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Wetland Characteristics and Waterbird Use of Wetlands in South-western Australia

S. A. Halse[A], *M. R. Williams*[B], *R. P. Jaensch*[CA] *and J. A. K. Lane*[A]

[A] Department of Conservation and Land Management, Wildlife Research Centre, P.O. Box 51, Wanneroo, W.A. 6065, Australia.
[B] Department of Conservation and Land Management, P.O. Box 104, Como, W.A. 6152, Australia.
[C] Royal Australasian Ornithologists Union, P.O. Box 199, Jolimont, W.A. 6104, Australia.

Abstract

The presence or absence of 61 waterbird species on 95 wetlands in south-western Australia was related to six wetland characteristics: salinity, emergent vegetation, water depth, pH, phosphorus level and wetland size. More species were associated with salinity and vegetation than with other wetland characteristics. There were more positive associations with brackish than with fresh or saline wetlands and few species occurred in hypersaline wetlands. Trees or shrubs and sedges were the vegetation with which most species were associated; few species were recorded on completely open wetlands or those with only samphire.

The 95 wetlands were classified into five groups on the basis of waterbird use. All wetland characteristics differed between groups but larger differences occurred in salinity, vegetation and water depth. The wetland group that supported most species also supported the highest numbers of waterbirds and most breeding species.

Introduction

Most work in Australia has related distribution and abundance of waterbirds to rainfall or changes in water level (e.g. Ford 1958; Crawford 1979; Gosper *et al.* 1983; Woodall 1985). With agriculture, urbanisation and other development causing changes in many wetlands (McComb and Lake 1988), we need to know the important habitats for waterbirds. Little is known about which characteristics of a wetland affect its use by waterbirds (Pressey 1984; Briggs 1988).

Nutrient levels have been shown to influence the number of waterbird species on some North American wetlands (Murphy *et al.* 1984) but not on four nutrient-rich wetlands in New South Wales (Briggs 1980). Vegetation can affect the number of waterbird species (Knight 1965; Broome and Jarman 1983) and the number of birds (Blackman and Locke 1985). Contour can be important: shoreline width and slope affected the number of red-capped plovers, *Charadrius ruficapillus*, in salt lakes in south-western Australia (Abensperg-Traun and Dickman 1989) and the number of waterbird species increased with array of water depths in artificial waterbodies in New South Wales (Broome and Jarman 1983). Shoreline complexity (Nilsson and Nilsson 1978) and size (Sillen and Solbreck 1977; Murphy *et al.* 1984) have often been shown to be important determinants of waterbird use.

Classification of wetlands on the basis of similarity of waterbird communities can be used with wetland inventory to assess habitat change (Halse *et al.* 1992*a*) and adequacy of a reserve system (Pressey 1984). Classification also assists management decisions because interpretation is easier as a result of information being ordered (Cowling 1977).

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Several classification schemes for waterbird habitat have been used in Australia (Riggert 1966; Goodrich 1970; Cowling 1977; Corrick and Norman 1980). None of these was formally analysed to show that the classification parameters were biologically meaningful, although Goodrich (1970) and Corrick and Norman (1980) provided a great deal of information about waterbird use of different categories of wetland. Analysis of the relationship between classifications and conservation values is essential (Pressey and Bedward 1991).

Goodsell (1990) examined the effects of salinity and pH on breeding of waterbirds at 67 wetlands in south-western Australia. We examined the usage by waterbirds of 95 wetlands in south-western Australia, including those studied by Goodsell, in relation to six wetland characteristics (1) to determine whether wetland characteristics influenced preferences of species for particular wetlands, (2) to classify wetlands into categories that related to waterbird use, and (3) to identify groups of waterbirds that used similar wetlands.

Methods

Study Area

The 95 wetlands were in the South-West and Eucla Land Divisions of Western Australia (Fig. 1).

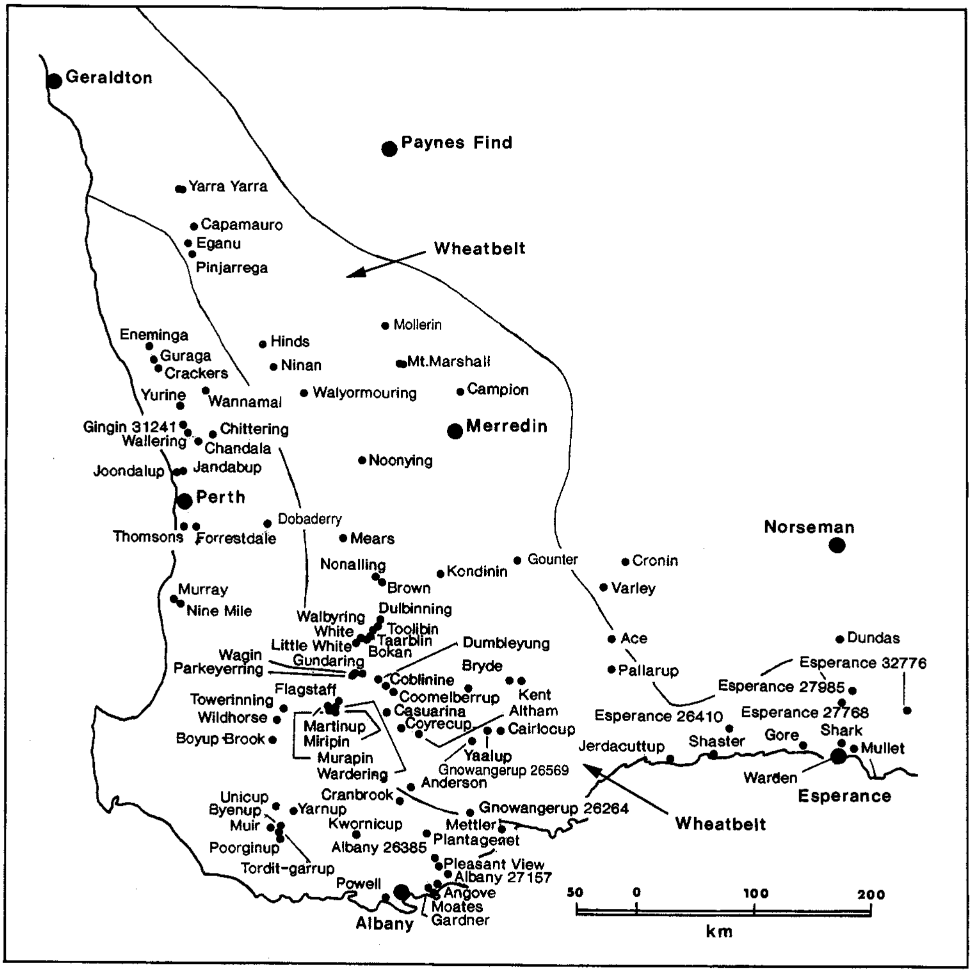

Fig. 1. Locations of the 95 wetlands studied in south-western Australia and position of the Wheatbelt.

All but one were at least partly in Crown or Local Government reserves. Farmland extended to within several metres of the high-water mark of a few wetlands, leaving little riparian vegetation (Halse *et al.* 1992*a*).

South-western Australia has cool, wet winters and hot, dry summers. Although occasional cyclonic rainfall in summer floods many wetlands (e.g. in January 1982), the usual flooding pattern begins in early winter, and depth is maximal in late winter or early spring (Lane and Munro 1983; Halse and Jaensch 1989). Annual rainfall diminishes with distance from the coast and most inland wetlands are seasonal or episodic. Naturally saline wetlands occur but secondarily saline wetlands are widespread. The latter have become saline because of agricultural salination (Lane and McComb 1988).

Most naturally hypersaline wetlands contain no vegetation below the high-water mark, although surrounding samphire (*Halosarcia/Sarcocornia*) marshes can become inundated when water levels are high. Naturally saline lakes often support salt-tolerant trees around the high-water mark but in secondarily saline wetlands increased salinity or water-logging usually kills trees or shrubs in the inundated area, leaving only stags. Freshwater wetlands support trees or shrubs and/or sedges around margins or throughout the inundated area (Halse *et al.* 1992*a*).

Nutrient levels can be high in urban wetlands and wetlands adjacent to farmland (Davis and Rolls 1987; Wrigley *et al.* 1988) because of leaching from septic tanks and fertiliser run-off, although elsewhere in south-western Australia nutrient levels are usually low because most soils are leached. Values of pH are highly variable (Lane and Munro 1983).

Waterbird Surveys

Waterbirds were surveyed between July 1981 and May 1985 using methods described by Jaensch *et al.* (1988). Numbers of birds of each species and any birds seen breeding were recorded in each survey. Scientific names of the waterbird species are given in Appendix 2.

Numbers of surveys per wetland ranged between 1 and 151. Problems of unequal sampling effort were examined by plotting species-accumulation curves for each wetland.

Impact of unequal sampling effort was minimised by restricting analyses of the effects of environmental variables to presence/absence data for 61 species of waterbird that were either widespread or moderately abundant in south-western Australia or, although recorded infrequently, were of special conservation interest.

Environmental Variables

Water depth, salinity and pH were measured every two months between July 1981 and May 1985 (see Lane and Munro 1983). Total phosphorus levels were measured every two months between July 1984 and May 1985 as an indicator of wetland productivity. The area of each wetland was calculated from aerial photography and, during 1987–88, the extent of vegetation inside the high-water mark was quantified by ground inspection (Halse *et al.* 1992*a*). Eight environmental variables were derived from the above measurements (Table 1, Appendix 1).

Fisher's exact tests were used to examine whether occurrence of waterbird species was related to the classificatory environmental variables (Mehta and Patel 1983). Associations with occurrence of species were deemed to exist if $P < 0\cdot10$ and associations among categories of classificatory variables were then examined using the cell deviation contribution to χ^2 to identify categories in which birds occurred more often than expected by chance. If a species showed equal preference for two categories of a variable, a value of 0·5 was ascribed to each when the numbers of species associated with the categories were calculated. Wilcoxon rank-sum tests were used with continuous environmental variables. Associations within continuous variables were determined as being with high or low values of the variable by comparing values for wetlands in which a species occurred with those where the species was absent.

Interdependencies between environmental variables were examined with Spearman's coefficients of rank correlation.

Classifications

Cluster analysis was used to classify wetlands according to waterbird species present. Wetlands with only one species were omitted to reduce stochastic variation (Gauch and Whittaker 1981). The matrix of 61 species present or absent at 91 wetlands was analysed with PATN (Belbin 1989). The Czekanowski metric was used to calculate dissimilarities between wetlands.

Table 1. Classificatory and continuous environmental variables measured on wetlands

ppt TDS, parts per thousand of total dissolved solids

Variable	Description
Saltness	Four categories: (1) fresh, TDS ⩽3 ppt, $N=24$; (2) brackish, September TDS <10 ppt, contained fresh water at times, $N=23$; (3) saline, September TDS 10–25 ppt, contained brackish water at times, $N=20$; (4) hypersaline, September TDS >25 ppt, $N=28$
September salinity	Average salinity in September 1981–85, if water present
Vegetation	Eight categories: (1) open, total vegetation cover[A] ⩽2%, $N=18$; (2) samphire, cover of samphire/low shrubs + herbs/grasses >2× cover of other life forms, $N=12$; (3) fringing dead trees, cover of dead trees >2× others and <25%, $N=12$; (4) extensive dead trees, cover of dead trees >2× others and ⩾25%, $N=9$; (5) fringing sedges, cover of sedges/rushes >2× others and <25%, $N=2$; (6) extensive sedges, cover of sedges/rushes >2× others and ⩾25%, $N=19$; (7) fringing trees, cover of trees/large shrubs >2× others and <25%, $N=14$; (8) extensive trees, cover of trees/large shrubs >2× others and ⩾25%, $N=9$
Permanence	Four categories: (1) permanent, contained water throughout 1981–85, $N=22$; (2) semi-permanent, dried 1 year, $N=19$; (3) seasonal, dried 2–3 years, $N=23$; (4) ephemeral, dried 4 years, $N=31$
September depth	Average depth in September 1981–85
September pH	Average pH in September 1981–85, if water present
Phosphorus	Average total phosphorus in unfiltered two-monthly samples July 1983–May 1984, if water present
Size	Area of wetland, including associated riparian vegetation

[A] Cover was calculated as percentage cover of vegetation below high-water mark within the part of the wetland that contained emergent vegetation rather than the whole lake (see Halse *et al.* 1992*a*).

Prior to clustering, distribution of dissimilarity measures was checked for normality and underestimated dissimilarity measures were recalculated with BIGD (Belbin *et al.* 1984). Wetlands were clustered using unweighted pair-group arithmetic averaging (UPGMA) (Sneath and Sokal 1973) with $\beta = -0{\cdot}25$. Groups of waterbird species with a similar pattern of occurrence were identified by cluster analysis using TWO-STEP (Austin and Belbin 1982) and UPGMA with $\beta = -0{\cdot}25$ on the same matrices. The validity of the resultant classifications was assessed by principal components ordination.

Characteristics of Wetland Groups

Relationships between environmental variables, three measures of waterbird use of wetlands (number of species, number of breeding species, maximum number of birds in one survey) and the wetland groups defined by cluster analyses were examined using Kruskal–Wallis tests (Hollander and Wolfe 1973). Homogeneity of variances of the ranks within each wetland group was tested using Box coefficients. Because of the unequal numbers of wetlands in each group, Box's bias ratio was also calculated (Day and Quinn 1989). These tests indicated that the assumptions of homoscedasticity underlying the Kruskal–Wallis tests were met.

Results

Species Accumulation Curves

For most wetlands, plots of cumulative number of species against number of surveys flattened out (e.g. Fig. 2*b*, *i*). Even where species accumulation curves continued to climb, probably all regularly occurring species had been recorded (Fig. 2*d*, *g*). Unless a wetland was dry (e.g. Crackers Swamp on the first two visits; Fig. 2*g*), the first few surveys revealed whether many species were likely to occur. The step-like pattern in the curves of some species-rich wetlands (Fig. 2*d*, *i*) was probably the result of the study being conducted over several years. With different annual conditions, species not previously recorded in a wetland sometimes appeared late in the study.

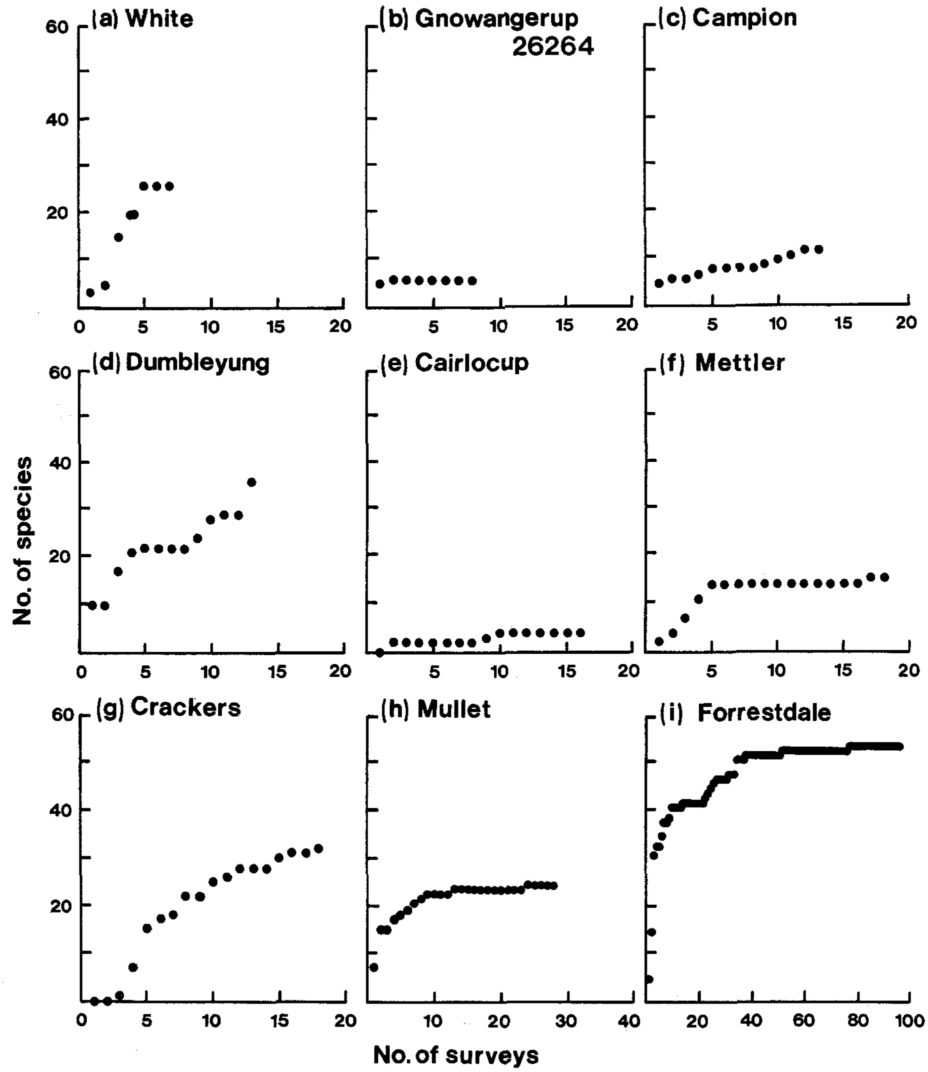

Fig. 2. Species accumulation curves for nine selected wetlands (*a*–*i*). Cumulative number of waterbird species (y-axis) recorded against number of surveys.

Table 2. Spearman's coefficients of rank correlation between environmental variables and their significance levels

***$P<0\cdot0001$; **$P<0\cdot001$; *$P<0\cdot01$; n.s., not significant. Note that Saltness, Vegetation and Permanence are classificatory variables

Variable	Saltness	September salinity	Vegetation	Permanence	September depth	September pH	Phosphorus	Size
Saltness	1·000	0·970***	0·640***	0·280*	−0·278*	0·211 n.s.	0·152 n.s.	0·546***
September salinity		1·000	0·651***	0·316*	−0·325**	0·167 n.s.	0·136 n.s.	0·562***
Vegetation			1·000	0·440***	−0·414***	0·055 n.s.	0·030 n.s.	0·372**
Permanence				1·000	−0·880***	−0·172 n.s.	0·255*	0·087 n.s.
September depth					1·000	0·325**	−0·295*	−0·082 n.s.
September pH						1·000	−0·091 n.s.	−0·019 n.s.
Phosphorus							1·000	−0·009 n.s.
Size								1·000

Environmental Variables

Strong interdependencies existed between environmental variables; these should be considered when interpreting results. There were highly significant correlations between Saltness and September salinity, and between Permanence and September depth (Table 2). Salinity and water-depth variables were strongly correlated with Vegetation, although less so with each other. Size was strongly correlated with salinity variables.

Environmental associations for each species are listed in Appendix 2. Environmental variables related to waterbird occurrence most often were (in decreasing order of frequency) Saltness, Vegetation and Permanence (Table 3). September salinity and September depth were not as closely associated with species occurrence as the equivalent classificatory variables Saltness and Permanence.

More waterbird species were associated with brackish water than with any other category of salinity (Table 3). The vegetation category with most positive associations was live trees or shrubs, although occurrences of many species were associated with sedges and dead trees. There were more associations with permanent wetlands than with other flooding regimes, although this may have been a consequence of permanent wetlands providing the only available water in late summer and autumn. When species exhibited associations within September pH and Phosphorus, it was usually for alkaline conditions and low phosphorus content (Table 3).

Table 3. Number of waterbird species positively associated with categories within each environmental variable

Only species that showed significant associations ($P<0\cdot10$) with variables are included. September salinity, September depth, and size are continuous variables; their association was deemed to be with high or low values (see text). September pH: acidic, pH $<6\cdot6$; neutral, pH $6\cdot6$–$7\cdot4$; alkaline, pH $>7\cdot4$. Phosphorus: low, $<0\cdot10$ mg L^{-1}; medium, $0\cdot10$–$0\cdot25$ mg L^{-1}; high, $>0\cdot25$ mg L^{-1}

	Saltness	September salinity	Vegetation	Permanence	September depth	September pH	Phosphorus	Size
	Brackish 25	High 5	Trees 17·5	Permanent 28	Deep 41	Alkaline 21	Low 13	Large 10
	Saline 9	Low 35	Sedges 15	Moderately permanent 10	Shallow 1	Neutral 8	Medium 1	Small 8
	Fresh 8		Dead trees 14·5	Seasonal 6		Acidic —	High 1	
	Hypersaline 7		Open 1	Episodic 1				
			Samphire 0					
Total	49	40	48	45	42	29	15	18

Classifications

Truncation of the waterbird and wetland cluster analyses at the five-group level gave ecologically interpretable groupings (Figs 3 and 4). Principal component ordinations supported these groupings: the first three axes accounted for 91% of the waterbird variance and 85% of the wetland variance, and groups were moderately well separated (Figs 5 and 6).

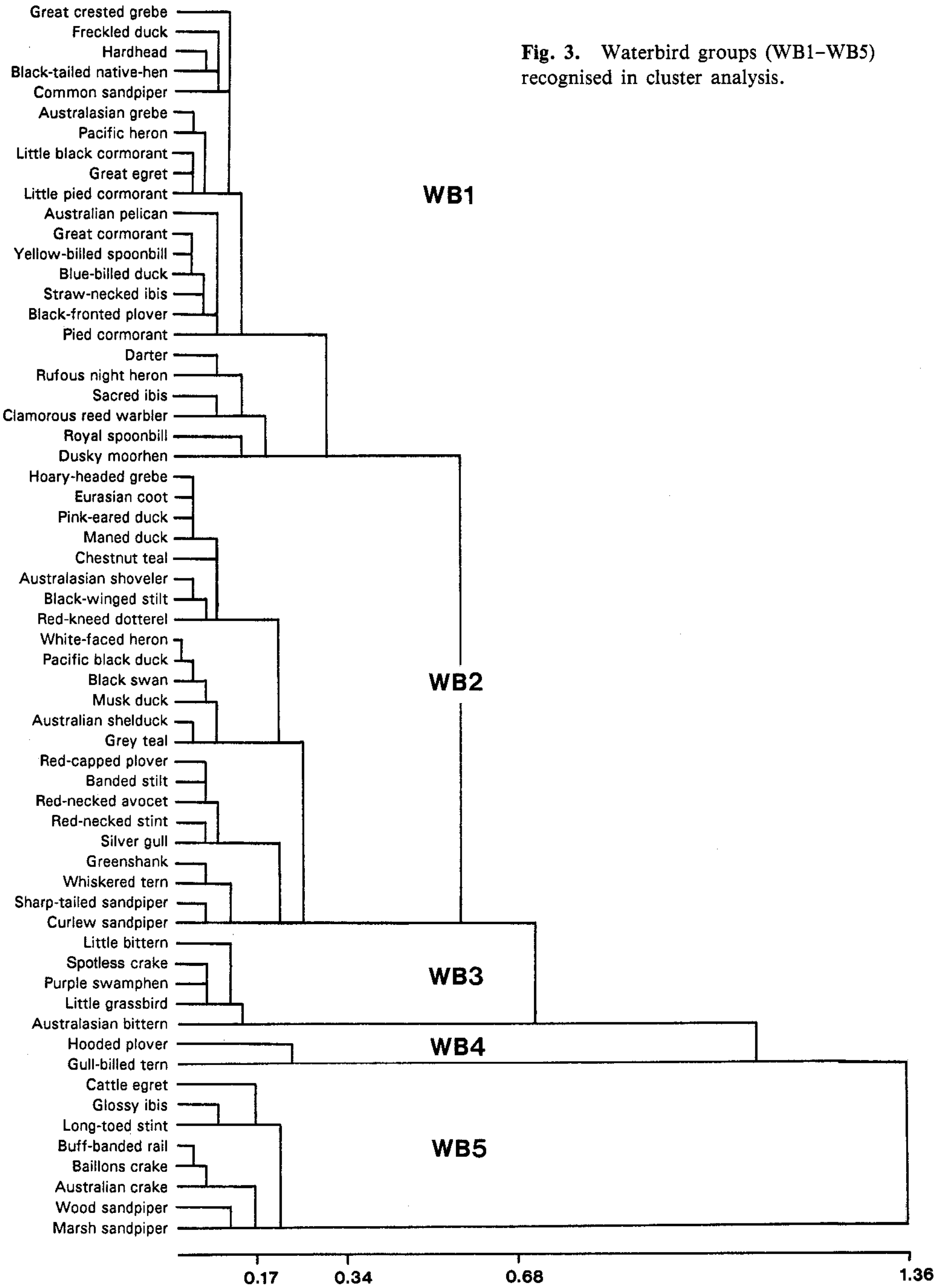

Fig. 3. Waterbird groups (WB1–WB5) recognised in cluster analysis.

Waterbird Group 1 (WB1) consisted of a large group of species that occurred in Wetland Groups 3–5 (WL3, WL4, WL5); they were absent from open hypersaline wetlands (WL1) and species-poor freshwater wetlands (WL2). WB2 contained a large group of species that

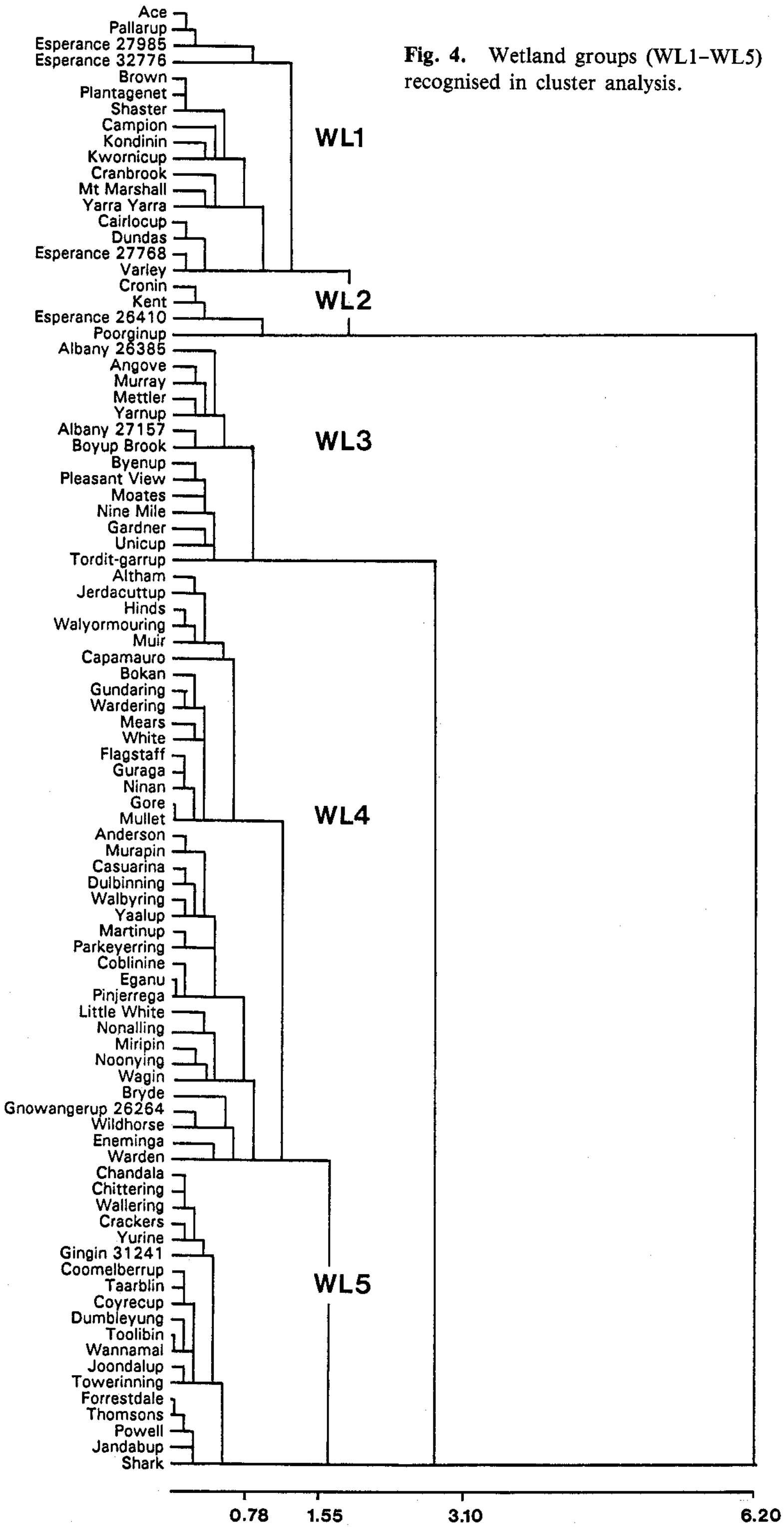

Fig. 4. Wetland groups (WL1–WL5) recognised in cluster analysis.

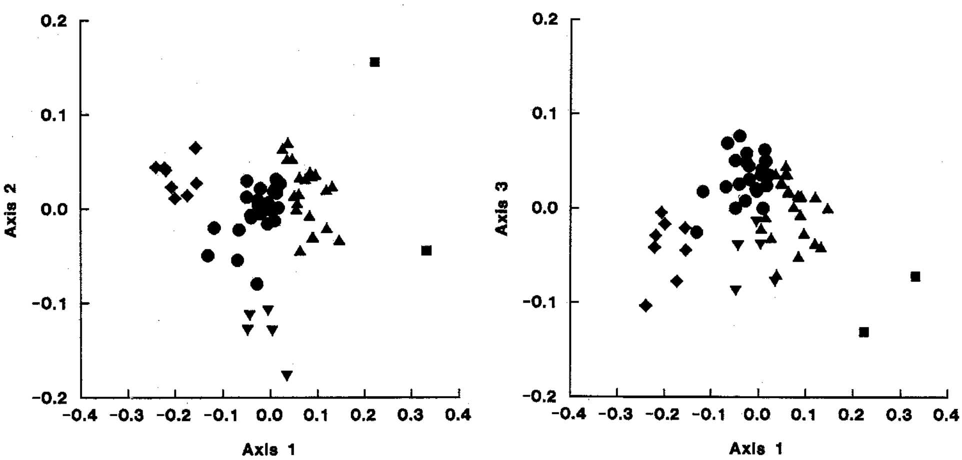

Fig. 5. Waterbird groups plotted on first three axes of principal components ordination. ●, WB1; ▲, WB2; ▼, WB3; ■, WB4; ◆, WB5.

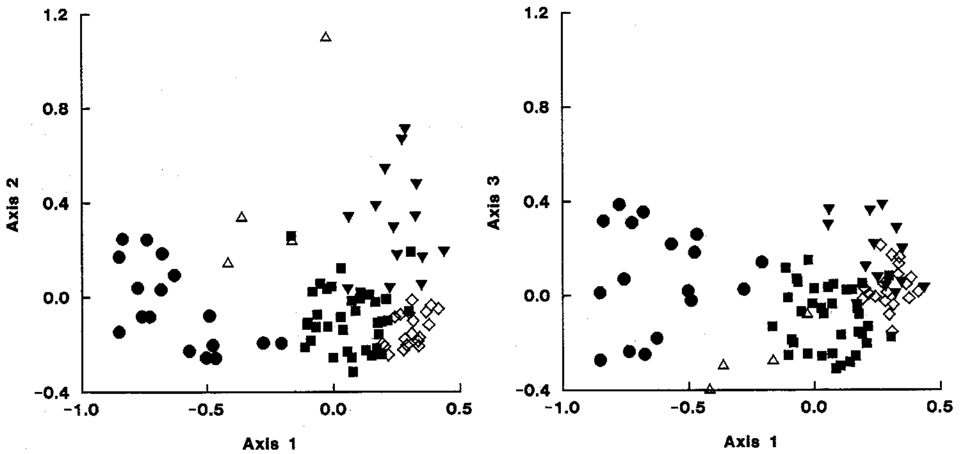

Fig. 6. Wetland groups plotted on first three axes of principal components ordination. ●, WL1; △, WL2; ▼, WL3; ■, WL4; ◇, WL5.

occurred in all wetland groups and had wide environmental tolerances. WB3 contained a small group of species restricted to wetlands with dense cover (WL3 and WL5). WB4 consisted of only the hooded plover and gull-billed tern, which were restricted to saline wetlands (WL1 and a few sites in WL4). WB5 contained a small group of species restricted to freshwater wetlands containing moderately dense vegetation (trees and sometimes sedges) (WL5).

Characteristics of Wetland Groups

Wetland Group 1 contained mostly hypersaline open wetlands that supported few waterbird species and little breeding (Table 4). A combination of unusually dry conditions and/or few surveys in WL2 localities may have resulted in their supporting few species and being

Table 4. *F*-ratios of Kruskal–Wallis tests between wetland groups for environmental and waterbird variables and mean values (±standard error) of each variable for each wetland group (WL1–WL5)

Sample sizes of wetland groups are shown in parentheses. All *F*-ratios shown are significant ($P<0\cdot001$)

Variable	*F*	WL1 (17)	WL2 (4)	WL3 (14)	WL4 (37)	WL5 (19)
Environmental						
September salinity (mg L^{-1})	38·4	128±18	0·64±0·14	1·25±0·35	29·1±6·0	5·7±2·4
Saltness	36·1	Hypersaline[A]	Fresh[A]	Fresh[A]	Saline[A]	Brackish[A]
Vegetation	33·2	Open[A]	Fringing trees[AB]	Extensive sedges[A]	Fringing dead trees[A]	Fringing trees[A]
September depth (m)	15·4	0·33±0·10	0·23±0·13	1·47±0·31	1·18±0·11	1·53±0·17
Permanence	12·5	Episodic[A]	Episodic[A]	Permanent[A]	Semi-permanent[A]	Permanent[A]
Phosphorus (mg L^{-1})	10·8	0·35±0·09	0·60±0·38	0·04±0·02	0·20±0·03	0·36±0·09
September pH	10·1	6·8±0·4	7·2±0·5	7·1±0·2	8·4±0·1	7·7±0·2
Size (ha)	5·3	1177±354	65±23	137±37	397±187	374±204
Waterbird						
No. of species	46·6	5·5±0·9	4·5±1·0	17·9±2·1	20·2±1·5	40·3±2·4
No. of breeding species	31·9	0·2±0·1	0·5±0·5	1·4±0·6	4·1±0·5	10·8±1·4
Maximum No. of birds	14·6	1010±781	60±48	1010±850	3599±737	5909±1651
No. of surveys	–	5·5±1·3	2·2±0·5	14·2±2·2	14·7±1·6	44·1±7·5

[A] Modal category.

[B] Most small, closed wetlands covered with a dense mixture of low shrubs and sedges would fit into this category (see text).

classified together. WL3 consisted mostly of freshwater wetlands with extensive areas of sedges that supported moderate numbers of species but little breeding. WL4 consisted mostly of secondarily saline wetlands with dead trees in the Wheatbelt (Fig. 1). WL4 localities supported moderate numbers of species, moderate breeding and high numbers of birds. WL5 consisted mostly of brackish wetlands with live trees although the group included five Wheatbelt wetlands with dead trees. WL5 localities supported the highest number of species, the most breeding and the highest numbers of birds.

Discussion

Environmental Factors

Salinity was an important determinant of waterbird use of wetlands in south-western Australia. Salinity is known to affect occurrence of plant and animal foods for waterbirds (Hart *et al.* 1990). Because there was a wide range of salinities on the wetlands in our study (Appendix 1; Lane and Munro 1983), there was scope for the effect of salinity on waterbird use of wetlands to be expressed.

The vegetation with which most species were associated (trees, shrubs, sedges and rushes) is killed by high levels of salinity (Bell and Froend 1990; Halse *et al.* 1992*a*). Many species of waterbird are unable to drink saline water. Even salt-tolerant species such as black swans, Australian shelducks and chestnut teal are restricted to drinking salinities of about 35 parts per thousand of total dissolved solids (ppt TDS), less than 20 ppt TDS and less than 10 ppt TDS, respectively, unless they have access to fresh water (Hughes 1976; Riggert 1977; Baudinette *et al.* 1982). A complicating factor, however, is that birds can fly to distant sources of fresh water and, thus, utilise lakes that are too saline to drink constantly (Lavery 1972; Norman 1983).

Only the hooded plover showed significant positive association with hypersaline conditions but many species were associated with brackish or saline, rather than fresh, wetlands. Whether this reflects fundamental species' preferences is unclear (cf. Missen and Timms 1974). Most wetlands in the Wheatbelt have become saline this century (Schofield *et al.* 1988; Halse *et al.* 1992*a*). Scarcity of fresh wetlands may have forced species to move into wetlands that are at the upper limit of their salinity tolerances.

Alternatively, many species may prefer brackish or saline conditions because of the increased productivity associated with elevated salinity (Bayly and Williams 1973, p. 76), provided vegetation is suitable and the species can meet the osmoregulatory challenge.

Although some categories of vegetation were causally related to salinity and the two factors were significantly correlated (Table 2), vegetation probably had effects on waterbird use of wetlands beyond the secondary effects due to its correlation with salinity. Many species require particular vegetation types; for example, bitterns and crakes are usually restricted to wetlands with dense cover (Jaensch *et al.* 1988; Marchant and Higgins 1990). Similarly, apparent preferences for deeper or permanent wetlands did not only reflect scarcity of other habitats in summer. Species such as cormorants require a minimum of about 1 m of water and, thus, are restricted to deeper wetlands (Halse 1987; Ambrose and Fazio 1989).

Waterbird Classification

The waterbird groups identified in the cluster analysis (Fig. 3) consisted of species that responded similarly, but independently, to environmental gradients. There was no evidence that occurrence of one species from a waterbird group facilitated the occurrence of others in the group. Occurrences of species of woodland and forest birds in south-eastern Australia were similarly independent (Recher *et al.* 1991).

For wetland managers the primary value of this waterbird classification is guidance, in conjunction with data on habitat associations of individual species, about which species are likely to be affected if habitat is modified for high-profile species. Because WB1–WB5 appear to consist of independently occurring species, they are not appropriate units for management. It should be remembered, also, when managing waterbirds, that occurrence of waterbird species on a wetland is influenced by conditions in areas remote from the wetland as well as by local conditions (Halse *et al.* 1992*b*).

Wetland Classification

The five wetland groups identified by cluster analysis (Fig. 4) conform with our experience of wetlands in south-western Australia and we believe all groups to be valid although some wetlands may have been mis-classified. For example, WL2 contained two wetlands, Lake Cronin and Esperance 26410, that were surveyed only once and twice, respectively, and rarely contained water during 1981–85. Subsequent surveys have shown that both wetlands sometimes support enough species to result in their being placed in another group. The other wetlands in WL2, especially Poorginup Swamp, contained comparatively dense cover, had a short period of inundation, supported few waterbirds and represent a common type of wetland, several of which were excluded from cluster analysis because they supported too few birds.

Wetlands in WL5 supported the highest numbers of waterbird species, the most breeding species and the largest numbers of birds. Typical wetlands in this group were brackish and permanent, and contained fringing trees or shrubs. Waters were characteristically alkaline in September and the waterbodies were moderately large with moderately high phosphorus levels (Table 4).

The environmental factors that differed most between wetland groups in this study (salinity, vegetation and water depth) were the principal parameters used in previous wetland classifications of wetlands as waterbird habitat (Riggert 1966; Goodrich 1970; Cowling 1977; Corrick and Norman 1980). Previous classifications did not produce wetland groups that were comparable to the ones in this study, however. The most likely reasons for differences are that (1) the earlier wetland groups were predetermined rather than being set by patterns of waterbird use; (2) water depth or permanence was generally regarded as more important than salinity or vegetation; and (3) the nature of wetland groups and important parameters for classification differ between regions.

In future work there is a need to quantify the salinity levels that preclude particular species from breeding in wetlands or using them as over-summer refuges. Freshwater sources outside saline wetlands should be identified. Until these data are available, it will be difficult for managers to formulate soundly based proposals for rehabilitation of secondarily saline wetlands.

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Appendix 1. Data on environmental and waterbird usage for the 95 wetlands

Number of surveys is also shown

Wetland	Saltness	September salinity (mg L^{-1})	Vegetation	Permanence	September depth (m)	September pH	Phosphorus (mg L^{-1})	Size (ha)	No. of species	No. of breeding species	Highest total count	No. of surveys
Ace	4	168·00	1	4	0·1	6·7	0·27	150	3	0	7	4
Albany 26385	2	1·40	6	2	0·7	6·9	0·05	126	15	1	37	13
Albany 27157	1	0·25	6	2	0·8	7·3	0·24	72	7	0	13	7
Altham	4	106·00	1	3	0·5	7·3	0·48	243	16	3	629	13
Anderson	4	136·00	4	2	1·4	8·2	0·17	186	17	1	2100	11
Angove	1	0·63	6	1	1·9	6·9	0·03	71	16	0	109	3
Bokan	3	15·00	2	3	0·8		0·21	41	20	7	1279	18
Boyup Brook	1	0·43	6	4	0·3	7·7	0·03	24	5	0	21	5
Brown	3	12·00	3	2	1·4	8·6	0·13	127	6	1	114	11
Bryde	1	0·66	8	3	0·7	7·7	0·91	97	14	6	138	10
Byenup	2	3·00	6	1	2·4	8·1	0·02	572	31	5	838	16
Cairlocup	4	168·00	1	4	0·07	8·1	0·16	284	4	0	105	16
Campion	4	138·00	1	4	0·6	4·1	0·11	611	12	1	402	13
Capamauro	4	47·00	2	4	0·6		0·24	146	10	3	704	7
Casuarina	3	9·40	4	2	1·5	9·2	0·41	58	16	4	1003	8
Chandala	1	1·00	8	2	0·9	6·8	1·07	97	38	20	5202	41
Chittering	2	2·50	8	1	1·3	7·2	0·12	148	39	15	2719	46
Coblinine	3	13·00	3	1	3·3	8·8	0·04	192	6	1	123	2
Coomelberrup	3	14·00	4	3	1·1	8·4	0·43	91	38	9	3459	28
Coyrecup	2	6·10	4	2	1·7	8·4	0·34	448	31	5	6922	17
Crackers	1	0·47	7	3	0·7	7·4	0·07	66	33	12	703	18
Cranbrook	4	58·00	1	4	0·3	8·4	0·17	82	3	0	14	1
Cronin	1	0·43	7	4	0·2	7·4	1·35	13	4	0	18	1
Dobaderry	1	0·28	5	4	0·6	6·7	0·31	63	1	0	2	3
Dulbinning	2	5·70	7	4	0·8	7·4	0·04	72	17	6	119	15
Dumbleyung	4	45·00	4	1	2·6	8·4	0·04	5561	37	5	24839	14
Dundas	4	157·00	1	4	0·2	7·4	1·40	834	3	0	9	1

Eganu	3	12·00	3	1	2·5	8·5	0·04	82	26	8	10990	19
Eneminga	1	0·36	7	2	2·1	8·3	0·51	62	12	4	144	2
Esperance 26410	1	0·96	8	4	0·05	6·7	0·30	105	7	2	9	2
Esperance 27768	4	76·00	1	4	0·02	4·8	0·27	131	2	0	5	2
Esperance 27985	4	214·00	1	4	0·07	3·7	0·24	12	2	0	2	2
Esperance 32776	4	88·00	1	4	0·04	7·3	0·34	4	3	0	2	2
Flagstaff	4	29·00	3	2	1·2	8·6	0·23	223	31	5	4410	26
Forrestdale	2	1·40	6	4	0·7	8·5	0·44	200	63	19	17500	97
Gardner	2	1·70	6	1	2·2	8·0	0·02	170	27	0	420	7
Gingin 31241	1	0·94	8	1	2·2	7·2	1·47	92	22	2	144	16
Gnowangerup 26264	2	4·80	1	4	0·09	8·3	0·50	174	18	5	2002	9
Gnowangerup 26569	4	46·00	2	4	0·3	9·9		8	1	0	2	6
Gore	4	85·00	8	2	1·2	8·1	0·29	738	40	6	14179	33
Gounter	4	264·00	1	4	0·2	2·7	0·03	118	1	0	2	1
Gundaring	3	25·00	4	1	1·7	8·3	0·32	308	29	8	1684	9
Guraga	2	5·70	1	1	2·2	8·7	0·20	250	39	2	7217	14
Hinds	4	81·40	3	2	0·9	7·7	0·16	159	19	4	9946	33
Jandabup	1	0·37	6	3	1·3	6·6	0·10	451	43	5	4438	41
Jerdacuttup	4	99·00	8	2	0·8	7·9	0·14	1203	19	0	429	4
Joondalup	1	0·75	5	1	3·0	8·5	0·03	458	52	15	6922	66
Kent	1	0·81	7	4	0·06	8·5		43	5	0	204	3
Kondinin	4	129·00	2	3	1·1	7·0	0·15	1517	9	0	189	1
Kwornicup	3	21·00	2	4	0·4	8·8	0·22	218	15	0	13417	16
Little White	3	14·00	3	3	1·1	9·5	0·13	43	16	4	1513	7
Martinup	3	12·00	4	1	1·3	9·2	0·06	84	16	8	1040	10
Mears	3	13·00	3	2	1·5	8·2	0·04	199	29	4	10958	13
Mettler	1	0·65	6	4	0·3	7·1	0·03	24	16	0	25	18
Miripin	2	7·30	7	3	0·9	9·4	0·10	28	20	4	2020	9
Moates	1	0·59	6	1	4·5	7·4	0·03	144	25	0	50	20
Mollerin	4	94·00	2	4	0·01	7·3	0·38	4882	1	0	2	4
Mt Marshall	4	230·00	1	4	0·02	2·8	0·20	106	3	0	7	4
Muir	2	6·50	2	3	0·3	7·4	0·20	4600	17	1	3012	15
Mullet	3	20·00	2	3	0·6	8·4	0·03	88	32	0	2048	26
Murapin	3	24·00	4	3	0·8	8·8	0·19	64	11	0	380	4
Murray	1	0·53	2	4	0·6	7·2	0·01	9	12	0	30	9
Ninan	4	45·00	3	2	1·8	7·8	0·08	722	30	9	4178	32
Nine Mile	1	0·36	6	1	1·7	6·6	0·04	15	22	5	79	20
Nonalling	2	9·30	3	3	1·1	8·4	0·06	20	11	4	391	4
Noonying	2	8·80	3	2	1·2	8·1	0·19	12	16	5	540	24

Appendix 1 (*continued*)

Wetland	Saltness	September salinity (mg L^{-1})	Vegetation	Permanence	September depth (m)	September pH	Phosphorus (mg L^{-1})	Size (ha)	No. of species	No. of breeding species	Highest total count	No. of surveys
Pallarup	4	233·00	1	4	0·04	6·5	1·00	1125	5	0	195	4
Parkeyerring	3	16·00	7	1	1·4	8·8	0·10	322	17	2	3316	10
Pinjarrega	4	37·00	7	2	2·0	8·6	0·11	697	25	3	10311	16
Plantagenet	4	140·00	1	4	0·6	7·8	0·06	200	8	1	110	4
Pleasant View	1	0·75	6	3	0·8	7·5	0·02	201	24	4	119	28
Poorginup	1	0·38	6	3	0·6	6·1	0·15	50	2	0	11	3
Powell	1	0·68	6	1	0·8	6·8	0·14	143	52	7	3537	36
Shark	2	1·60	6	1	2·2	7·7	0·50	9	40	3	3071	37
Shaster	3	21·00	1	4	0·3	7·6	0·14	1479	9	0	1024	7
Taarblin	3	14·00	3	3	1·0	8·1	0·08	916	31	9	4241	20
Thomsons	2	1·10	6	3	1·0	6·9	0·28	213	60	11	21177	151
Toolibin	2	2·40	7	3	1·6	7·6	0·11	296	41	22	1646	48
Torditgarrup	1	1·10	6	1	2·7	7·7	0·01	686	14	0	12036	7
Towerinning	2	8·00	7	1	2·8	8·2	0·04	180	36	14	1243	23
Unicup	2	5·10	6	3	0·6	4·9	0·02	281	25	1	329	28
Varley	4	125·00	1	4	0·09	7·1	0·75	1051	3	0	122	3
Wagin	3	20·00	1	3	0·9	8·5	0·09	63	10	3	725	5
Walbyring	2	2·60	7	3	0·8	7·8	0·12	53	19	7	1017	17
Wallering	2	2·00	8	4	0·8	8·3	0·55	9	35	10	212	48
Walyormouring	3	12·00	2	4	0·6	8·9	0·18	1010	28	9	4473	37
Wannamal	2	5·90	7	2	1·5	8·4	0·22	240	45	18	4158	55
Warden	4	122·00	7	2	0·8	8·0	0·19	665	36	2	16919	26
Wardering	3	9·40	2	2	1·1	9·3	0·07	45	27	11	6682	23
White	3	18·00	3	3	0·9	8·9	0·06	208	27	1	8399	7
Wildhorse	2	6·30	4	3	0·8	8·4	0·10	4	11	1	63	5
Yaalup	1	0·24	8	1	1·6	7·0	0·42	16	18	6	91	24
Yarnup	1	1·00	6	1	1·1	6·7	0·05	25	12	4	32	18
Yarra Yarra	4	209·00	2	4	0·2	7·9	0·26	1213	3	0	1451	2
Yurine	2	0·73	7	1	1·8	6·9	0·76	8	29	4	135	35

Appendix 2. Results of Fisher's exact and Wilcoxon rank-sum tests of whether there were significant associations between eight environmental variables and the occurrence of 61 waterbird species

Preferred habitat type is indicated when an association existed. *N*, number of wetlands where species occurred; $^{**}P<0.001$; $^{*}P<0.01$; $^{+}P<0.10$

Species	*N*	Saltness	September salinity	Vegetation	Permanence	September depth	September pH	Phosphorus	Size
Great crested grebe *Podiceps cristatus*	18	+ Brackish		+ Extensive dead trees	** Permanent	** Deep	+ Alkaline	+ Low	
Hoary-headed grebe *Poliocephalus poliocephalus*	49	+ Brackish		* Extensive dead trees	** Permanent	** Deep	+ Alkaline		
Australasian grebe *Tachybaptus novaehollandiae*	37	+ Brackish	+ Low	* Extensive dead trees	** Permanent	** Deep			
Australian pelican *Pelicanus conspicillatus*	24	* Brackish	+ Low	* Extensive trees	* Permanent	** Deep			
Darter *Anhinga melanogaster*	13	** Brackish	+ Low	+ Extensive trees	* Permanent	** Deep			+ Small
Great cormorant *Phalacrocorax carbo*	26	+ Brackish	+ Low	+ Fringing trees	** Permanent	** Deep			
Pied cormorant *Phalocrocorax varius*	14			+ Fringing trees	+ Permanent	** Deep		* Low	
Little black cormorant *Phalocrocorax sulcirostris*	39	+ Brackish	* Low	* Extensive sedges	** Permanent	** Deep		+ Low	
Little pied cormorant *Phalacrocorax melanoleucos*	47	* Brackish	* Low	* Fringing trees	** Permanent	** Deep	+ Alkaline		
Pacific heron *Ardea pacifica*	32	** Brackish	* Low	+ Extensive trees	+ Permanent	** Deep			

Appendix 2 (*continued*)

Species	*N*	Saltness	September salinity	Vegetation	Permanence	September depth	September pH	Phosphorus	Size
White-faced heron *Ardea novaehollandiae*	69	** Brackish	** Low	** Extensive live/dead trees	** Permanent	** Deep	+ Alkaline	+ Low	** Small
Great egret *Egretta alba*	36	** Brackish	* Low	* Fringing trees	** Permanent	** Deep			
Cattle egret *Ardeola ibis*	2		+ Low	+ Fringing sedges					
Rufous night heron *Nycticorax caledonicus*	20	** Brackish	** Low	** Fringing trees	+ Permanent	** Deep		+ High	+ Small
Little bittern *Ixobrychus minutus*	10	** Fresh	** Low	** Extensive sedges	+ Permanent		* Neutral		
Australasian bittern *Botaurus poiciloptilus*	15	** Fresh	** Low	** Extensive sedges	+ Permanent	+ Deep	* Neutral	+ Low	
Glossy ibis *Plegadis falcinellus*	5		+ Low	+ Fringing sedges					
Sacred ibis *Threskiornis aesthiopica*	22	** Brackish	** Low	** Fringing dead trees	* Permanent	* Deep	+ Neutral		+ Large
Straw-necked ibis *Threskiornis spinicollis*	26	** Brackish	** Low	+ Extensive sedges	+ Permanent	** Deep			
Royal spoonbill *Platalea regia*	5		+ Low	+ Extensive trees			+ Neutral		

Yellow-tailed spoonbill *Platalea flavipes*	25	* Brackish	* Low	+ Extensive trees	* Permanent	** Deep			
Black swan *Cygnus atratus*	64	** Brackish	+ Low	* Extensive dead trees	** Seasonal	** Deep	** Alkaline	+ Low	
Freckled duck *Stictonetta naevosa*	21	+ Brackish		* Fringing trees		* Deep			
Australian shelduck *Tadorna tadornoides*	81	* Brackish	+ High				+ Alkaline		+ Large
Pacific black duck *Anas superciliosa*	71	** Fresh	** Low	** Extensive sedges	** Permanent	** Deep	* Alkaline	+ Low	+ Small
Grey teal *Anas gibberifrons*	73	+ Brackish		** Fringing trees	* Seasonal	* Deep	** Alkaline		+ Small
Chestnut teal *Anas castanea*	25	* Saline		* Extensive dead trees	+ Permanent	** Deep	* Alkaline		
Australasian shoveler *Anas rhynchotis*	48	** Brackish		** Fringing dead trees	* Moderately permanent	** Deep	** Alkaline		
Pink-eared duck *Malacorhynchus membranaceus*	49	+ Brackish		** Extensive trees	** Moderately permanent	** Deep	* Alkaline		
Hardhead *Aythya australis*	37	* Saline		* Extensive dead trees	** Permanent	** Deep	+ Alkaline		
Maned duck *Chenonetta jubata*	47	** Brackish	+ Low	** Fringing trees	* Permanent	** Deep	+ Alkaline		
Blue-billed duck *Oxyura australis*	29	* Brackish	+ Low		** Permanent	** Deep	+ Alkaline		

Appendix 2 (*continued*)

Species	*N*	Saltness	September salinity	Vegetation	Permanence	September depth	September pH	Phosphorus	Size
Musk duck	56	*	**	**	**	**	+	+	
Biziura lobata		Brackish	Low	Extensive sedges	Permanent	Deep	Alkaline	Low	
Buff-banded rail	5	+	+						
Rallus philippensis		Brackish	Low						
Baillons crake	6	+	+	+					
Porzana pusilla		Brackish	Low	Extensive sedges					
Australian crake	4	+	+	+					
Porzana fluminea		Brackish	Low	Extensive sedges					
Spotless crake	20	**	**	**	+	+	*	*	
Porzana tabuensis		Fresh	Low	Extensive sedges	Permanent	Deep	Neutral	Low	
Black-tailed native hen	29	+	+	**	*	**	+		
Gallinula ventralis		Brackish	Low	Extensive trees	Moderately permanent	Deep	Alkaline		
Dusky moorhen	9	+	+	*					
Gallinula tenebrosa		Brackish	Low	Extensive trees					
Purple swamphen	24	**	**	**	+	+	+	+	+
Porphyrio porphyrio		Fresh	Low	Extensive sedges	Permanent	Deep	Neutral	Low	Small
Eurasian coot	53	**	+	**	**	**	**		+
Fulica atra		Brackish	Low	Extensive dead trees	Permanent	Deep	Alkaline		Large
Red-kneed dotterel	30	*		**	*	**	**		
Erythrogonys cinctus		Saline		Fringing dead trees	Moderately permanent	Deep	Alkaline		

Hooded plover *Charadrius rubicollis*	17	** Hypersaline	** High	* Open	+ Episodic	+ Shallow			+ Large
Red-capped plover *Charadrius ruficapillus*	39	** Saline	+ High		+ Moderately permanent				+ Large
Black-fronted plover *Charadrius melanops*	32	* Brackish	+ Low	** Fringing trees	** Moderately permanent	** Deep			
Black-winged stilt *Himantopus himantopus*	46	* Brackish		+ Fringing dead trees	** Moderately permanent	* Deep	+ Alkaline		
Banded stilt *Cladorhynchus leucocephalus*	35	+ Saline	+ High	+ Fringing dead trees			* Alkaline	+ Moderate	+ Large
Red-necked avocet *Recurvirostra novaehollandiae*	34	+ Saline	+ High	+ Fringing dead trees					+ Large
Wood sandpiper *Tringa glareola*	7			+ Extensive sedges					
Common sandpiper *Tringa hypoleucos*	19	+ Brackish		+ Extensive dead trees	* Moderately permanent	* Deep	+ Alkaline		
Greenshank *Tringa nebularia*	36				* Moderately permanent	* Deep			
Marsh sandpiper *Tringa stagnatilis*	4								
Sharp-tailed sandpiper *Calidris acuminata*	24				* Seasonal				
Red-necked stint *Calidris ruficollis*	31	+ Saline							+ Large

Appendix 2 (*continued*)

Species	*N*	Saltness	September salinity	Vegetation	Permanence	September depth	September pH	Phosphorus	Size
Long-toed stint *Calidris subminuta*	3		+ Low						
Curlew sandpiper *Calidris ferruginea*	19								* Large
Silver gull *Larus novaehollandiae*	39	** Saline			* Seasonal	* Deep	** Alkaline	* Low	
Whiskered tern *Chlidonias hybrida*	21				+ Seasonal	+ Deep			+ Large
Gull-billed tern *Gelochelidon nilotica*	4				+ Moderately permanent				
Clamorous reed warbler *Acrocephalus stentoreus*	27	+ Fresh	** Low	** Extensive sedges	+ Permanent	* Deep	+ Neutral	+ Low	+ Small
Little grassbird *Megalurus gramineus*	26	* Fresh	** Low	** Extensive sedges	* Permanent	* Deep	* Neutral	* Low	+ Small

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