no coverage of the water by emergent vegetation and 5 = complete cover of the water. Mown grass was considered present when the perimeter of shoreline was abutted by more than 5 m of mown grass and was estimated as 0 = no mown grass abutting shoreline and 5 = a wetland completely surrounded by a mown grass border of greater than 5 m width.

For each wetland system two connectivity variables were calculated: the distance (km) to the nearest wetland and the number of wetlands within a 1 km radius.

Three potential disturbance variables were estimated. The first was the ‘waterbird security’, the maximum distance a bird can retreat from the presence of a disturbance factor, such as people on the shoreline, without leaving the waterbody. Likert scales were used to quantify the disturbance variables ‘urban encroachment’ and ‘access’. Urban encroachment was present when a pond had housing within 100 m and roads within 50 m and was assessed so that 0 = no housing within 100 m and no roads within 50 m of a wetland and 5 = a wetland completely surrounded by housing and roads. Access was considered to be present where the shoreline could be easily reached by prams and bicycles so that 0 = a wetland shoreline completely inaccessible to prams and bicycles and 5 = easily accessible to prams and bicycles.

Catchment area characteristics were measured to establish whether waterbirds' use of wetlands was affected by potentially increased levels of pollutants that may be associated with water run-off (Walsh et al. 2005). Catchment boundaries were calculated from a digital elevation model, and this model was used to determine catchment area (km^2). Total connected impervious layer (TI) is defined as the proportion of a catchment covered by surfaces impermeable to water (Walsh et al. 2005) and was calculated using maps of impervious surfaces attributed with distances to stormwater drains (source: Melbourne Water corporation, see Walsh and Kunapo 2009). TI was then used to calculate the first catchment variable, ratio of wetland area to the total connected impervious area times the wetland area ($W_{A/TIA}$). This index represents the capacity of a wetland to treat stormwater, and is considered more generally as a useful measure of the ability of a wetland to manage pollution (Danger and Walsh 2008). The ($W_{A/TCA}$), the second catchment variable, the ratio of wetland area to total catchment area is an index of the capacity of the wetland to treat all catchment runoff, including stormwater. These two variables, $W_{A/TIA}$ and $W_{A/TCA,}$ were determined for 47 waterbodies for which catchments were clearly defined. Catchment variables were not applicable to one SWTS (comprising 3 waterbodies), two of the urban lakes, where the water source was treated water from the nearby sewage treatment plant (the Eastern Treatment Plant) and one other urban lake.

Data Analysis

Pairwise correlations between waterbird abundance and density and all of the physical and water chemistry characteristics were calculated using Spearman's rank correlation coefficient (ρ). The dataset for the species and guilds comprised the mean densities of waterbirds across all four sampling occasions, with individual ponds (n = 53) being the sampling units. If a waterbird species or guild was observed on fewer than five wetlands that species was eliminated from the analysis. When multiple hypotheses are tested, as was the case here, there are arguments both for and against making an adjustment to the significance level for the Type-I error rate. To this end, in addition to reporting un-adjusted probabilities ($P \leq 0.05$ and $P \leq 0.01$), we report the Dunn-Šidák-corrected P value (Ury 1976). However, the strength of the correlations is plainly of greater concern here than the P values.

At a community level, which includes all waterbird species, we investigated relationships in March 2010 with physical characteristics and water chemistry parameters using the BIOENV procedure in PRIMER (Clarke and Ainsworth 1993) and the Spearman rank correlation coefficient with a maximum number of variables per solution of ≤ 10. Both waterbird abundance and density data were used. Water chemistry variables were normalised by $\log_{10}$ transformation prior to calculation of Euclidean distance matrices and the following variables excluded due to highly significant ($P < 0.001$) inter-correlations ($r > 0.8$): DOC (with BOD), NO_X (with NO_3^--N), PO_4^{3-} (with total P), TDS (with EC) and Kjeldahl N (with CHLA). Hg, Pb, Cd, total S and all pesticides were removed as they were below detection limits. Thus, chemical variables for analysis included BOD, CHLA, COD, EC, Zn, Cu, TP, B, NH_4^+-N, NO_2^--N, NO_3^--N, pH (as $[H^+]$), and turbidity. Physical characteristics were also normalised prior to calculation of Euclidean distance matrices. Wetland perimeter was excluded from analysis as it was highly correlated with wetland area ($r = 0.98$; $P < 0.0001$). Thus, physical characteristics for analysis included wetland size, shoreline irregularity index, littoral angle, buffer zone, vegetated perimeter, emergent vegetation, mown grass, distance to the nearest wetland (within 1 km), number of wetlands within 1 km, waterbird security distance, urban encroachment, access, $W_{A/TCA}$ and $W_{A/TIA}$. Shoreline irregularity index, littoral angle and catchment area were $\log_{10}(x + 1)$-transformed and wetland size, security distance, proximity to nearest wetland were square root transformed prior to analysis. Statistical significance of the BIOENV results was tested using the global BIOENV match permutation test (using 999 permutations). Relationships between waterbird community composition (based on both abundance and density) and phytoplankton community composition were examined with the RELATE procedure of PRIMER (Clarke and Gorley 2006) using the Spearman rank correlation coefficient. Statistical significance of the RELATE results was tested using the global RELATE match permutation test (9999 permutations).

The question of whether the abundance and density of individual species of waterbirds or functional groups of waterbirds (based on foraging activities; Table 2) differed between urban lakes and SWTSs was addressed through an analysis of the 31 wetland systems. That is, in this context the individual waterbodies within a stormwater treatment system were subsamples of a complete system, and thus counts from all ponds within a system were pooled to obtain a number for the sampling unit. The effect of wetland type on waterbird abundance and density was analysed using linear mixed models which employed restricted maximum likelihood (REML; Patterson and Thompson 1971) in Genstat (V11, Lawes Agricultural Trust, IACR-Rothamsted). The fixed effect of wetland type was tested using a Wald statistic. All waterbird data were $\log_{10}$ transformed.

For abundance analyses only, the mixed model was simplified for several species/feeding guilds in order to obtain convergence by removing one or more random effects. Also, negative variances were found, or the analysis failed to converge, in those waterbird species or guilds where ten or fewer birds were counted, and these were eliminated from the analysis. The species in this category were the filter feeding group of waterfowl (10 birds), Domestic Goose (8), Australasian Shoveler (*Anas rhynchotis*) (6), Yellow-billed Spoonbill (*Platalea regia*) (7), Great Egret (*Ardea alba*) (3), Pied Cormorant (*Phalacrococorax melanoleucos*) (5), Magpie Goose (*Anseranas semipalmata*) (2), unidentified small plover (2), Musk Duck (*Biziura lobata*) (1), Black-fronted Dotterel (*Charadrius melanops*), (1) Black-tailed Native-hen (*Gallinulla entralis*) (1), and Straw-necked Ibis (*Threskiornis spinicollis*) (5).

Permutational Multivariate Analysis of Variance (PERMANOVA; Anderson 2001; Anderson et al. 2008) was used to test the effect of wetland type, season and year on the composition of waterbird communities, on the basis of abundance and density. For this analysis the sampling units were the 31 wetland systems. Significance testing of the Bray-Curtis similarity measures (also on $\log_{10}(x + 1)$-transformed data) and *post hoc* comparisons (at $P \leq 0.05$) were made using 9,999 permutations. Permuted residuals were calculated under a reduced model, and Type III sums of squares were used because of the unbalanced nature of the design (Anderson et al. 2008). All multivariate analyses were performed with PERMANOVA+ (V1.0.4, PRIMER-E, Plymouth, UK).

Results

In total, 5,897waterbirds representing 35 species were recorded over the duration of the study (Table 2). Only three “species” (Mallard *Anas platyrhynchos*, Domestic Duck *Anas* sp. and Domestic Goose *Anser* sp.), which accounted for 1.5% of the total abundance, are not native to Australia. The mean number of individual waterbirds per hectare was 14.3 for urban lakes and 23.4 for SWTS ponds with a corresponding species richness per hectare of 3.0 and 3.8 respectively.

Urban wetland variables and waterbirds

Pursuit predators, some waterfowl, Australian White Ibis (*Threskiornis molucca*) and Silver Gull (*Larus novaehollandiae*) were positively correlated with wetland area whereas the Rallidae and dabbling ducks were negatively correlated with wetland area (Table 3). Australian Pelican and Darter were very weakly positively correlated with shoreline irregularity index and there were almost no correlations between waterbirds and littoral angle (Table 3). Rallidae and waders, and also the most common Rallidae species, were positively correlated with vegetated perimeter, whereas herbivorous waterfowl were negatively correlated with vegetated perimeter. Domestic Duck, Mallard, Silver Gull, Little Black Cormorant (*Phalacrocorax sulcirostris*) and pursuit predators were negatively correlated with macrophyte cover, whereas Purple Swamphen (*Porphyrio porphyrio*) and Rallidae were positively correlated with macrophyte cover. There were few substantial correlations between waterbird species and the physical variables of buffer zone, mown grass, distance to nearest wetland, number of wetlands within 1 km, and urban encroachment (Table 3). Four species of pursuit predators (and their associated functional group), four waterfowl species, Australian White Ibis and long-legged waders were positively correlated with security distance (Table 3). Domestic Duck and Silver Gull were positively correlated with access whereas Eurasian Coot (*Fulica atra*), Rallidae and diving ducks were negatively correlated with access (Table 3). The Rallidae functional group and associated individual species were negatively correlated with both catchment variables ($W_{A/TCA}$, $W_{A/TIA}$), whereas Australian Wood Duck (*Chenonetta jubata*), pursuit predators and herbivorous waterfowl were positively correlated with these variables (Table 3).

Purple Swamp Hen and Dusky Moorhen (*Gallinula tenebrosa*) were positively correlated with Zn, Australian Wood Duck positively correlated and Purple Swamp Hen negatively correlated with DOC, and Purple Swamp Hen was negatively correlated with both EC and pH (Table 4). There were other significant but even weaker correlations with water chemistry (Table 4).

BIOENV analysis indicated that waterbird community composition was not correlated with water chemistry (Appendix B) according to either waterbird abundance ($\rho = 0.16$, $P = 0.171$) or density ($\rho = 0.09$, $P = 0.685$). Waterbird community composition was, however, significantly correlated with wetland physical characteristics (Table 5). Waterbird community composition based on abundance was most consistently correlated with vegetated perimeter, surface area, distance to nearest wetland and mown grass with the strongest correlation, but still weak, also including the catchment variable $W_{A/TCA}$ ($\rho = 0.29$, $P = 0.001$; Table 5). Results for the density data were similar to correlations based on abundance, but also included number of wetlands within 1 km and security distance (Table 5). The strongest correlation was produced with surface area, vegetated perimeter, mown grass, distance to nearest wetland, number of wetlands within 1 km, security distance, access and $W_{A/TCA}$ ($\rho = 0.31$, $P = 0.001$; Table 5).

Waterbird community composition was weakly correlated with the composition of the phytoplankton (Appendix C) community for both abundance ($\rho = 0.21$, $P = 0.003$) and density ($\rho = 0.16$, $P = 0.022$). The community composition of phytoplankton was significantly correlated with water chemistry. The best model for phytoplankton ($\rho = 0.36$, $P = 0.012$) included BOD, CHLA, B and pH.

Urban lakes versus storm water treatment systems

PERMANOVA indicated that there were no significant differences ($P > 0.05$) in the community composition of waterbirds according to wetland type ($\rho = 0.603$, $P = 0.157$; abundance, density respectively), sampling year ($\rho = 0.107$, $P = 0.102$) or season ($\rho = 0.087$, $P = 0.121$). There were no significant interaction effects. PERMANOVA of waterbird composition based on functional groups mirrors that for the analysis based on species, i.e. there were no significant differences in the community composition of functional groups of waterbirds according to wetland type ($\rho = 0.510$, $P = 0.088$; abundance, density respectively), sampling year ($\rho = 0.064$, $P = 0.177$) or season ($\rho = 0.229$, $P = 0.184$), again with no significant interaction effects. Univariate analyses of individual species/guilds for abundance and density are presented in Appendices D and E, respectively.

Ninety-one genera of phytoplankton were identified. The most common genera across both wetland types (> 100,000 mL^{-1} for all 53 wetlands) were *Phormidium, Chlamydomonas, Aphanocapsa, Aphaniizomenon* and *Aphanothece*. There were no significant differences in the community composition of phytoplankton ($P = 0.366$) between wetland types, but there was a significant block effect ($P < 0.001$).

Discussion

Urban wetland variables and waterbirds

The use of artificial urban wetlands by waterbirds was correlated with an array of wetland physical characteristics (Tables 3 and 5) and water chemistry variables (Table 4). Surface area proved to be an important explanatory variable for many species and groups, not just in terms of abundance (which would be expected by default) but in terms of density: the smallest wetlands in this study were not as valuable for waterbirds as would be expected if waterbirds distributed themselves simply in proportion to wetland area.

The relationship of surface area to bird density was positive for pursuit predators such as cormorants and pelicans, which favoured large wetlands, but negative for dabbling ducks and Rallidae (crakes and rails), which favoured small wetlands. The wetlands in our study were generally small and the apparent effects of surface area applied at that scale. “Waterbird security distance” appeared to have similar effects to area on more or less the same suite of species (Darter, other pursuit predators such as cormorant species, Hardhead, Black Swan (*Cygnus atratus*), Domestic Duck, Mallard, White Ibis and long-legged waders) and this is not surprising as the largest wetlands generally provided the greatest opportunity for birds to take refuge far from a given point of disturbance. Similarly, Australian Pelican and Darter both showed very weak positive relationships with the shoreline irregularity index, which tended to be higher in large than small wetlands, so this may be largely an area effect and provides an alternative view to previous work reporting waterbirds prefer wetlands with peripheral complexity (Hansson et al. 2005).

Planting trees and shrubs is a common management activity, applied to enhance the value of wetlands by buffering them against adverse influences (Bregnballe et al. 2009; Sharma and Saini 2012), which in urban environments are adjacent suburban or industrial habitats. Hence it was surprising to find no relationship between our “buffer zone” variable (relating to woody vegetation round each wetland) and the density of any waterbird species or group, with the sole exception of Little Black Cormorant. Cormorants make extensive use of woody vegetation for perching, roosting and nesting (Fjeldså 1985), and it is not surprising that they benefit from planting buffer zones of trees or shrubs. Vegetated perimeter was negatively correlated with some waders and Rallidae, and positively correlated with herbivorous waterfowl, which confirms the view that ponds with tall vegetation (> 1 m) may be avoided due to a decreased ability to detect predators (White and Main 2005). One of the problems with planting trees and shrubs is that they reduce the space occupied by open ground or short grass, and those open habitats are favoured for loafing and roosting by many waterbird species. Some of these birds (e.g. Australian Wood Duck, Black Swan and Eurasian Coot) also feed to some extent on short grass: indeed this is a major food source for Australian Wood Duck (Kingsford 1989). Such herbivorous waterfowl collectively responded positively to vegetated perimeter, although one of the constituent species (Eurasian Coot) showed the reverse relationship, reflecting the complexity of individual species’ requirements: all these species also take a range of aquatic food. However, the current data suggest that few waterbirds species benefit from planting tall vegetation around the perimeters of urban wetlands such as those considered in this study.

Accessibility for people proved a positive influence on two species (Silver Gull and Domestic Duck), which depend heavily on food handouts from people at urban wetlands (Smith and Carlile 1993). The same two species showed positive relationships with mown grass, possibly for much the same reason: grass is only mown at wetlands with high human visitation rates, and many of the visitors go there to “feed bread to the birds”. Silver Gulls also make use of mown grass as a habitat for loafing. Surprisingly, two species which make use of short grass for foraging (Australian Wood Duck, which feeds on the grass itself, and Masked Lapwing, which forages over short grass for insects) showed no significant relationship with the amount of mown grass. Both species occupy large home ranges and may be using suitable habitats within a larger area of each wetland than was considered here. Human accessibility proved a negative influence on crakes and rails (and two of the constituent species in this guild, Purple Swamphen and Eurasian Coot) and diving ducks, suggesting that those groups may avoid wetlands where human disturbance is too great. However, these relationships could also be driven by habitat features and the negative correlation of Hardhead with $W_{A/TIA}$ may be an area effect as Hardhead dive for food to depths of about 3 m (Frith et al. 1969) and prefer large deep waters with abundant aquatic vegetation (Fjeldså, 1985). Crakes and rails (and Purple Swamphens specifically) were positively related to macrophyte cover, and these birds are habitually found at wetlands with dense swards of tall emergent vegetation (Norman and Mumford 1985), whereas the negative correlation of Australian Pelican and other waterbirds (Little Black Cormorant, Domestic Duck, Mallard and Silver Gull) with macrophyte cover highlights the significance of open water for these species and supports previous work (Corrick and Norman 1980; Fjeldså 1985). The urban wetlands that are most accessible to people are generally not those with dense swards of emergent vegetation. Hence we doubt that access is the primary driver of this observed relationship with rallids but may be a factor for diving ducks.

Several authors have discussed the spatial arrangement of wetlands, and the need to ensure functional connectivity (Kingsford et al. 2010). However, at the scale of the current study, little evidence was found to support these propositions (and none to contradict them: no negative relationships were found with two measures of connectivity). Just one poorly represented species (Great Cormorant, *Phalacrocorax sulcirostris*) showed a significant relationship with the number of wetlands within 1 km, and no species showed a significant relationship with the distance to the closest wetland. The relationship for Great

Cormorant was positive and is consistent with the mobility of the species, which is known to move readily between wetlands on a daily basis (Marchant and Higgins 1990).

Urban lakes versus stormwater treatment systems

The greater abundance of White-faced Heron and wading waterbirds as a group on SWTS ponds is probably related to their foraging preference for open areas over of shallow water (Lowe 1983; Marchant and Higgins 1990). The lower abundance and density of wading waterbirds on the urban lakes, when compared with the SWTS ponds, was not explained by the correlation with vegetated perimeter, as the proportion of vegetated perimeter for both wetland types was similar (Appendix A). The water depth over much of the urban lakes would have been too great for foraging. Masked Lapwings, the predominant waterbird in the waders group, and waders as a group, had a greater abundance and density on SWTS ponds, probably as a result of their preference for short-grassed areas at the margins of shallow terrestrial wetlands (Favaloro 1944; Marchant and Higgins 1993).

Implications for the construction of artificial wetlands in an urban environment

In suburban Melbourne, 117 stormwater retention systems have been built to capture nutrients and hold water in order to control flooding and to provide public amenity and environmental benefits (Melbourne Water 2013). Urban lakes are being constructed for human recreational and public amenity purposes. These SWTS ponds and urban lakes can provide valuable habitat for waterbirds and it is apparent from this study that waterbirds are using this additional habitat. The large number of species (35) and the large number of waterbirds counted over the four study periods (5,897) indicate that these urban ponds are used by a diversity of waterbirds. Murray and Hamilton (2010) also documented the importance of waste stabilisation ponds for waterbirds. Moreover, in a study on the use of different types of wetlands by waterfowl in south-eastern Australia, Murray et al. (2012) found that waste stabilisation ponds supported 22 individuals per hectare and 0.54 species per hectare and these numbers were more than four times the numbers of waterfowl supported by four natural wetland types. The number of individuals and species per hectare for these artificial urban wetlands are comparable with, or greater than, those of waste stabilisation ponds and so their importance to waterbirds is obvious. The present study shows that there are opportunities for increasing the value of artificial urban wetlands for waterbirds, by attention to a number of basic design features.

Differences in community composition of waterbirds between wetland types are related to physical variables, and not water chemistry, and these differences may explain the contributions to dissimilarity between wetland types made by waterbirds. This study encourages urban planners to construct wetlands of sufficient area with low vegetation (< 1m.) around a proportion of their perimeter. Most waterbirds select habitat where they are secure and not threatened by human encroachment. Therefore wetlands constructed with waterbirds in mind should have inbuilt separation from human activity. It has been stated that wetlands should be near alternative wetlands to which birds can move if threatened (Haig et al. 1998), but that requirement did not emerge from our study and a wetland of adequate size with shoreline protection appears sufficient.

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Table 1 Description of wetland types and the block structure used for sampling purposes

Block	Urban Lakes	Stormwater Treatment Systems (ponds)	Total Ponds	Total Systems
West	8	2 (9, 4)	21	10
North	8	2 (3, 5)	16	10
East	9	2 (3, 4)	16	11
Total	25	6 (28)	53	31

The numbers of ponds within stormwater systems are shown in brackets.

Table 2 Functional groupings of 35 species of waterbirds detected on the 53 Lower Dandenong Valley wetlands according to their foraging activities.

				Waterfowl and grebe			
Waders (Charadriiformes)	Long-legged waders (Ciconiiformes)	Swamphens and coot (Rallidae)	Pursuit predators	Diving	Dabbling	Filtering	Herbivorous
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 amongst tall grasses, sedges	Active vertebrate predators at wetlands (may also feed on inverts, but not exclusively)	Generally spend much of their time on/in the water (especially when feeding) or grazing on adjacent vegetation			
Black-fronted Dotterel *Charadrius melanops*	Australian White Ibis *Threskiornis molucca*	Black-tailed Native Hen *Gallinulla ventralis*	Silver Gull *Larus novaehollandiae*	Blue-billed Duck *Oxyura australis*	Pacific Black Duck *Anas superciliosa*	Australasian Shoveler *Anas rhynchotis*	Magpie Goose *Anseranas semipalmata*
Masked Lapwing *Vanellus miles*	Straw-necked Ibis *Threskiornis spinicollis*	Purple Swamphen *Porphyrio porphyrio*		Musk Duck *Biziura lobata*	Grey Teal *Anas gracilis*		Australian Wood Duck *Chenonetta jubata*
	Great Egret *Ardea alba*	Dusky Moorhen *Gallinula tenebrosa*	Australian Pelican *Pelecanus conspicillatus*	Hoary-headed Grebe *Policephalus policephalus*	Chestnut Teal *Anas castanea*		
Small Plover sp.	Egret sp. *Ardea* sp.	Eurasian Coot *Fulica atra*	Great Cormorant *Phalacrocorax sulcirostris*	Hardhead *Aythya australis*	Australasian Grebe *Tachybaptus novaehollandiae*		Black Swan *Cygnus atratus*
	White-faced Heron *Egretta novaehollandiae*		Darter *Anhinga melanogaster*		Mallard *Anas Platyrhynchos*		Domestic Goose

			Domestic Duck
		Little Black Cormorant *Phalacrocorax sulcirostris*	
	Yellow-billed Spoonbill *Platalea regia*	Little Pied Cormorant *Phalacrococorax melanoleucos*	
		Pied Cormorant *Phalacrococorax varius*	

Table 3 Spearman rank correlation coefficients (ρ) of 25 waterbird species and 7 functional groupings of waterbird species (based on density data) with 14 physical characteristics of urban wetlands.

Species	Area	Shore irreg. index	Litt. angle	Buffer zone	Vegetated perimeter	Macro-phyte (cover)	Mown grass	Dist. Close. wetl.	No. Wetl. (1 km)	Security distance	Access	Urban	$W_{A/TCA}$	$W_{A/TIA}$
Individual species														
Australian Pelican	0.33*	0.32*	-0.18	-0.06	-0.04	-0.29*	0.16	-0.1	-0.12	0.26	0.3	0.15	0.07	0.10
Darter	0.52***	0.31*	-0.22	0.21	0.23	-0.24	0.25	-0.04	0.02	0.55***	0.11	-0.12	0.33	0.39**
Pied Cormorant	0.35**	-0.02	-0.10	0.26	0.07	-0.06	0.02	-0.17	-0.02	0.36**	-0.12	-0.05	0.26	0.23
Little Pied Cormorant	0.32*	0.21	-0.14	0.02	0.17	-0.03	0.03	-0.02	-0.04	0.46**	-0.18	-0.17	0.13	0.23
Great Cormorant	0.46**	0.23	0.14	-0.11	0.22	-0.18	0.36	-0.17	0.28*	0.33	0.14	0.06	0.13	0.17
Little Black Cormorant	0.39**	-0.02	-0.01	0.34*	0.20	-0.34*	0.02	-0.26	0.12	0.41**	0.02	-0.13	0.24	0.31*
Australasian Grebe	-0.07	-0.25	-0.20	-0.07	-0.01	0.03	-0.13	-0.10	-0.13	0.11	-0.25	-0.19	-0.00	0.02
Hoary-headed Grebe	0.27*	-0.17	-0.09	0.11	0.07	-0.13	-0.20	0.07	0.06	0.40**	-0.23	-0.11	0.16	020
Black Swan	0.39**	0.19	-0.13	-0.17	0.09	-0.17	0.19	-0.16	0.06	0.40**	0.08	-0.06	0.04	0.07
Domestic Duck	0.38**	0.13	0.18	-0.05	0.26	-0.40**	0.31*	-0.07	0.07	0.32*	0.40**	0.24	0.16	0.09
Mallard	0.37**	-0.09	0.13	0.09	0.12	-0.43**	0.09	0.11	-0.03	0.34*	0.18	0.15	0.25	0.25
Pacific Black Duck	-0.21	-0.08	0.05	-0.07	-0.18	-0.06	0.18	0.15	-0.25	-0.17	0.10	-0.13	-0.02	-0.07
Grey Teal	0.04	0.08	-0.18	0.14	0.18	-0.05	-0.17	0.01	0.20	0.12	-0.20	-0.17	-0.01	0.039
Chestnut Teal	-0.06	-0.01	-0.13	-0.04	-0.20	0.10	0.05	-0.20	0.21	-0.04	-0.20	-0.22	-0.23	-0.19
Hardhead	-0.05	0.15	0.07	-0.26	-0.13	0.14	0.15	0.01	0.18	-0.07	-0.20	0.05	-0.23	-0.30*
Australian Wood Duck	0.10	0.01	0.19	-0.10	0.27	-0.25	0.17	0.04	-0.25	0.04	0.20	0.05	0.40**	0.39**
Blue-billed Duck	0.12	0.06	0.04	0.14	0.11	-0.15	0.04	0.16	0.05	0.16	-0.15	-0.02	-0.05	-0.09
Dusky Moorhen	-0.24	0.10	-0.18	-0.24	-0.15	0.19	0.02	-0.11	0.24	-0.11	-0.30	-0.04	-0.44**	-0.45**
Purple Swamphen	-0.38**	0.02	-0.23	-0.22	-0.45**	0.45**	0.12	-0.12	0.27	-0.25	-0.39**	0.15	-0.61***	-0.65***
Eurasian Coot	-0.04	-0.01	-0.12	-0.15	-0.35*	0.14	0.05	-0.15	0.25	0.06	-0.45**	-0.02	-0.35*	-0.32*
White-faced Heron	0.14	0.02	-0.21	-0.13	-0.25	-0.01	0.22	0.16	-0.214	0.25	0.10	-0.06	-0.20	-0.09
Australian White Ibis	0.31*	0.21	-0.05	-0.07	0.04	-0.17	0.08	0.04	-0.10	0.36**	0.04	-0.13	-0.15	-0.04*
Masked Lapwing	0.01	0.07	-0.20	-0.16	-0.38**	0.13	0.23	-0.12	-0.12	0.01	-0.07	0.06	0.04	-0.01
Silver Gull	0.39**	0.18	0.08	-0.11	0.12	-0.50***	0.32*	-0.01	0.06	0.27	0.35*	0.28*	0.11	0.10
Functional groups														
Waders	0.01	0.01	-0.23	-0.15	-0.41**	0.14	0.19	-0.07	-0.16	0.05	-0.13	0.10	0.05	0.03
Long-legged wading birds	0.25	-0.03	-0.12	-0.17	-0.17	-0.10	0.25	0.06	-0.12	0.32**	0.09	-0.12	-0.14	-0.05
Swamphens and coot	-0.39**	-0.03	-0.18	-0.27	-0.44**	0.37**	0.10	-0.14	0.27	-0.23	-0.47***	0.02	-0.56***	-0.58***

Pursuit predators	0.45**	0.14	-0.02	0.11	0.21	-0.40**	0.07	-0.16	0.08	0.45*	0.07	-0.04	0.40**	0.45**
Diving ducks	0.11	-0.05	-0.02	-0.07	-0.09	-0.03	-0.05	0.05	0.18	0.16	-0.34*	-0.05	-0.08	-0.12
Dabbling ducks	-0.29*	-0.16	-0.00	-0.07	-0.18	-0.03	0.16	0.10	-0.18	-0.22	0.04	-0.15	-0.07	-0.11
Herbivorous waterfowl	0.19	0.01	0.19	-0.11	0.28*	-0.23	0.20	0.04	-0.24	0.14	0.16	0.04	0.43**	0.42**

*$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.00012$ (Dunn-Šidák adjustment)

“Mallards” and Domestic Ducks were analysed separately. If they had plumage like a male Mallard they were classified as Mallards and if they were white or Cayuga-type (dark with white breasts), Khaki Campbells or other Domestic Duck species they were classified as Domestic Ducks. Most of the “Mallards” in Melbourne show signs of hybridisation with domestic ducks (e.g. they are typically oversize, and poor fliers).

Table 4 Spearman rank correlation coefficients (ρ) of 25 waterbird species and 7 functional groupings of waterbird species (based on density data) with 12 water chemistry characteristics of urban wetlands.

Species	B	Cu	TN	TP	Zn	BOD	CHLA	COD	DOC	EC	pH	Turbidity
Individual species												
Australian Pelican	0.23	-0.07	0.11	-0.09	0.06	0.00	0.01	-0.08	0.01	0.29*	0.07	0.29*
Darter	0.23	0.01	-0.14	-0.27	-0.02	-0.03	-0.11	-0.22	-0.03	0.21	0.29	0.28*
Pied Cormorant	0.06	0.17	-0.06	0.01	-0.02	-0.06	-0.10	0.02	0.08	-0.08	0.07	0.16
Little Pied Cormorant	0.27	0.10	0.15	0.05	-0.10	0.08	0.02	0.11	0.24	0.17	0.17	0.09
Great Cormorant	0.02	0.19	-0.18	-0.32*	-0.13	0.04	-0.04	-0.11	0.06	-0.03	0.19	-0.14
Little Black Cormorant	0.17	0.02	0.09	-0.05	-0.22	0.08	-0.02	0.03	0.22	0.03	0.14	0.03
Australasian Grebe	0.24	0.10	0.22	0.33*	0.05	0.04	-0.01	0.28*	0.16	0.10	0.05	-0.04
Hoary-headed Grebe	0.17	0.15	0.10	0.07	-0.20	0.00	-0.14	0.23	0.24	0.02	0.19	-0.21
Black Swan	0.34*	-0.05	0.03	-0.06	0.06	0.02	-0.14	-0.09	0.15	0.23	0.21	-0.03
Domestic Duck	0.15	-0.07	-0.21	-0.32*	-0.15	-0.03	-0.10	-0.24	-0.07	0.00	0.04	0.01
Mallard (domestic hybrid)	0.08	0.12	-0.17	0.38**	-0.22	-0.15	-0.14	-0.05	0.03	-0.02	0.21	-0.09
Pacific Black Duck	-0.08	0.03	0.14	0.10	0.04	0.12	0.02	0.10	0.03	-0.10	-0.14	-0.06
Grey Teal	0.00	0.17	-0.08	0.02	0.20	-0.23	-0.26	-0.06	0.01	-0.10	0.02	-0.17
Chestnut Teal	0.17	0.12	0.01	0.25	0.21	-0.08	-0.16	0.02	-0.17	-0.16	-0.08	-0.20
Hardhead	-0.20	-0.10	-0.33	-0.01	0.15	-0.26	-0.05	-0.28*	-0.21	-0.20	-0.11	-0.33*
Australian Wood Duck	0.09	0.26	0.26	0.16	-0.29*	0.24	0.07	0.29	0.41**	0.15	0.27	-0.08
Blue-billed Duck	-0.01	-0.18	-0.08	0.07	0.03	-0.04	-0.03	-0.07	-0.04	-0.20	-0.15	-0.12
Dusky Moorhen	0.03	-0.06	-0.16	0.10	0.49***	-0.19	-0.16	-0.19	-0.26	-0.26	-0.23	-0.19
Purple Swamphen	-0.14	-0.21	-0.20	0.19	0.52***	-0.14	0.05	-0.20	-0.51***	-0.46**	-0.56***	-0.01
Eurasian Coot	0.15	-0.09	-0.19	0.16	0.25	-0.17	-0.05	-0.13	-0.14	-0.37**	-0.10	-0.36**
White-faced Heron	0.14	0.13	0.06	0.01	0.03	-0.05	-0.15	-0.09	-0.08	0.22	0.08	0.12
Australian White Ibis	0.14	0.26	0.08	-0.14	-0.06	0.02	-0.10	0.04	0.24	0.26	0.23	0.22
Masked Lapwing	0.35	-0.12	0.05	-0.01	0.13	0.06	-0.01	-0.02	-0.26	-0.06	-0.07	0.21
Silver Gull	0.12	0.07	-0.02	-0.32*	-0.19	-0.02	0.01	-0.02	-0.01	0.11	0.11	0.13
Functional groups												
Waders	0.35*	-0.09	0.06	-0.01	0.11	0.04	-0.06	0.03	-0.21	-0.02	-0.02	0.18
Long-legged wading birds	0.14	0.25	0.04	-0.08	-0.04	-0.03	-0.19	-0.04	0.03	0.20	0.23	0.05
Swamphens and coot	-0.01	-0.20	-0.16	0.23	0.51***	-0.18	-0.03	-0.16	-0.39**	-0.48***	-0.40**	-0.26
Pursuit predators	0.21	0.12	0.18	-0.12	-0.31*	0.12	0.08	0.16	0.25	0.18	0.16	0.14
Diving ducks	-0.04	-0.01	-0.20	0.11	0.01	-0.19	-0.10	-0.04	-0.02	-0.20	0.01	-0.45
Dabbling ducks	-0.05	0.06	0.13	0.14	0.07	0.09	0.00	0.12	0.01	-0.13	-0.12	-1.15
Herbivorous waterfowl	0.11	0.22	0.20	0.07	-0.29	0.22	0.05	0.23	0.40**	0.13	0.28*	-0.10

*$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.00013$ (Dunn-Šidák adjustment)

B (Boron); Cu (Copper); TN (total nitrogen); TP (total phosphorus); Zn (Zinc); BOD (biochemical oxygen demand); CHLA (Chlorophyll*a*); COD (chemical oxygen demand); DOC (dissolved organic carbon); EC (electrical conductivity)

“Mallards” and Domestic Ducks were analysed separately. If they had plumage like a male Mallard they were classified as Mallards and if they were white or Cayuga-type (dark with white breasts), Khaki Campbells or other Domestic Duck species they were classified as Domestic Ducks.

Table 5 Spearman rank correlation coefficients (ρ) from BIOENV analysis of waterbird community composition in the lower Dandenong Valley, south-eastern Australia (based on abundance and density data) with physical characteristics. NA = not applicable.

	53 wetlands		47 wetlands	
Property	Abundance	Density	Abundance	Density
Surface area	0.17	0.12	0.19	0.13
Shoreline irregularity index	0.09			
Buffer zone		0.10		
Vegetated perimeter	0.18	0.16	0.19	0.15
Mown grass	0.06		0.09	0.08
Distance nearest wetland (km)	0.15	0.12	0.20	0.16
Number wetlands (1 km)		0.14		0.13
Security distance		0.08		0.11
Access	0.11	0.14		0.15
$W_{A/TCA}$	NA	NA	0.07	0.11
Total ρ	0.26**	0.27**	0.29**	0.31**

Analysis of ‘all wetlands’ excluded the ratio of wetland area to total catchment area($W_{A/TCA}$) and the ratio of wetland area to the total connected impervious area times the wetland area ($W_{A/TIA}$) (that could only be determined for 47 wetlands)

Analysis of ‘47 wetlands’ included all physical properties (i.e., included $W_{A/TCA}$ and $W_{A/TIA}$), but excluded 6 wetlands for which $W_{A/TCA}$ and $W_{A/TIA}$ could not be determined (3 urban lakes and 3 stormwater treatment ponds within the one system)

Correlation coefficients are given for the best combination of water variables and for each variable contained within the best combination

Significance of correlations were determined by the global BIOENV match permutation test (999 permutations; PRIMER), $^{**}P \leq 0.01$

Table does not include physical variables that were included in the BIOENV analysis but were not correlated with waterbird community composition (i.e., shoreline irregularity, littoral angle, emergent vegetation, urban encroachment, and $W_{A}/_{TIA}$)

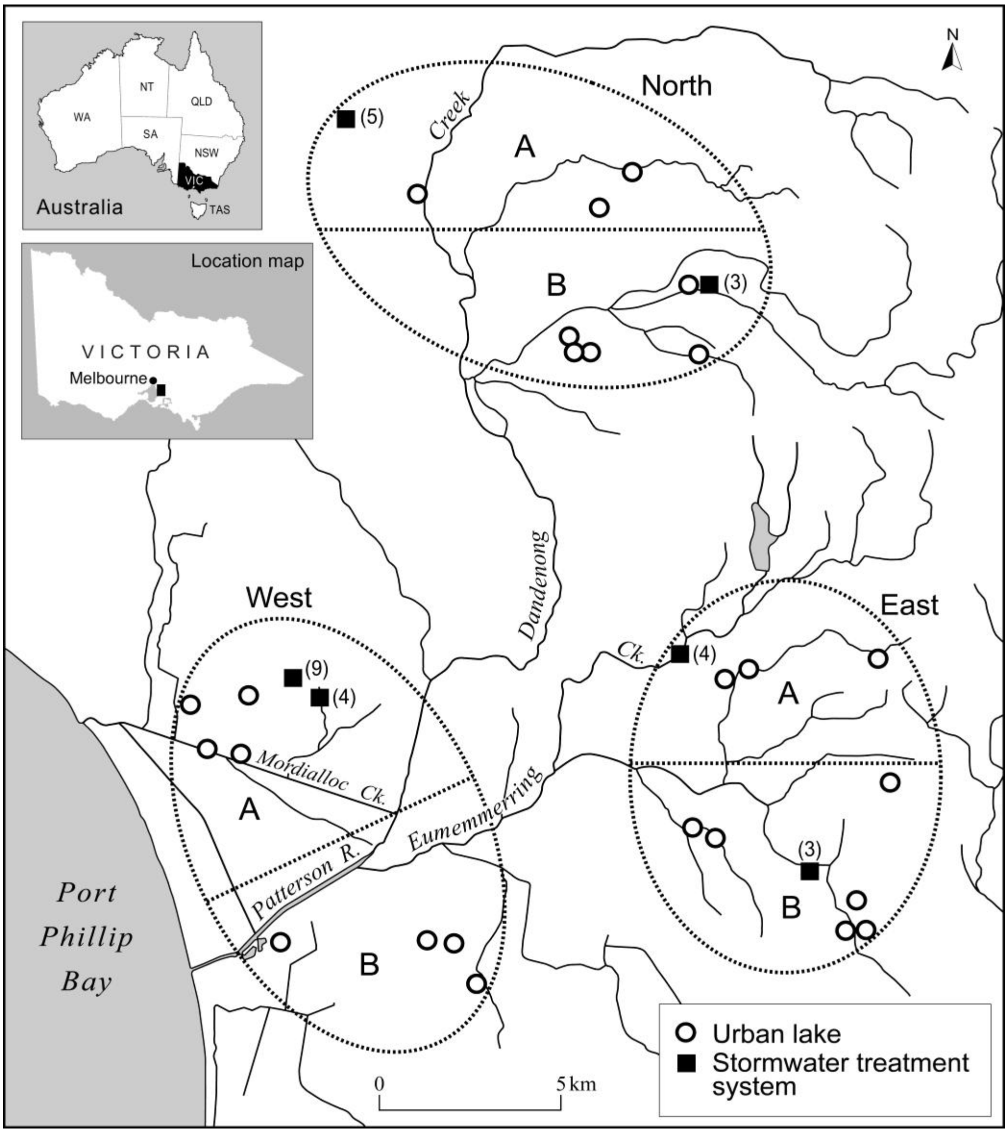

Fig. 1 Location of the two wetland types sampled within the Lower Dandenong Valley. Wetlands were located within three blocks (North, East and West) that each comprised two strata (A and B). Numbers within brackets indicate the number of ponds within each stormwater system